A Comparative UK-German Study of Hydrogen Fuel Cell Innovative Activity

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Summary

In this thesis, four questions are answered about the nature of hydrogen fuel cell (HFC) research, demonstration and development (RD&D) activity in the UK and Germany: 1) how, when and where HFC innovation and diffusion has occurred, 2) which socio-technical factors best explain the nature and pace of HFC innovation and diffusion, 3) what would add and enrich theoretical and methodological approaches to researching HFCs within Innovation Studies, and 4) what policy options follow on from these insights. Firstly, a theoretical contribution involves a critique of the Technologically-specific Innovation Systems (TSISs) heuristic in terms of concepts of agency and structure, system delineation, system indicators and the quality of policy guidance. The knowledge gaps that are revealed suggest methodological modifications to the TSIS approach to event histories in terms of *organisational funding* – whether events are public, private and public-private – and *geographical location* should also be included in analyses of HFC innovation and diffusion. Secondly, an empirical contribution is made: the provision of two HFC Technological Innovation System (TIS) case studies from the UK and Germany. This evidence suggests sustained positive feedback between system functions is beginning to occur in this niche sector. Over time, HFC technologies are shown to coevolve and branch along certain pathways - and not others - depending upon structural barriers and enablers encountered by HFC actors. Thirdly, there is a contribution to policy based upon the empirical evidence. State actors should recognize that they can take responsibility for encouraging HFC growth and development. Empirically, public-private partnerships (PPPs), when used in combination with state procurement, were shown to offer HFC actors the greatest levels of agency when cutting unit costs and accelerating diffusion. Ultimately, there may well be hybridised or alternative forms of the TSIS heuristic that fare better in their analyses of HFC innovation and diffusion, however, future lines of HFC research using this approach are not advocated here. I have reached this conclusion because the knowledge gaps that I have identified with the TSIS heuristic are likely insurmountable given the TSIS heuristic's neofunctionalist ontology.

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Dedication

This research is dedicated to my wife, Katy, and to our children. They have supported me consistently on this project and their patience has been tested. Along with the support of wider family and friends, I could not have reached this far without all of you.

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List of Abbreviations

AFC	Alkaline Fuel Cell
AFV	Alternative Fueled Vehicle
AIM	Alternative Investment Market
AIP	Air-independent Propulsion
APU	Auxiliary Power Unit
BIS	Department for Business, Innovation & Skills
BMFT	Federal Ministry of Research & Technology
BMVBS	Federal Ministry for Transportation, Building & Urban Affairs
BMVg	Federal Ministry of Defence
BMVI	Federal Ministry of Transport & Digital Infrastructure
BMT	British Maritime Technology
BP	British Petroleum
CCC	Committee on Climate Change
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture & Storage
CEGB	Central Electricity Generating Board
CEP	Clean Energy Partnership
CFCL	Ceramic Fuel Cells Ltd
CHP	combined heat and power
CJBD	CJB Developments Ltd
CME	Coordinated Market Economy
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CoCoNuke	Conservation, Coal & Nuclear
DECC	Department of Energy & Climate Change
DEFRA	Department for Environment, Food & Rural Affairs
DfT	Department for Transport
DH	District Heating
DLR	German Aerospace Institute
DMFC	Direct Methanol Fuel Cell
DoSH	Delivery of Sustainable Hydrogen (EPSRC Supergen XIV study)
DTI	Department for Trade & Industry
DWV	German Hydrogen Association
EAP	Environmental Action Plan
EC	European Commission
ECCC	Energy & Climate Change Committee
ECL	Energy Conversion Ltd
EEC	European Economic Community
EEG	Renewable Energy Sources Act (*Erneuerbare-Energien-Gesetz)*
EHA	Event History Analysis
EPSRC	Engineering & Physical Sciences Research Council
ERA	Electrical Research Association
ETF	Environmental Transformation Fund
EU	European Union
EV	Electric Vehicle
FCB	*Fuel Cells Bulletin*
FCH-JTI	European Fuel Cells & Hydrogen Joint Technology Initiative
FCEV	Fuel Cell Electric Vehicle
FCV	Fuel Cell Vehicle
FIST	Future Infantry Soldier Technology
FoE	Friends of the Earth
GH_2	Gaseous Hydrogen
GKN	Guest, Keen and Nettlefolds
GLA	Greater London Authority
H_2	Hydrogen
HDW	Howaldtswerke-Deutsche Werft
HFC	Hydrogen Fuel Cell
HFS	Hydrogen Filling Station

HMG	Her Majesty’s Government
ICE	Internal Combustion Engine
IDD	Interpoint Distance Distribution
IPC	Infrastructure Planning Commission
IS	Innovation Systems
JV	Joint Venture
kW	Kilowatt
LCEA	Low Carbon Economic Area
LCFS	Low Carbon Fuel Standard
LCICG	Low Carbon Innovation Coordination Group
LCIG	Low Carbon Innovation Group
LEB	Local Electricity Board
LEP	Local Enterprise Partnerships
LH_2	Liquid Hydrogen
LHP	London Hydrogen Partnership
LME	Liberal Market Economy
LQ	Location Quotient
MCFC	Molten Carbonate Fuel Cell
MLP	Multi-level Perspective
MNC	Multinational Company
NaOH	Sodium Hydroxide
NASA	National Aeronautics & Space Administration
NBW-NRW	North Rhine-Westphalia Fuel Cells & Hydrogen Network
NECAR	New Electric Car
NEPI	New Environmental Policy Instrument
NGO	Non-governmental Organisation
NIP	National Innovation Programme (Hydrogen & Fuel Cell Technologies)
NIS	National Innovation System
NOW GmbH	National Organization [for] Hydrogen & Fuel Cell Technology
NRDC	National Research Development Corporation
NSI	National System of Innovation
O_2	Oxygen
OEM	Original Equipment Manufacturer
OLEV	Office of Low Emission Vehicle
PAFC	Phosphoric Acid Fuel Cell
PEMFC	Proton Exchange Membrane Fuel Cell
PPP	Public-private Partnership
R&D	Research & Development
RDA	Regional Development Agency
RD&D	Research, Design and Development
RFC	Regenerative Fuel Cell
RIS	Regional Innovation System
RQ	Research Question
RSI	Regional System of Innovation
SHFCA	Scottish Hydrogen & Fuel Cell Association
SI	Systems Innovation
SIS	Sectoral Innovation System
SME	Small- & Medium-sized Enterprise
SNA	Social Network Analysis
SNM	Strategic Niche Management
SOE	Sociology of Expectations
SOFC	Solid Oxide Fuel Cell
SPD	Social Democrat Party
SSGT	Ship Submersible Gas Turbine
SSI	Sectoral System of Innovation
STP	Science and Technology Push
StrEG	Electricity Feed-In Act *(Stromeinspeisungsgesetz)*
STS	Science, Technology & Society
SWB	Bavarian Solar-Hydrogen-Project (*Solar Wasserstoff Bayern*)
TA	Technological Assessment

TES	Transport Energy Strategy
TfL	Transport for London
TIS	Technological Innovation System
TM	Transition Management
TS	Technological System
TSB	Technology Strategy Board
TSIS	Technologically-specific Innovation System
TVHP	Tees Valley Hydrogen Project
UKAEA	UK Atomic Energy Authority
UKHFCA	UK Hydrogen Fuel Cell Association
ULEV	Ultra-low Emission Vehicle
UPS	Uninterruptable Power Supply
VC	Venture Capital
VSEL	Vickers Shipbuilding & Engineering Ltd.
VINNOVA	Swedish Agency for Innovation Systems
WDA	Welsh Development Agency
WHAT	Whitehall Hydrogen Action Team
WIBA	Hydrogen Initiative Bavaria
ZSW	Center for Solar Energy & Hydrogen Research

Chapter 1: A Comparative UK-German Study

1.0 Introduction

This thesis is about hydrogen fuel cells (HFCs), a disruptive set of clean technologies (Hardman et al., 2013).[1] HFCs store and release electrical energy cleanly and on demand. When installed in a range of stationary and mobile devices, this 'cleantech' has the potential to help regional and national policy makers meet internationally-agreed air pollution, decarbonization and renewable energy targets (Walsh, 1990, Hall and Vredenburg, 2012). However, on the basis of empirical investigations, the way that HFC innovation and diffusion is conceived of needs to alter to more fully reflect the evidence on the ground.

From the 1950s to the present, HFC research and development (R&D) has occurred cyclically. Often HFC R&D has been driven by the research agenda of an individual typically pursuing a single niche product at the behest of an institutional actor. By the 2000s, however, HFC R&D became established as a potential future global industry. Yet, in the countries and regions where HFC innovation has occurred, diffusion has taken place at different rates and in different ways (Tanner, 2014, Tanner, 2016). In attempting to explain how and why such uneven development occurs, proponents of Innovation Studies, a research field which emerged in the 1980s, use analyses of the institutional reasons for 'developmental gaps' between countries to advocate national policies aimed at 'catching up' with more developed countries (cf. Lundvall, 1985, Lundvall, 1992, Freeman, 1987, Dosi et al., 1988). One strand of theorizing in Innovation Studies focuses on technologies: Technological Systems (TSs), Technological Innovation Systems (TISs) and Technologically-specific Innovation Systems (TSISs). This work has suggested that innovation can take place anywhere in space and time. Innovative activity, it is claimed, is established via a universal ease of access to resources by actors thanks to 'global technological opportunity sets' (Carlsson, 1997, Carlsson et al., 2002) and maintained by cumulative causation (Myrdal and Sitohang, 1957). Criticism of technological opportunity sets has come from human geographers who similarly seek to describe and explain the processes behind uneven development (cf. Smith, 2010). It has been suggested that socio-economic concepts of space and place should be incorporated

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[1] Bower and Christensen (1995, 53) define a disruptive technology: "[A] corporation consists of business units with finite life spans: the technological and market bases of any business will eventually disappear. Disruptive technologies are part of that cycle … [C]ompanies must give managers of disruptive innovation free rein to realize the technology's full potential - even … [if it means] killing the mainstream business."

into Innovation Studies' technologically-focused heuristics as part of a spatial turn to strengthen notions of causality (Coenen and Díaz López, 2010, Coenen et al., 2012, Coenen and Truffer, 2012). However, so far, only a small number of relevant case studies exist (e.g. Binz et al., 2014, Binz et al., 2016).

This was the intellectual context in which I began working on this thesis. I gathered primary and secondary source data on HFCs for the Engineering and Physical Sciences Research Council's (EPSRC) Supergen XIV Delivery of Sustainable Hydrogen (DoSH) 4.2 study between 2011 and 2013 (Contestabile et al., 2013). This data revealed that HFC innovation was not taking place anywhere, but instead it occurred in very specific places and at particular times. In this way, this data was at least anecdotally suggestive of the need to place greater emphasis on the impact of space and place on the social processes revealed in TIS/TSIS analyses. The data also suggested that HFC policy guidance needed to better reflect the evidence on the ground (cf. Hacking and Eames, 2012). At the time, theoretical and policy understandings of the socio-technical processes involved in producing different HFC innovative pathways for different countries and regions were being sought (e.g. Mans et al., 2008, Park, 2009a, McDowall, 2010, Madsen and Andersen, 2010). More generally, this growing empirical body of knowledge was informing necessarily long-term and sustainable policy approaches to adopting new and potentially disruptive clean technologies (Foxon and Pearson, 2008, Foxon et al., 2010, Hardman et al., 2013). I therefore specifically set out in this thesis to develop a comparative understanding of *how*, *when*, *where* and *why* technological innovation and diffusion with HFCs is significantly different in the UK and Germany. In these two countries, their R&D base is world-class, but their national and regional institutional arrangements are very different (Contestabile et al., 2013). Thus, in the broad context of the still evolving spatial turn in Innovation Studies, I offer my own empirical, methodological and policy insights into HFC innovation and diffusion in both of these countries using a modified version of the TSIS heuristic. I also put forward a theoretical contribution, but this is *not* in terms of a new innovation heuristic. Rather, my critique of approaches to HFC innovation and diffusion (Chapter 2) is the theoretical contribution that sets up my enquiries in this thesis and ideally creates a platform for further research.

In Section 1.1 below, I outline my personal mission statement. This describes the research journey ahead: why I embarked upon it and what I expect to find. In Section 1.2, I outline the nature of HFC technologies. There is a typology of fuel cell types. This typology covers how HFCs have evolved over time to meet evolving technical challenges. In Sections 1.3 and 1.4, I contextualize how the four research questions and five activities for this thesis emerged. These questions and activities evolved from the findings of the EPSRC Supergen XIV DoSH 4.2 research study undertaken between 2011 and 2013 (Contestabile et al., 2013). In Section 1.5, I describe how my research questions and activities relate to the case study investigation of HFC innovation in the UK and Germany (Chapters 4 to 6). In Chapter 7, I return to my research questions and activities to reflect on how these have been answered.

1.1 Personal Mission Statement

This section summarises why I pursued this particular research journey and what lies ahead in each chapter of the thesis. I begin with my 'Personal Mission Statement' in Text Box 1:

Text Box 1: Personal Mission Statement

With the research I undertook for the DoSH study, empirical evidence from the UK and Germany suggested that there were socio-spatial dimensions operating as part of the socio-technical ones revealed by the TIS/TSIS heuristics (Hacking and Eames, 2012). These processes were likely significant in any analysis of agency and structure of HFC actors involved in innovation and diffusion. This evidence touched on a long-standing debate about whether innovation can arise anywhere in time and space (Carlsson, 1995, Carlsson, 1997, Carlsson et al., 2002) or whether place-specific social processes limit (or channel) the pathways for innovation and diffusion (cf. Freeman, 1987, Cooke et al., 1997, Coenen et al., 2012, Morgan, 2013).

Firstly, I found that the ownership of historic innovation 'events' – whether public, private or public-private – was important. There was a rapid rise in public-private partnerships with hydrogen RD&D and infrastructure from the 1990s onwards offering greater agency to actors. Secondly, the spatial dimension of such events – their geographical and relational contexts – appeared similarly significant. At the time, the spatial dimension of innovation events was being theorized as having an important role in understanding the nature of the causality:

> "Without explicitly elaborating why actors in particular [Technological Innovation Systems or TISs] choose to pursue their activities in particular regional and national contexts, it is very difficult to isolate individual success factors … … [A] spatially naïve TIS concept runs the risk of obscuring simple, place-specific causal relationships behind a more general systems analysis, that in turn lacks explanatory power." (Coenen et al., 2012, 970).

Time *and* place therefore appeared to matter to how innovation and diffusion events play out when analysed through the TIS/TSIS lenses. From this, the *organisational* and *spatial* dimensions of innovative events are the key points of departure from the TIS/TSIS approaches otherwise used in this thesis.

To pursue this agenda further, I began a parallel research journey to the DoSH study in 2011. I wanted to see how the TIS/TSIS approaches performed with HFC-specific data over a longer time frame. This, I hoped, would better evidence the long-term evolution of a national HFC TIS in terms of its *resilience* (cf. Holling, 1973, Walker et al., 2004, Fiksel, 2006), and reveal how significant the two added organisational and spatial dimensions of innovative behaviour could be for HFC technologies in these two countries.

On the basis of this new analysis and an assessment of what the empirical data means for the TSIS approach, I have developed policy guidance for UK HFC actors wishing to catch up' with German levels of HFC innovation and diffusion (Chapter 7). To achieve this, I critically reviewed the literature on innovation with particular reference to HFC activity (Chapter 2). I then developed a unique methodological approach based on a neopragmatic methodology (Chapter 3). I was then able to characterise HFC innovative activity in the UK and Germany between the 1950s and 2012, more than doubling the time frame of the DoSH study (Chapters 4 and 5). The two case studies draw on qualitative and quantitative data and are informed by innovation theory. Based on this empirical evidence, I then compared and contrasted HFC innovative activity between these two countries in terms of the socio-technical barriers and enablers that most influenced change (Chapter 6). This comparative country analysis includes insights based on institutional and spatio-temporal indicators that go beyond the TSIS methodology. Analysis in Chapter 7 of the results of Chapters 4 to 6 help me to make an assessment of the TSIS heuristic's ability to capture the nature of HFC innovation and diffusion in these two cases. Finally, this theoretical debate in Chapter 7 enables me to make suggestions for future HFC empirical research and for future HFC policies in the UK.

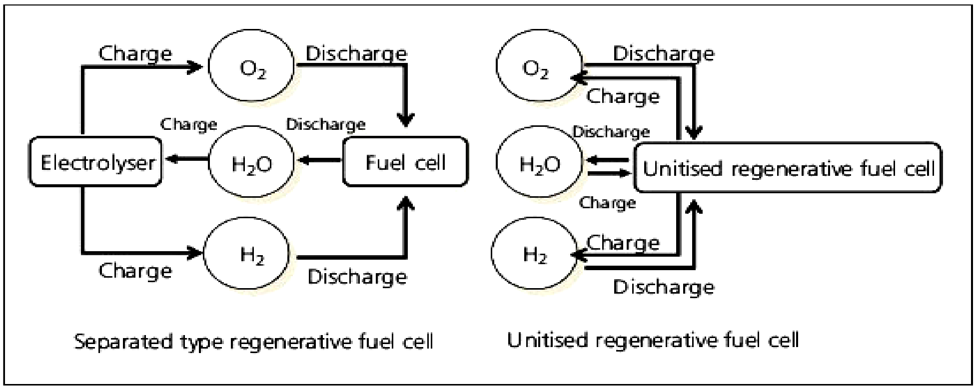
The technical thread running throughout the activities described in the text box above is HFC-related technologies. I examine these technologies in more detail in the next section before describing my research questions and activities.

1.2 The Nature of HFC Technologies

As a set of related technologies, HFCs have long had a strong appeal to scientists and engineers. This interest comes from HFCs' potential for storing and producing energy cleanly and their ability to supply potable water and cabin air humidification in pressurised transport systems such as aircraft, spacecraft and submarines (Adams et al., 1963, Walsh, 1990). It was the Welsh physicist, William Grove, who invented the first fuel cell in 1842. Based on research undertaken at the London Institution where Grove was a professor of physics, his new device could produce electrical energy cleanly via the splitting and recombination of hydrogen and oxygen in water (Appleby, 1990, Perry and Fuller, 2002).

The basic principle of an HFC is simple: an electrochemical reaction in a fuel cell involves the conversion of chemical energy from a fuel source into electricity. When hydrogen is used as the fuel source there is no carbon produced in the process. The only 'waste' products are water and oxygen. The whole process, run in a system called a 'regenerative fuel cell' that is shown in Text Box 2 below, can also be run in reverse to reproduce the original feedstock, or fuel, via an electrolyser.

Text Box 2: Regenerative Fuel Cell Systems



source: Cameron (2011, 113)

There are two forms of 'regenerative fuel cell' (RFC) system shown above. On the left, a 'separated type' includes a separate fuel cell and electrolyser. In this system, the fuel cell's electrochemical process turns oxygen (O_2) and hydrogen (H_2) fuel into water (H_20) and electrical energy. The electrolyser can then run this electrochemical process in reverse using electrical energy to split the water back into oxygen and hydrogen. This system's ability to store and release oxygen and hydrogen and so produce electrical energy on demand via the fuel cell, was a significant technical breakthrough and is the technical cornerstone of visions for a low-carbon ‘hydrogen economy’. On the right of the diagram above is an alternative ‘unitised regenerative fuel cell’ in which a single device can run the electrochemical reactions both forwards and in reverse.

Figure 1 shows that there are a variety of routes from hydrogen feedstock sources at the top of the diagram - whether fossil, renewable or nuclear - to their final use in a range of fuel cell types at the bottom of the diagram. In terms of the hydrogen storage options *en route*, there are two other main storage options:

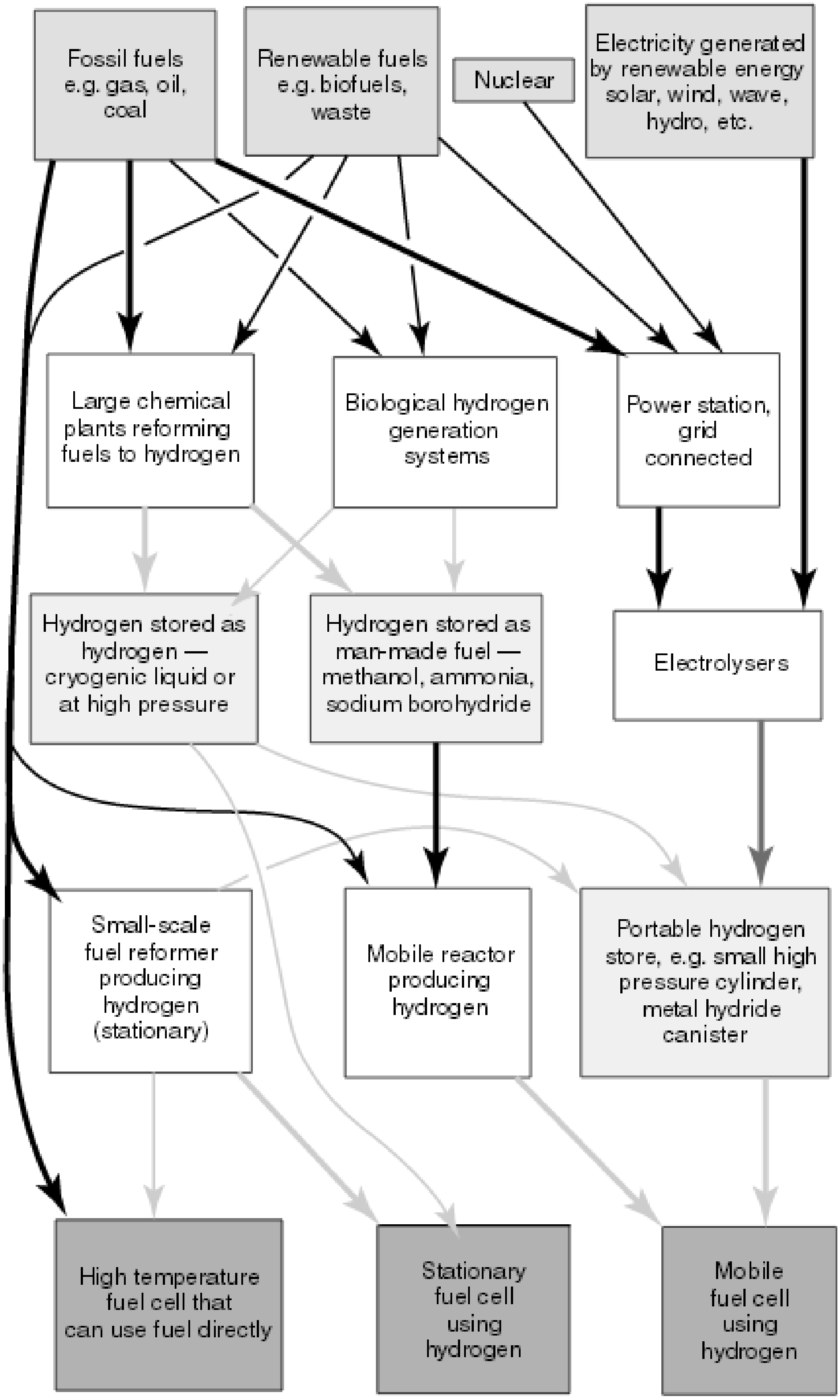
i) ‘Hydrogen stored as hydrogen’ - either compressed, liquefied, or contained within absorbent material, or

ii) ‘Hydrogen stored in hydrogen-rich chemicals’ – i.e. man-made fuels such as ammonia and methanol.

The latter’s chemicals release their hydrogen much more easily than fossil fuels and can be used in mobile systems (Larminie et al., 2003). Recent HFC proponents advocate producing hydrogen feedstocks in as low-carbon a manner as possible (Hall and Vredenburg, 2012). This move has arisen because the greatest decarbonization gains, and hence sustainability benefits, can be made with the greenest hydrogen feedstock.

Table 1 shows that, over time, different fuel cell types have been pursued as researchers have sought to overcome evolving technical challenges (Suurs et al., 2009). Table 1 also reveals how the tasks performed for specific applications and the demands of different operating environments have helped determine which HFC type has ultimately been developed. For example, industrial combined heat and power (CHP) applications typically require high-temperature solid oxide fuel cells (SOFCs). By contrast, domestic micro-CHP markets may well end up being dominated by lower-temperature Proton Exchange Membrane Fuel Cells (PEMFCs) due to the proximity of the units to their end users, i.e. the risk of ignition from a hydrogen gas leak is a concern given that it is odourless, colourless and tasteless. This human factor is the same for mobility applications such as Fuel Cell Vehicles (FCVs), auxiliary power units (APUs) and air-independent propulsion (AIP) in submarines.

Of the six types of HFCs shown in Table 1, the operational characteristics of each differs depending on the different materials used to solve the technical challenges. Each fuel cell type is thus named after the electrolyte used in the main chemical



based on: Larminie et al. (2003, 231)

Figure 1: Different Supply and Storage Routes for Hydrogen Feedstocks Going to Fuel Cells

Table 1: Six Fuel Cell Types

Attributes **Fuel cell type**	**Electrolyte**	**Electrodes**	**Fuel / Oxidant**	**Temperature range (ºC)**	**Typical application**	**Technology generation**	**1st Demos / Applications**
Alkaline Fuel Cell (AFC)	Aqueous solution of sodium or potassium hydroxide	Carbon with a platinum electrocatalyst	H_2 / O_2	25 to 250	Stationary power / FCVs	1st generation (1G)	Bacon (Mid-1950s) NASA manned missions (Mid-1960s)
Direct Methanol Fuel Cell (DMFC)	Proton conducting polymer membrane	Carbon with a platinum electrocatalyst	CH_3OH / O_2	50 to 120	FCVs	1st generation (1G)	Shell FCV RD&D (Mid-1960s)s
Phosphoric Acid Fuel Cell (PAFC)	Phosphoric acid	Polytetrafluoroethylene (PTFE)-bonded Pt/C	H_2 / O_2	150 to 200	CHP	1st generation (1G)	UTC Inc. & Fuji Electric power plants (1970s)
Molten Carbonate Fuel Cell (MCFC)	Molten potassium lithium carbonate mixture	Nickel Monoxide (NiO) / lithium aluminate (LiAlO2)	H_2 & CO (syngas)	600 to 1000	CHP from energy-from-waste (EfW)	2nd generation (2G)	FuelCell Energy, Inc. power plants (Mid-2010s)
Solid Oxide Fuel Cell (SOFC)	Solid ceramic inorganic oxide	Nickel oxide - Yttria-stabilized zirconia for coatings (NiO/YSZ)	H_2, CO / O_2	600 to 1000	CHP	3rd generation (3G)	Versa Power Systems power plants (Mid-2010s)
Proton Exchange Membrane Fuel Cell (PEMFC)	Proton conducting polymer membrane	Carbon with a platinum electrocatalyst	H_2 / O_2	60 to 100	FCVs; Uninterruptable Power Supply (UPS)	3rd generation (3G)	Mid-1960s (NASA)

based on: Ormerod (2003), Suurs et al. (2009)

reaction. Alkaline Fuel Cells (AFCs) use an aqueous solution of sodium or potassium hydroxide with carbon electrodes with a platinum electrocatalyst, plus hydrogen (H_2) as fuel and oxygen (O_2) as the oxidant. AFCs need very pure hydrogen for their fuel due to cell component poisoning by carbon monoxide (CO) and carbon dioxide (CO_2). The strong alkaline solution can also be problematic. Phosphoric Acid Fuel Cells (PAFCs), however, can operate using hydrogen fuel that contains CO_2. Molten Carbonate Fuel Cells (MCFCs), which are not prone to CO or CO_2 poisoning, have shown promise over AFCs and PAFCs (Suurs et al., 2009). Proton Exchange Membrane Fuel Cell (PEMFCs), meanwhile, are poisoned by CO and require an expensive fuel processor and appropriate infrastructure to convert hydrocarbon fuels into hydrogen and CO_2, so eliminating the CO (Ormerod, 2003).

As scientists and engineers have sought to overcome these technical challenges, the different HFC types pursued form an evolving technological typology (Suurs et al., 2009):

- first-generation (1G) - fuel cell technologies based on AFCs and PAFCs,
- Second-generation (2G) - fuel cell technologies including MCFCs, and
- Third-generation (3G) - technologies involving SOFCs and PEMFCs.

As Suurs et al. (2009) indicate, the organisation of HFC technologies has become ever more complex in recent years as 3G fuel cells have become more dominant.

HFC applications began to appear in the mid-20th Century. The first ones involved defence, transport and stationary power and examples from Germany and the UK are given below. During the Second World War, British and German engineers developed fuel cell technologies for submarine propulsion. This development led to the use of electrolysis in submarines to produce fresh water and oxygen from sea water (Stokes, 1998). Thanks to state support, one of these engineers, Thomas Francis Bacon, patented his own alkaline fuel cell (AFC) in the 1950s known as the ‘Bacon Cell’. In a demonstration in Cambridge in England in 1959, a 30-cell battery generated about 6 kilowatts (kW) and powered a welding tool and a fork-lift truck (Bacon, 1969, Eisler, 2009). In November 1967, Bacon was involved with Energy Conversion Ltd, a state-supported energy research partnership, which demonstrated a 5kW 'total-energy' fuel cell system at the International Building Exhibition in London. This prototype micro-combined-heat-and-power (CHP) unit was powered by natural gas. It could provide “electric lighting and power for the family house or for larger complexes such as blocks of flats and schools.” (Pederson, 1968, 82).

That same month in 1967, researchers at Varta Batterie AG near Frankfurt in Germany, jointly filed a patent for a wind-powered off-grid fuel cell energy system with the engineering giant Siemens. The system was demonstrated by leading German electrochemist, Dr. August Winsel, who used the fuel cell to power a television mast.

Also in 1967, engineers at Shell Research Ltd.'s Thornton Research Centre, at Ellesmere Port in Merseyside, built the first demonstration hybrid fuel cell electric vehicle (FCEV). Shell worked closely with the Lucas Research Centre, part of the vehicle component manufacturer, which had designed a solid state control system for the electric motor. Fuel cells in the rear of a Daf 44 car contained hydrazine hydrate which reacted with air to produce electricity. Additional energy for acceleration came from lead-acid batteries which could be kept charged by the fuel cells during periods of low energy consumption. The car had a top speed of 80 kph, weighed nearly 50 percent more than the standard Daf 44 and the hydrazine was difficult to handle. This made this first FCEV demonstration a proof of concept rather than a practical venture (McNicol, 1999).

From these examples of the RD&D of early applications and right up to those still emerging in 2012 - the end point of this study - fuel cells of different sizes, configurations and outputs have been used in an ever-increasing range of applications. However, in this study, I have chosen to focus on applications in the three particular sectors highlighted by the early demonstrations above and which have become the most active sectors since: defence, mobility and stationary power. This means that the list of HFC applications detailed in the following chapters is not exhaustive, but it does represent detailed historic activity from what have turned out to be three very significant sub-sectors of HFC innovative activity. In terms of answering the research questions, this broad range of material offers a good surrogate for analyzing trends across all areas of HFC activity in these two countries.

With the six leading HFC designs – AFCs, DMFCs, PAFCs, MCFCs, SOFCs and PEMFCs – that are outlined here, I now turn to the EPSRC Supergen XIV DoSH research I undertook between 2010 and 2013. Specifically, I relate below how the experience of putting together the DoSH working papers with their broad social, economic and technical contexts that HFC actors have faced (and continue to face) informed the research questions and activities pursued in this thesis.

1.3 Supergen XIV Delivery of Sustainable Hydrogen (DoSH) Consortium

Since 1998, the EPSRC had been working with a range of actors in government (e.g. the Department of Energy and Climate Change, DECC) and with HFC entrepreneurs and academics to develop HFC research. These institutions, firms and individuals were responding to a global renewal in interest in HFCs not seen since the 1960s and 1970s. This disruptive set of technologies was being framed as a way for individual countries to meet ever-more stringent internationally-agreed carbon reduction commitments such as the Kyoto Protocol (UNFCCC, 1997, ICEPT, 2002). HFC actors in the UK, as in other leading countries such as Germany, the US, Japan and South Korea, promoted visions of a ‘hydrogen economy’.[2] These actors have since made renewed efforts in the hope that the UK state will act to capitalize on advances that the country’s world-class HFC researchers make. The challenge for HFC actors has always been to gain greater agency by overcoming structural barriers. In this sense, HFC activity came to be more formally recognized as *socio-technical*, i.e. technical advances that are dependent on co-evolution with institutions (Eames and McDowall, 2006, McDowall and Eames, 2006b). Pursuing the vision of a hydrogen economy with a roadmap and political champions can be an enabler of HFC diffusion. Such efforts can help to maintain a myriad of related institutions and actors in support of a project or broader transition (McDowall, 2012). Cutting HFC unit costs via mass production, for example, remains a key barrier to diffusion, while expectations about the potential of hydrogen and fuel cells drives investment and research (Eames and McDowall, 2010, 95). Such sociotechnical understandings of HFC activity with their attendant HFC-specific policy implications have come to the fore during a steady increase in the UK and German states’ use of public-private partnerships (PPPs). Anecdotally, these HFC PPP networks which began in the 1990s appear to have raised the agency of individual actors and so helped to achieve HFC research outcomes and new infrastructure. However, little is known for sure about how the sociotechnical dynamics of these networks play out over time and they rarely feature in the HFC literature - exceptions include Hodson and Marvin (2010).

In 2008, the EPSRC’s Supergen XIV DoSH consortium began researching a number of chemical and physical means of producing hydrogen from carbonaceous and non-carbonaceous sources (Metcalfe et al., 2008). Made up of fourteen research teams working at twelve UK universities, the DoSH consortium’s intention was to deliver new technologies capable of clean and cost-effective conversion of low-carbon electricity and various carbon sources, including biomass and waste, into hydrogen. I was involved in the fourth and final DoSH work package led by co-investigator, Prof. Malcolm Eames at Cardiff University. This research focused on

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[2] Bockris (2002, 732) defines the ‘hydrogen economy’ as a state where “hydrogen would be used to transport energy from renewables (at nuclear or solar sources [or wind, geothermal and energy-from-waste sources]) over large distances; and to store it (for supply to cities) in large amounts.”

management, knowledge transfer, dissemination and networking. I describe these activities in more detail in the next section.

1.4 Supergen DoSH 4.2 Study: Activities

At Cardiff, Prof. Eames, Dr. Vicki Stevenson, Jenifer Baxter and I undertook the research linked to work package four. This work involved promoting HFC knowledge dissemination via a robust empirically and theoretically grounded evidence base. An analysis was made of HFC innovation systems and how they might be linked to socio-technical transitions in energy. As defined by Herrmann (2009, 336), socio-technical systems:

> “integrate technical and organizational structures and are related to varying stakeholders and their different perspectives … They are also characterized by a continuous evolution which is influenced by interests, conflicts and power relations.”

Given this context, DoSH work package 4 was able to include insights for HFC policy making as part of the promotion and development of a low carbon economy (Metcalfe et al., 2008).

1.4.1 German-UK Comparison

From December 2010, my role was to gather and analyze data on HFC innovation from both Germany and the UK. They were selected for comparison because both were European Union (EU) states, both had adopted challenging long-term targets to cut greenhouse gas emissions by 80% by 2050, both had an active research base in HFCs and both were participants in the European Fuel Cells and Hydrogen Joint Technology Initiative (FCH-JTI).

1.4.2 Activities and Objectives

Prof. Eames and I sought to understand why, in 2011-2, the UK was not at the forefront of HFC market preparations being made by central and/or regional governments in other countries, such as Germany, Japan, South Korea and the United States, despite the UK being known for undertaking world-class HFC RD&D. Before describing the findings of the DoSH study, I will outline the DoSH methodology because this impacts upon the nature of the data available for this thesis as well as its research design.

1.4.3 Methodology

To answer questions about the UK and Germany's relative development of HFCs, it was decided that two socio-technical heuristics from the neo-Schumpeterian approach to the nature of innovation would be useful. These were Technological Innovation Systems (TISs) (Carlsson, 1995, Carlsson, 1997) and Technology-Specific Innovation Systems (TSISs) (Hekkert et al., 2007a) were selected because their methodologies helped to identify the social, economic and technical barriers to the adoption of HFC technologies.

The TSIS heuristic was chosen in particular for its ability to make national case study comparisons of technological co-evolution in terms of system structure *and* function (Hacking, 2013). To do this, the TSIS heuristic imports a neofunctionalist approach into the existing co-evolutionary, structural and functionalist assumptions of TISs.

In essence, the TSIS approach to innovation is based upon the principle of cumulative causation (Myrdal and Sitohang, 1957). Performance is measured by quantifying positive and/or negative feedback between seven functional indicators of innovative activity in a TIS (Hekkert et al., 2007a, Suurs, 2009):

1) **Entrepreneurial activities –** projects with a commercial aim, demonstrations, portfolio expansions
2) **Knowledge development** – studies, laboratory trials, prototypes developed
3) **Knowledge diffusion –** conferences, workshops, alliances between actors, joint ventures, setting up platforms/branch organisations
4) **Guidance of the search** – expectations, promises, policy targets, standards, research outcomes
5) **Market formation** – regulations supporting niche markets, generic tax exemptions, 'obligatory use'
6) **Resource mobilization –** subsidies, investment, infrastructure developments
7) **Advocacy coalitions –** lobbies, advice

As Suurs (2009, 26) notes:

> "System functions are likely to interact with each other, and as they do, a cumulative causation process may be set in motion that directs the TIS through its 'formative stage' into a 'take-off' stage ... In the ideal case, the TIS will develop and expand its influence, thereby propelling the emerging ... technology towards a stage of market diffusion."

Figure 2 suggests that the socio-technical processes associated with each of seven TSIS functions can become mutually reinforcing. This activity occurs in combinations of virtuous (i.e. positive) feedback loops – marked in Figure 2 as loops A, B and C. In the literature these loops are termed 'motors': e.g. 'motors of change' (Hekkert et al., 2007a), 'motors of innovation' (Suurs and Hekkert, 2009b), and 'motors of sustainable innovation' (Suurs and Hekkert, 2012).

This Innovation Systems approach suggests that there is a nested hierarchy of systems in which a national HFC TIS is part of a system, sub-system and component technologies (Hekkert et al., 2007a). As shown in orange in Figure 3, a global TSIS for HFCs contains all the global and national actors and institutions which co-evolve with HFC technologies. In this particular example, the HFC technologies are automotive. A National System of Innovation (NSI) for either Germany or the UK is shown in green in Figure 3. This contains all national-level actors and institutions linked to HFCs and is integrated into the TSIS. The NSI in Figure 3 contains innovative HFC activity in the blue Sectoral Systems of Innovation (SSIs) box. These SSIs include a wide range of technologies linked to HFC mobility, hydrogen supply and storage. In terms of knowledge flow in the SSIs, whilst embedded in their national systems these systems are also directly linked to the global TSIS through multinational ownership.

1.4.4 Data Gathering and Analysis

I built up HFC market data on each country, approached potential contributors and then interviewed them in person or by telephone. Strict anonymity was offered to all. Later on, I managed a small team of PhD students from the Welsh School of Architecture who assisted with coding the qualitative interviews. Results and analysis were presented periodically to the DoSH consortium and at conferences aimed at energy, HFCs, policy makers, low-carbon innovation and Innovation Studies.

1.4.5 Findings of the DoSH WP4.2 Study

The DoSH study concluded that, in terms of the experience with HFCs between the 1990s and 2012, there was little qualitative difference between German and UK RD&D efforts. However, the empirical data revealed that, in terms of *all* activity more broadly linked to HFC innovation, including infrastructure provision, these countries were on very different technological pathways by 2012 (Hacking et al., 2013).

By 2012, due largely to the lack in the UK of a coordinated and well-funded national HFC RD&D programme, the country was falling behind in terms of RD&D activity and the relative provision of infrastructure (cf. Williamson, 2010). In Germany, by contrast,

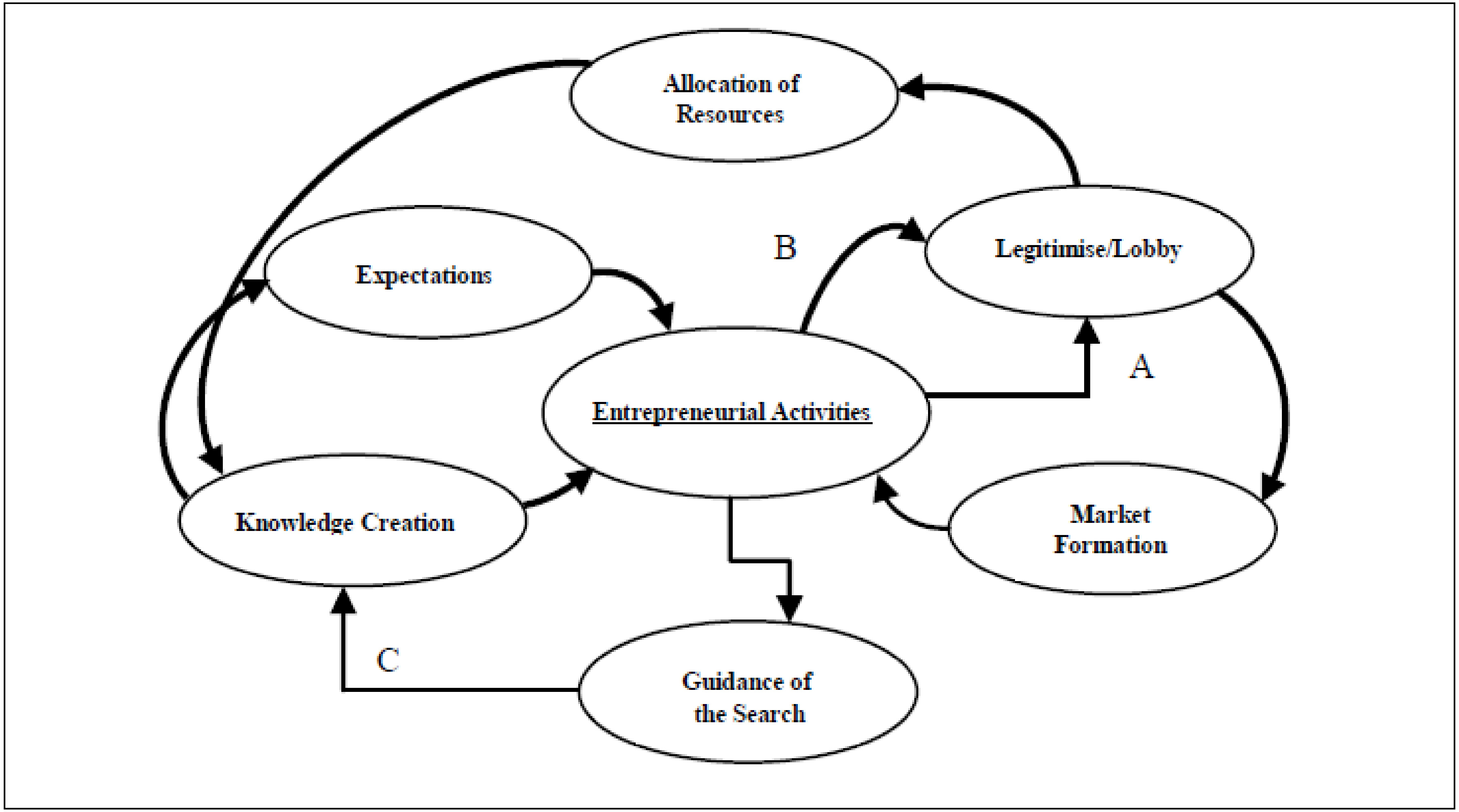


Figure 2: Feedback Loops in the TSIS Heuristic

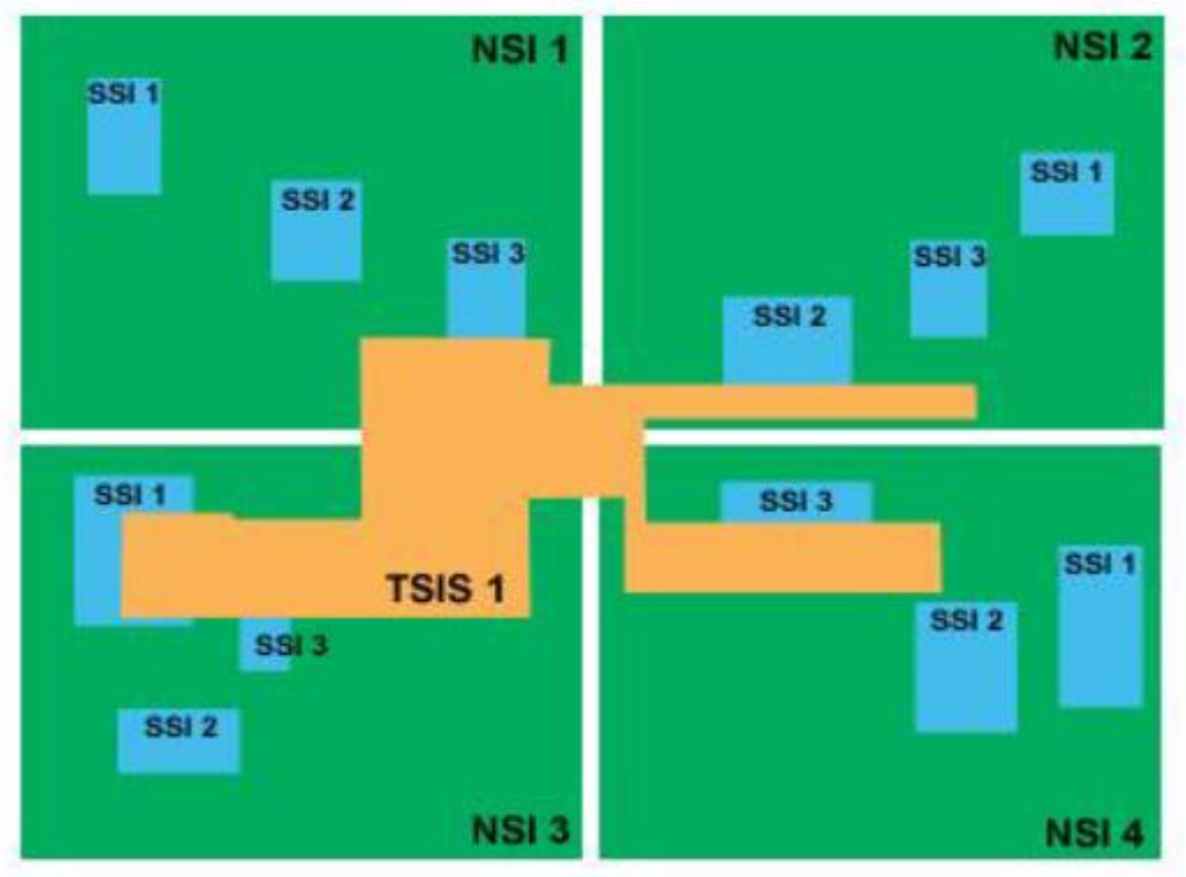


Figure 3: Nested Hierarchy of Analytical Containers (in a Four-Country TSIS)

a number of federal-level policies and initiatives had played a part in developing an enabling framework for public and private hydrogen fuel cell investments since 1998 (Garche et al., 2009, Ehret and Dignum, 2012). The German federal state's framework for HFC activity is the National Innovation Programme (Hydrogen and Fuel Cell Technologies) (NIP). Adopted in 2006, the NIP was developed by the Federal Ministry of Transport and Digital Infrastructure (BMVI). It includes a federal-level roadmap for implementing the growth of HFC markets. Then, in September 2009, with a state-sponsored public-private partnership, National Organization [for] Hydrogen and Fuel Cell Technology (NOW GmbH) up and running, a Memorandum of Understanding (MOU) on 'H_2Mobility' was signed between the German government and several multinational vehicle OEMs and energy majors. This was aimed at aligning actors and encouraging investment in hydrogen fuel cell infrastructure (FCB, 2009, Bonhoff et al., 2012). Given such distinct institutional differences, the range of contrasting indicators listed in the next paragraph below were largely anticipated.

As both countries moved towards emerging niche HFC markets in the decade leading up to 2012, the key structural difference was the greater degree of state management in Germany's economy. This 'varieties of capitalism' analysis of comparative capitalism is firm-centred, does not neglect trade unions, and highlights the role that business associations and other types of relationships among firms play in the political economy (cf. Hall and Soskice, 2001). In Germany's case, advantages can be seen to stem from fully devolved federal system providing two national tiers of funding. Further structural factors of concern to the UK HFC TIS were also identified in the DoSH study:

i) the lack of a top-down, politically-sanctioned medium- to long-term vision of the development of an HFC industrial sector,
ii) the short-term trading emphasis of Britain's capital markets,
iii) persistent under-resourcing and under-valuation of education and training,
iv) less effective institutional links between universities doing hydrogen research, development and demonstration and (former) regional development agencies, local planning authorities and private enterprise,
v) the lack of a national champion in the automotive sector may be a significant factor in terms of lack of government political priority and strategic support leading to poor funding allocation, and
vi) national policy makers have largely focused on electric vehicle prospects and ignored the global vehicle industry's stated long-term vision of moving towards HFC mobility.

In functional terms, the TSIS approach revealed, amongst a range of insights, that a medium- to long-range vision for HFCs has had a significant impact on the guidance of the search function in Germany, aligning actors and focusing the provision of resources for RD&D and market efforts (cf. McDowall, 2012).

In conclusion, work package 4.2 of the DoSH project reported on structural *and* functional aspects of the two case studies. Thanks to the TSIS approach, several key comparative factors that helped to explain the different HFC innovation pathways in Germany and the UK were identified.

1.4.6 Provisional Conclusions of the DoSH WP4.2 Study

What was not anticipated in the German-UK DoSH study was the degree to which these countries' different HFC innovation pathways were being shaped by specific national *and* regional institutional contexts. In terms of the system configuration suggested for HFC mobility in Figure 3, another sub-tier of nested systems' organization appeared to be lacking: regional systems of innovation (RSIs) (cf. Cooke et al., 1997). This emergent territorial context in which this HFC activity was taking place appeared significant. It suggested that space and place mattered in the analysis as much as time. However, this dimension was not fully accounted for in the TSIS methodology (cf. Hacking and Eames, 2012).

Longitudinal data from the TSIS methodological approach was suggesting that some regions where human, financial and physical resources were made available early on were exhibiting a degree of path dependency at later times (cf. Grabher, 1993, Garud and Ahlstrom, 1997, Simmie, 2012, Morgan, 2013, Matos-Castaño et al., 2014). Grabher (1993, 260-4) suggests that there are three types of 'lock in' that actors need to overcome in order to create new technological pathways (or 'path creation'):

1) **Functional lock-in** – Close intraregional relations are typically embedded in long-standing personal connections. This can result in an inability to successfully scan the wider economic environment and so adapt the firm to new information and ways of operating.

2) **Cognitive lock-in** – Mutual corporate orientations based on 1) typically involve a common technical language. 'Groupthink' then emerges where firms strongly defend existing technological pathways.

3) **Political lock-in** – Politico-administrative systems, working closely with industry struggling with 1) and/or 2), can keep nations and regions set on a course which may well have become a dead end particularly after infrastructural investments have been made.

Each of these processes can influence the development of the national HFC TIS. In Germany, the key case in point was Bavaria, a Land active in HFC RD&D from the 1960s. When HFC RD&D activity began to pick up in Bavaria in the early 1990s, the regional authorities did not wait for federal-level HFC policies to appear. Instead, they went ahead with their own instruments which, ultimately, appeared to have the effect of encouraging skeptical national policymakers to follow suit from 1998 and further develop a new HFC pathway.

At the same time, other potential limitations were identified with the TIS and TSIS approaches. These include micro-macro conceptions of actors' agency and structure. For example, Suurs et al. (2009, 9652), in their research into Dutch HFCs, report that: "the TIS approach could benefit from a more sophisticated actor concept." Reliance on the reductionism of systems theory may mean certain TIS and TSIS studies lack overt recognition of actors' power relations and their strategic motivation (Shove and Walker, 2007, Genus and Coles, 2008). TIS event narratives which begin to reveal actors' agency and structure may yet be ahistorical and aspatial when time is used as an independent variable. The neofunctional approach therefore privileges time over space in the analysis (Coenen and Díaz López, 2010, Coenen et al., 2012). Further concerns include causality between events (cf. Kern, 2012) and the need for further empirical testing in order to arrive at more formal, predictive powers (Geels, 2011, Coenen et al., 2012, Truffer and Coenen, 2012, Suurs and Hekkert, 2012). However, advocates of the social constructivist assumptions of the Systems Innovation (SI) and Sociology of Expectations' (SOE) heuristics from Innovation Studies suggest that efforts to establish more agreement on quantitative and qualitative system indicators, which would increase the transferability of results between case study results, may well be erroneous. Only measures of technological expectations, they claim, can give a meaningful insight into system performance (Alkemade and Suurs, 2012). These theoretical concerns are examined in more detail in Chapter 2's critical literature review which informed the formulation of the research questions.

Given these potential theoretical concerns outlined above, methodological efforts were made to incorporate further quantitative and qualitative indicator data into the analysis pursued with the DoSH study. Significant numbers of interviews and quantitative corporate data covering employee numbers and locations were added particularly covering the organizational nature of public-private partnership (PPP) activity because of the added agency associated with such partnerships. This went beyond the original scope of the TSIS approach, and permitted aspects of HFC innovative activity to emerge that might be unexpected. This additional data was triangulated with the TIS event data for Germany and the UK going back to the 1990s.

This thesis therefore picks up on these further lines of research from the DoSH German-UK study by pursuing the following four methodological additions:

1) national HFC Technological Innovation System (TIS) event narratives are coded for the *organizational funding status* of the projects linked to events - this data is then triangulated with other sources to overcome concerns about conceptions of agency and structure linked to power relations,

2) national HFC TIS event narratives are coded for *geographical location* - this data is then triangulated with other sources to overcome concerns about conceptions of agency and structure linked to causality (as well as the lack of analysis at the regional and sub-regional levels in the TSIS heuristic),

3) broad actor inclusion in HFC networks is made to allay concerns about conceptions of agency and structure related to causation and *ex ante* system delineation,

4) text boxes are used in national HFC TIS event narratives at technological branching points summarising micro-level (i.e. project-level) material – citing and sourcing micro-level (i.e. project-level) material more overtly in the analysis than in standard TSIS analyses offers broader insights into conceptions of agency and structure of HFC actors involved in socio-technical contestations.

These methodological additions and how I achieved them are outlined below where I make reference to the development of new research questions, linked research activities and a chapter summary.

1.5 Research Questions and Activities

I began formulating expanded research questions and activities for this thesis once it was clear that significant further research questions were arising from the analysis in the DoSH study (Hacking and Eames, 2012, Hacking et al., 2013). The DoSH case study data suggested that in Germany and the UK regions within these nations have particular HFC resources whether labour, finance, raw materials or markets. HFC actor-networks form in order to gain access to these resources, a process which exhibits path dependency. Thus, history *and* space and place matter in the analysis of German and UK HFC innovation and diffusion (cf. Hacking and Eames, 2012). Over time in Germany, and later in the UK, public and private funds became available simultaneously at the regional, national and supranational levels. This coordinated access to financial resources helped to further de-risk private investments. The federal and devolved nature of regional governance and associated HFC-targeted policies, including hi-tech clustering policies, has helped reinforce the emerging competitive advantages in both countries.

When comparing German and UK hydrogen and fuel cell activity, insights from other Innovation Studies' heuristics are therefore particularly relevant. These include National Systems of Innovation (NSIs), Regional Systems of Innovation (RSIs) and Sectoral Systems of Innovation (SSIs) (Lundvall, 1992, Breschi and Malerba, 1996, Cooke et al., 1997). While a long-term political vision is required to hold public and private actors together in HFC R&D activity, such networked activity also needs operationalizing at different levels/scales. This recognition, alongside the critiques of the TIS and TSIS heuristics outlined above, suggests that HFC innovation might better be explored in terms of "a 'nested', fluid and complex interpenetration of scales of activity" (Hodson and Marvin, 2010, 214). Here, the territorial context of HFC activity would be given greater weight in national case study analyses of innovation and diffusion.

Four research questions (RQs) emerged from the critical literature review in Chapter 2 and the results of the DoSH study. These RQs are shown in Text Box 3 below:

Text Box 3: Research Questions (RQs)

1) 'How, when and where has innovation and diffusion of Hydrogen Fuel Cell (HFC) technologies taken place in the UK and Germany?'

2) 'Which socio-technical factors have had the most influence on the nature and pace of HFC innovation and diffusion in these cases and why?'

3) ‘Based on answering RQs 1 & 2, are there research suggestions that would add and enrich existing theoretical and methodological approaches in Innovation Studies?’

4) ‘What are the policy options that follow on from answering RQs 1, 2 & 3?’

The theoretical aspect of RQ3 will specifically be answered with the critical literature review in Chapter 2 where it will be argued that a range of processes, including power relations, path dependency and space and place, impact upon the innovation process. These research questions then determined the five research activities listed in Text Box 4 below:

Text Box 4: Research Activities

1) Develop a critique of Innovation Studies’ approaches to HFC innovation and diffusion based upon knowledge gaps in the literature;

2) Characterise HFC innovative activity in Germany and the UK between the 1950s and 2012, via two case studies that draw on qualitative and quantitative data and are informed by innovation theory. Analyse events and processes in terms of *how*, *when* and *where*;

3) Based on triangulating this empirical evidence, construct a comparative analysis of HFC innovative activity between these two countries in terms of the socio-technical factors that influence change. Contrast events and processes in terms of *how, when, where* and *why*;

4) Based on triangulating the TSIS and my extended methods, construct a comparative analysis of how effectively the TSIS heuristic captured the nature of these patterns of HFC innovation and diffusion - include the influence of system barriers and enablers, as revealed by analysis of the UK and German data;

5) Develop suggestions for future empirical and methodological work on HFC innovation and policy in the UK.

The flow diagram in Figure 4 shows how these research questions and activities relate to the overall structure of the thesis.

As part of the research for the thesis, the existing DoSH datasets were updated and expanded via a revised methodology (see Figure 6 in Chapter 3). These updates were achieved iteratively through cross-referencing HFC actor data with a research colleague at University College London, Will McDowall. I also added new TIS event data for Germany and the UK taking the timelines back to the major upswing in interest in HFCs in the late 1950s. Following on from these research questions and activities is a summary of the next six chapters.

1.6 Chapter Summaries

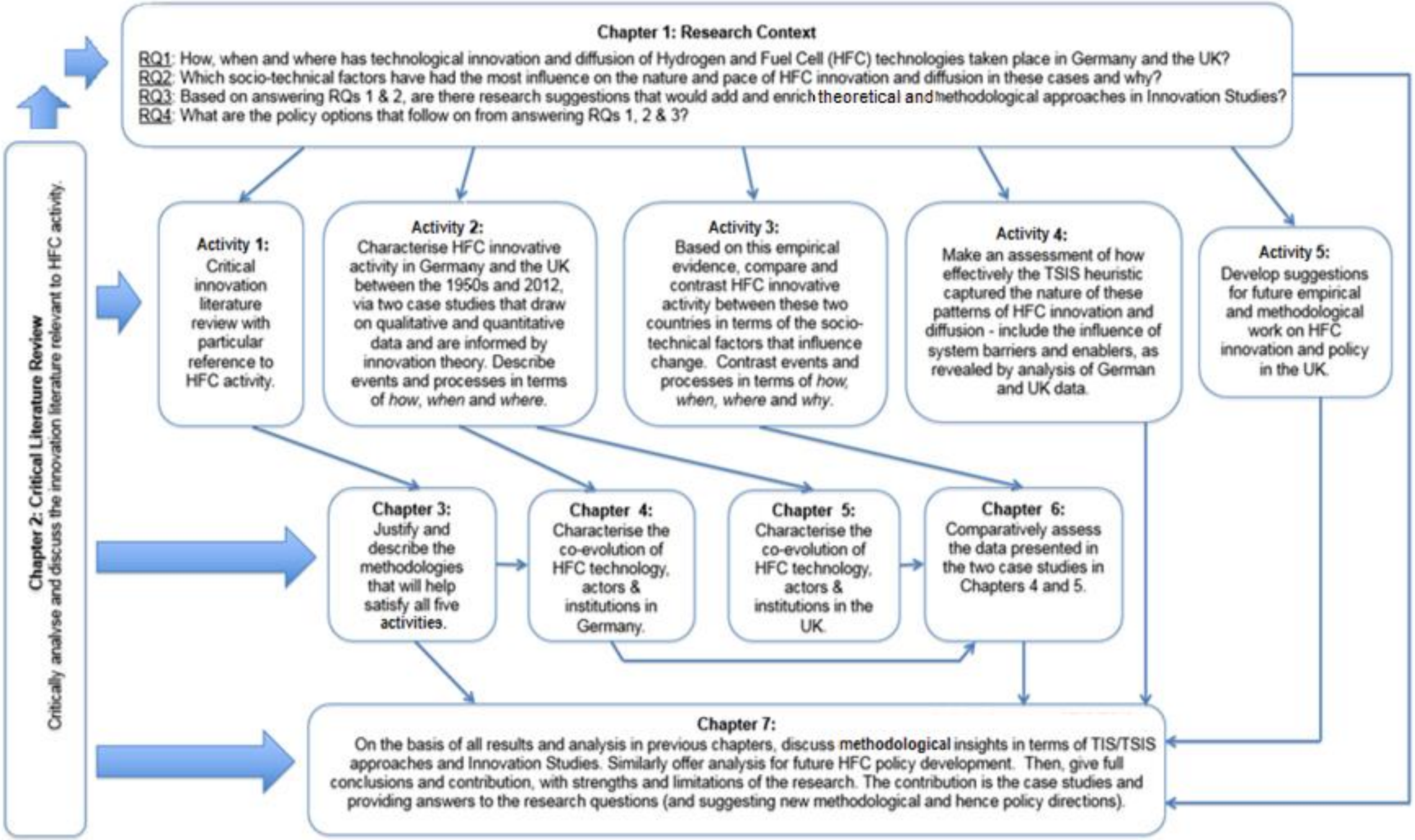
The specific research questions given in Text Box 3 and in Figure 4 determine the chapter summaries which I outline here.

Chapter 2 addresses Activity 1 via a critical review of the Innovation Studies' literature. This critique of the literature is central to the entire thesis as it informs the research questions, the activities, methodology, analysis and conclusions. The literature review has a particular focus on HFC innovation and diffusion. Heuristics from Innovation Systems (IS), Systems Innovation (SI) and the Sociology of Expectations (SOE) approaches are critiqued in four interlinked thematic areas: a) micro-macro conceptions of actors' agency and structure, b) system delineation, c) system indicators, and d) policy.

Chapter 3 helps to achieve Activities 2 and 3 by setting out a mixed-methods case study design that is informed by innovation theory and the critical review in Chapter 2. The preparation and analysis of quantitative and qualitative indicators, such as evidence for system feedback and for governance via expectations, will be made from data collected for the EPSRC's DoSH consortium between 2011 and 2013 as well as from further data collected in 2014-15. Both sets of data are analyzed using Event History Analysis (EHA).

Chapter 4 addresses Activity 2 by presenting a case study of the evolution of the UK HFC innovation system between 1954 and 2012 based on a range of indicators. This includes event history data, actor locational and employee data, and interview material, presented as a narrative of events. This case study reveals how the UK has begun to overcome a range of technical, economic, institutional and societal barriers with HFC technologies. This success came thanks to a range of institutional factors including public-private partnerships (PPPs) and targeted policymaking beneficial to HFC actors.

Chapter 5 addresses Activity 2 with a case study of German HFC RD&D activity.



Chapter 1: Research Context

RQ1: How, when and where has technological innovation and diffusion of Hydrogen and Fuel Cell (HFC) technologies taken place in Germany and the UK?

RQ2: Which socio-technical factors have had the most influence on the nature and pace of HFC innovation and diffusion in these cases and why?

RQ3: Based on answering RQs 1 & 2, are there research suggestions that would add and enrich theoretical and methodological approaches in Innovation Studies?

RQ4: What are the policy options that follow on from answering RQs 1, 2 & 3?

Chapter 2: Critical Literature Review

Critically analyse and discuss the innovation literature relevant to HFC activity.

Activity 1: Critical innovation literature review with particular reference to HFC activity.

Activity 2: Characterise HFC innovative activity in Germany and the UK between the 1950s and 2012, via two case studies that draw on qualitative and quantitative data and are informed by innovation theory. Describe events and processes in terms of *how, when* and *where*.

Activity 3: Based on this empirical evidence, compare and contrast HFC innovative activity between these two countries in terms of the socio-technical factors that influence change. Contrast events and processes in terms of *how, when, where* and *why*.

Activity 4: Make an assessment of how effectively the TSIS heuristic captured the nature of these patterns of HFC innovation and diffusion - include the influence of system barriers and enablers, as revealed by analysis of German and UK data.

Activity 5: Develop suggestions for future empirical and methodological work on HFC innovation and policy in the UK.

Chapter 3: Justify and describe the methodologies that will help satisfy all five activities.

Chapter 4: Characterise the co-evolution of HFC technology, actors & institutions in Germany.

Chapter 5: Characterise the co-evolution of HFC technology, actors & institutions in the UK.

Chapter 6: Comparatively assess the data presented in the two case studies in Chapters 4 and 5.

Chapter 7: On the basis of all results and analysis in previous chapters, discuss methodological insights in terms of TIS/TSIS approaches and Innovation Studies. Similarly offer analysis for future HFC policy development. Then, give full conclusions and contribution, with strengths and limitations of the research. The contribution is the case studies and providing answers to the research questions (and suggesting new methodological and hence policy directions).

Figure 4: Structure of this Thesis

It is structured in parallel to Chapter 4 and begins in 1959. Success has come thanks to a range of institutional factors including PPPs and targeted policymaking beneficial to HFC actors.

Chapter 6 addresses Activity 3 by explaining how and why HFC technology advanced at different rates in Germany and the UK at both the national and regional levels. This is achieved via a comparative analysis of the indicators used in the case studies. For example, quantitative data on HFC innovative activity reveals functional shifts over time and this is supported by qualitative data on shifting expectations for specific HFC applications. Such indicators reveal how and why the UK came to face greater institutional and market barriers than Germany by 2012.

Chapter 7 addresses Activity 4 by identifying how the TSIS heuristic performed against the case study evidence. This assessment is in terms of how the TSIS approach captured the dynamic nature of the co-evolution of HFC technologies and their associated institutions. This analysis concludes that the Innovation Studies' heuristic originally considered for the DoSH study – the TSIS model – could benefit from methodological improvements when viewed against the empirical evidence of HFC innovation in the UK and Germany. This includes more overt use of micro-level interview data and the highlighting of the organizational and spatial contexts in which HFC events take place. These improvements would further boost confidence in TSIS analyses of causality made via historical event data.

Chapter 7 also addresses Activity 5 by reviewing the contributions, strengths and limitations of my analysis and then offers suggestions for further research and policy. Strengths include the empirically rich, detailed longitudinal comparative case studies. Limitations involve the use of data designed for a different study, the lack of a counterfactual case study data and the relative lack of historic micro-level qualitative data which would have further boosted confidence in the analysis of causality. Further research includes examining other possible indicators such as 'relative networked power' with data drawn from participatory stakeholder dialogue and social network analysis (Wieczorek et al., 2013, Breukers et al., 2014).

1.6 Summary

I began this chapter by establishing that HFCs are disruptive technologies which can store and release electricity cleanly via an electrochemical reaction. If deployed with renewable energy sources, HFCs have the potential to help policy makers decarbonize national and regional energy systems. This involves a range of measures required to meet internationally-agreed decarbonisation targets. However, the reasons why HFCs begin to 'take off' in one country, or one region, but not in another, or only in a reduced way, are not well understood. In this introduction, I went on to suggest that this thesis offers an improved empirical and theoretical understanding of the socio-technical differences between two nations innovating in HFC niches: the UK and Germany. I have presented four research questions and five research activities that are central to this case study investigation of HFC innovation and diffusion. I have made it clear that these research questions and activities evolved out of my previous socio-economic research into HFC innovation for the UK's EPSRC Supergen XIV DoSH project. By updating and expanding upon the research undertaken for the DoSH study that I researched, this new work offers a more comprehensive and more robust comparative analysis based on the dynamic nature of HFC co-evolution in Germany and the UK from the 1950s to 2012. The strength of this study is the rich empirical mix of the co-evolution of a disruptive technology with its associated conceptual understanding of actors and institutions.

In the next chapter, I make a critical review of the Innovation Studies literature. This critique is key to the thesis because it puts into context the academic debates underpinning the entire study from the research questions right through to the conclusions.

Chapter 2: Critique of Approaches to HFC Innovation & Diffusion

2.0 Introduction

In this chapter, I expand and develop my critique of Innovations Studies' heuristics. This assessment reveals gaps in the knowledge base for HFC innovation and diffusion activity (Activity 1 from Text Box 4). Based on the academic literature, this critique indicates how my analysis of the strengths and weaknesses of Innovation Studies' approaches with regards to HFCs was arrived at. In Chapter 1, I indicated that the reasons why hydrogen fuel cell (HFC) innovative activity begins to take off in one country (or one region or locality) but not in another are not well understood. To investigate this, I previously made empirical investigations whilst researching on the Engineering and Physical Sciences Research Council's (EPSRC) Delivery of Sustainable Hydrogen (DoSH) study (Contestabile et al., 2013). That comparative research on HFC activity in the UK and Germany was undertaken using the Technologically-specific Innovation Systems (TSIS) heuristic from Innovation Studies. On the basis of the DoSH study, I concluded that the ways that HFC innovation and diffusion are currently conceived of – at least via the TSIS approach – should be altered to better reflect the empirical evidence of HFC innovation and diffusion that I had found on the ground (Hacking and Eames, 2012).

In this chapter, I focus in particular on the strengths and weaknesses of the TSIS heuristic and its precursor, the Technological Innovation Systems (TIS) heuristic. I chose to focus my critique mainly on the TSIS heuristic because of its increasing use in academic and policy circles. I had also used the TSIS heuristic in the prior EPSRC DoSH study to gather HFC data on the UK and Germany. My critique of approaches to HFC innovation and diffusion is divided into four interlinked and emergent themes involving the Innovation Systems, Systems Innovation and the Sociology of Expectations strands of theorizing. These thematic areas cover: a) micro-macro conceptions of actors' agency and structure, b) system delineation, c) system indicators, and d) policy guidance. This critique is of key importance to this thesis because, having identified knowledge gaps, I then use it to help identify which combination of methodological tools can help to strengthen my analysis. This chapter also contributes to shaping the research design in Chapter 3's methodology and methods as well as providing the context for the insights from the evidence base. These insights all touch on my comparative assertions made in Chapters 6 and 7 about the nature of sustainable innovation, knowledge transfer, the commercialisation of HFC technologies, and on policies for the promotion and development of HFCs.

These policy suggestions will be made within the framing of broader, normative moves towards low-carbon national and regional economies in general. In sum, this chapter helps me to refine, address and answer all of the research questions and complete my research activities.

In terms of this chapter's structure, I initially discuss identifying knowledge gaps via an overview of different ontological approaches to theory-building for sustainability transitions in social science (cf. Geels, 2010) in Section 2.2. Different ontologies are briefly explored in order to compare and contrast the central assumptions of the full range of Innovation Studies' heuristics. Such ontological comparisons form the basis of epistemic differences – i.e. what researchers regard as valid knowledge - between these heuristics and this is where the potential for knowledge gaps first takes shape.

In Section 2.3, I critically review the development and use of Innovation Studies' heuristics. Their differing ontologies mean that they have evolved into three epistemic categories: Innovation Systems (IS), Systems Innovation (SI) and the Sociology of Expectations (SOE). Each heuristic from each category offers more advanced understandings of the nature of innovation and diffusion when compared to neo-classical economic approaches (such as Rational Choice). However, each heuristic, which is constantly being revised by Innovation Studies theorists as 'works in progress', also has its own potential shortcomings linked to HFC-specific knowledge gaps. Each heuristic is critically examined in Section 2.3 in terms of the four emergent themes from the literature which I outlined above. I then critically review HFC literature and identify specific knowledge gaps using the same four themes.

In Section 2.4, I conclude the chapter by indicating how my critique has helped me to decide what I should do in the later chapters. I summarize what the knowledge gaps are and how and why they might be analyzed more effectively. I also outline my suggested solutions, which are developed more fully in Chapter 3, where I extend the coding frame used with the TSIS heuristic to gather additional data about the organizational funding and the geographical location of HFC events. I summarize what I have achieved in this chapter in Section 2.5.

In the next section, I have outlined the ontological approaches used by Innovation Studies' heuristics to explain the nature of sustainability transitions. I have done this in order to focus in greater detail on the relative performance of all heuristics, but, in particular, on how the TIS/TSIS approaches are able to deal with my research questions.

2.2 Ontological Approaches to Sustainability Transitions

Sustainability transitions, including moves towards a low-carbon economy, are multi-dimensional in nature (Markard et al., 2012). Such transitions are approached in different ways by different disciplines with different ontologies. Assumptions about causal relationships therefore differ and this leads to the over- or under-emphasis of certain explanatory factors (Geels, 2010). With Innovation Studies, actors have relative degrees of transformative capacity or *agency*, a term broadly defined as the freedom to act independently (Giddens, 1979). However, this freedom to act is constrained by *structure*, the broader social, economic and technical arrangements (or *institutions*) in which actors are embedded and which influence or limit choices and opportunities (Giddens, 1984).[3] Theoretical conceptions of how micro-level notions about the agency of individuals mesh together with macro-level conceptions of the structure of an individual's environment - the so-called 'micro-macro problem' - are problematic for many Innovation Studies heuristics including TISs and TSISs (Callon and Latour, 1981, Wiley, 1988, Tsekeris and Lydaki, 2011).

Ontological choice carries distinct implications for any analysis of sustainability transitions. As Geels (2010, 496) notes: "[Particular] studies of transitions ... inevitably highlight certain aspects and background others." Given this caveat, Table 2 outlines seven leading ontologies in the social sciences as identified by (Geels, 2010) in terms of four broad dimensions:

- a) analytical approach,
- b) conceptions of agency and structure,
- c) default system orientation: stability vs. dynamism, and
- d) explanatory factors offered for transitions.

The first approach shown in Table 2, Rational Choice, is a micro- and macro-level perspective which underpins neo-classical economics. Here, self-interested, fully-informed and utilitarian causal agents attempt to maximize utility. They were later reconceptualised as 'boundedly rational' actors (Simon, 1947) who engage in 'satisficing' because they cannot determine optimal solutions. The default system orientation is stability (equilibrium) or incremental change

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[3] Giddens (1979) argues that social structure can be regarded as a system of norms which both channels and is the result of social action.

Table 2: Characteristics of Transitions in Different Ontologies

Ontology	Analytical approach	Agency / structure	Default system orientation	Explanatory factors offered for transitions	Proponents
Rational Choice	Self-interested, boundedly rational, utilitarian causal agents ‘satisfice’ to meet their needs.	Micro and macro levels.	Stability (equilibrium) or incremental change.	Difficult. Requires exogenous impulse (price changes) followed by gradual adjustment (of resource allocation).	Jevons (1862 / 1884), Marshall (1890)
Structuralism	Cognitive ‘deep structures’ are the causal agents that provide meaning and a sense of direction for actors.	Micro and macro levels.	Stability.	Difficult. Changing ideologies and belief systems often remain exogenous.	De Saussure (1916), Lévi-Strauss (1955)
Functionalism (Systems Theory)	The social system is the causal agent. It has needs/goals for actors who fulfil functions, tasks or roles.	Macro and meso levels.	Stability (system equilibrium).	Difficult. Requires exogenous shocks, followed by gradual adjustments.[a]	Durkheim (1895/2014), Bertalanffy (1945), Bertalanffy (1951), Parsons (1949), Parsons (1951)
Evolutionary	There is a population of heterogeneous and boundedly rational causal agents who do not optimize, but satisfice.	Micro and macro level.	Dynamic stability (incremental change along lineages) and radical change (speciation, niches, competition).	Endogenous change (radical innovations) and/or exogenous changes in selection pressures.	Darwin (1859/1991), Marx (1867), Schumpeter (1911/1934), Schumpeter (1942/2013)
Conflict and Power Struggle	Collective actors (e.g. social movements, special-interest groups) with conflicting goals and interests.	Macro.	Stability (powerful actors suppress change), incremental change (‘reform’ to accommodate protests) and radical change (‘overthrow’ by challengers).	Endogenous struggles between incumbents and challengers.	Marx (1867), Mills (1956), (Dahrendorf, 1959), De Beauvoir (1949/1997)

based on: Geels (2010)

[a] Complex systems theory acknowledges that endogenous processes may create ‘conditions for change’ where external shocks have big effects.

Table 2: Characteristics of Transitions in Different Ontologies

Ontology	**Analytical approach**	**Agency / structure**	**Default system orientation**	**Explanatory factors offered for transitions**	**Proponents**
Social Constructivism	Causal agents are creative and continuously engaged in inter-subjective sense-making and learning.	Micro and macro.	Ongoing change and sense-making.	Radical change through endogenous second-order learning processes (change in cognitive frames).	Vygotsky (1930/1980), Vygotsky (1934/1987)
Relationism	Relations and ongoing interactions of actors with fluid identities are the causal agents.	Micro and macro.	Continuous process (change or reproduction).	Unclear. No distinction between radical or incremental change. Focus on micro-processes and local projects.	Durkheim (1912/2012), Mannheim (1929/1936)

based on: Geels (2010)

(cf. Bush, 1945a, Bush, 1945b, Schmookler, 1954, Schmookler, 1957, Isenson, 1968, Mowery and Rosenberg, 1979, Rennings, 2000, Taylor, 2008, Nemet, 2009, Peters et al., 2012). These heuristics posit a simple straight line from R&D to finished products (Lundvall, 2007).

In Table 2, structuralism is shown to be a micro- or macro-scale approach where causal agents are 'cognitive deep structures' which provide meaning and a sense of direction for actors (Geels, 2010). Structuralist approaches involve a stable social system and a number of common assumptions:

i) every system has a structure,
ii) structures determine the position of system elements, and
iii) structural laws deal with co-existence rather than change.

These assumptions suggests that proponents of structuralist heuristics – including the TIS and TSIS in part - regard changing ideologies and belief systems as exogenous to the system (Geels, 2010). Structuralism is useful for analysing processes at the macro-scale but has been criticized for ahistorical, deterministic and mechanical analyses (Giddens, 1976).

Table 2 shows that functionalism, when studied alongside structuralism, produces macro level analyses via systems theory. According to Hekkert et al. (2007a), structural-functionalism has two key tenets:

i) the social world has an objective reality accessible by applying the traditional positivist methods of the natural sciences, and
ii) models used are based on the analogy of how an individual organism might represent society.[4]

The social system is the causal agent. It has its own needs/goals and actors fulfilling functions, tasks and/or roles (Geels, 2010). Functionalism (and neofunctionalism) do not, however, suggest the origin, motivation and context in which agency is exercised. Accounting for social change is difficult given that equilibria are sought at the system level (Merton, 1948/1968, Hellström, 2004). Structural contradictions and conflict are not well theorised (cf. Shove and Walker, 2007) . This means that explanations of

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[4] Note that Hekkert et al (2007a) reject Parsons' structural-functionalism in their work on technological innovation systems (TISs), preferring a more neofunctional approach.

transitionary change via the TIS and TSIS heuristics look to exogenous shocks followed by gradual adjustments rather than endogenous factors (Geels, 2010).

The evolutionary ontological approach, which all Innovation Studies heuristics are also linked to, can be pursued at the micro- and macro-levels (Table 2). Here, heterogeneous and boundedly rational causal agents do not seek to optimize, but satisfice instead (cf. Simon, 1947, Simon, 1956). The default orientation of the system is dynamic stability (incremental change occurs in terms of variations from a common descent) plus radical change (speciation, niches and competition). Both exogenous and endogenous factors can be evolutionary selection pressures (Geels, 2010). However, evolutionary assumptions can lead to over reliance on the reductionism of systems theory (cf. Howells, 1999). An overt recognition of power relations may be lacking and ahistorical and aspatial understandings may be promoted (Shove and Walker, 2007, Genus and Coles, 2008, Coenen and Díaz López, 2010, Coenen et al., 2012).

Social constructivism, associated with SI and SOE heuristics, is a way of examining how individual actors make sense of the world via the collaborative construction of artefacts with shared meanings (Table 2).[5] In this approach, the agency of actors and the structure they face derives from learning, creativity and dynamic inter-subjective sense-making (Geels, 2010). Radical change is possible through endogenous second-order learning processes (i.e. changes in cognitive frames) (cf. Callon, 1998, MacKenzie et al., 2007, Callon et al., 2009). Positivists find this ontology problematic because there is no fixed point of objective reference (Collins and Yearley, 1992, Winner, 1993, Bijker, 1993).

Relationism is the final ontological approach shown in Table 2. It relates to the social context of human thought, how knowledge is connected through networks and what effects prevailing ideas have on societies (e.g. Berger and Luckmann, 1966, Foucault, 1975, Latour, 1987). Causal agents are the ongoing interactions of actors with fluid identities (Geels, 2010). In terms of explanations of transitions, no distinction between radical or incremental change is made. The focus tends to be on micro-level processes and local projects. Relationist explanations for transitions have been called "unclear" (Geels, 2010, 504), but relationist methodologies have contributed to transitions theorising via Actor Network Theory, for example (Callon, 1986, Latour, 1987, Law, 1992).

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[5] As compared to social constructionism which focuses on shared beliefs rather than artefacts.

In summary, moving from Rational Choice to Relationism in Table 2, there is a general shift from stable systems offering exogenous factors for change to dynamic ones offering endogenous ones. Also, the default system orientation shifts from systems seeking stability to those involving dynamic change. Similarly, notions of agency shift from predominantly macro level to predominantly micro level. Finally, this characterisation is useful to this thesis because, in the next section, it permits a better understanding of the methodological orientations of the various Innovation Studies heuristics. These heuristics are critiqued in terms of different epistemic communities (cf. Fagerberg et al., 2005): Innovation Systems (IS), Systems Innovation (SI) and Sociology of Expectations (SOE). Ultimately, this review of ontological approaches to sustainability transitions will be returned to in Chapter 7’s methodological discussion. In the next section, I chart the historic evolution of the three strands of Innovation Studies before giving a thematic critique of these heuristics in Section 2.4.

2.3 Historical Development of Innovation Studies Heuristics

In this section, the shared antecedents of Innovation Systems (IS), Systems Innovation (SI) and Sociology of Expectations (SOE) heuristics are outlined. Overall, the potential shortcomings of one strand of Innovation Studies thinking are shown to lead to reassessments as well as the development of the next strand.

Joseph Schumpeter, known as the ‘father of evolutionary economics’, offered several “flashes of illumination” (Hodgson, 1997, 149) into the nature of innovation (Schumpeter, 1911/1934, Schumpeter, 1939, Schumpeter, 1942/2013). In the 1960s, neo-Schumpeterian researchers reassessed the relative merits of the rational choice approaches to innovation and restated Schumpeter’s view that innovation is central to economic growth (Fonseca, 2002). Neoclassical economic approaches to innovation were tested against empirical evidence (Pavitt, 1998). Large-scale case studies of the innovation-diffusion process in the global electronics, plastics and chemical sectors were undertaken (Freeman, 1963, Freeman et al., 1965, Freeman, 1968). For the neo-Schumpeterians, these studies confirmed the dynamic nature of markets: they do not move towards equilibrium as neoliberal economic theory predicts (Freeman, 1987). Innovation and learning were shown to be crucial for firms who are continually in search for competitive advantage: “[N]ot to innovate is to die” (Freeman, 1974, 256). A macro-level innovation theory, the ‘Nelson-Winter-Dosi’ model emerged in the 1980s (Dosi, 1988, Dosi et al., 1988). Based on the theory of paradigm shifts (Kuhn, 1962), this heuristic provided the basis for the development of

IS and SI heuristics. The evolutionary approach to the diffusion of knowledge was based on search routines:

> "[I]n practically all parts of the economy, and at all times, we expect to find ongoing processes of learning, searching and exploring, which result in new products, new techniques, new forms of organization and new markets" (Lundvall, 1992, 8)

Critics of this evolutionary approach were concerned, however, about its implied determinism:

> "[I]ntentional or purposeful behaviour … is problematic … How [can] genuine choice and purposeful behaviour be reconciled with any deterministic model – cultural, biological, utilitarian or whatever – of human behaviour [...?]" (Hodgson, 1997, 139-140)

Similarly, Fagerberg (2003, 152) suggests that the Nelson-Winter-Dosi model demands further micro-macro theorising:

> "[I]f what Nelson and Winter do is to apply Schumpeter's principle of heterogeneous agents to the firm level (rather than to individuals). This … raises many new questions … [e.g.] what is the relationship between individual cognition and collective cognition? How do firms 'think'?"

With these concerns in mind, I describe the development of the three strands of Innovation Studies theorising in the next three sections.

2.3.1 Innovation Systems (IS) Heuristics

In the 1990s, the 'Nelson-Winter-Dosi' model of innovation (Dosi, 1988, Dosi et al., 1988) began evolving into related but distinct Innovation Systems (IS) heuristics: National Systems of Innovation (NSIs) (Lundvall, 1992), Regional Systems (RSIs) (Braczyk et al., 1998), Sectoral Systems of Innovation (SSIs) (Breschi and Malerba, 1996) and Technological Innovation Systems (TISs) (Carlsson and Stankiewicz, 1991)[6]. These approaches mix evolutionary, structural and functional theoretical

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[6] These approaches were originally referred to as 'National Innovation Systems' (NISs), 'Regional Innovation Systems' (RISs), and 'Sectoral Innovation Systems' (SISs).

assumptions to produce macro-level, non-deterministic accounts of technological development based on the bounded rationality of actors. The co-evolution of organizational forms and technologies is charted (cf. Nelson and Winter, 1982). Although macroeconomic in outlook, IS heuristics are more sophisticated than the technology-push, demand-pull approaches from neo-classical economics in terms of agency and structure.[7]

Since the mid 2000s, one particular neofunctionalist approach based on the TS and TIS heuristics, the Technologically-specific Innovation System (TSIS) heuristic, has shown particular promise theoretically and in its application to innovation policy in Sweden (Hekkert et al., 2007a, Bergek et al., 2008). As stated in Section 1.4.3 in Chapter 1, the TSIS heuristic was chosen for the EPSRC's DoSH consortium's comparative study of HFCs in Germany because of its ability to make national case study comparisons of technological co-evolution in terms of system structure *and* function (Hacking, 2013). To do this, the TSIS heuristic imports a neofunctionalist approach into the existing co-evolutionary, structural and functionalist assumptions of TISs. In essence, the TSIS approach to innovation is based upon the principle of cumulative causation (Myrdal and Sitohang, 1957). Performance is measured by quantifying positive and/or negative feedback between seven functional indicators of innovative activity in a TIS (Hekkert et al., 2007a, Suurs, 2009).

However, as I first stated in Section 1.4.6, the degree to which the UK and Germany's different HFC innovation pathways were being shaped by specific national *and* regional institutional contexts was not anticipated and appeared significant. Yet this dimension was not fully accounted for in the TSIS methodology (cf. Hacking and Eames, 2012).

2.3.1.1 Innovation Systems (IS) Heuristics - Policy Implications

In policy terms, an NSI approach stresses the more intangible investments in technological learning activities by institutions, the links amongst them as well as incentive structures and competencies (Patel and Pavitt, 1994). Such activity is designed to avoid low corporate R&D spending and low spending in terms of workforce skills. Both of these help determine long-term economic growth rates and national demand for basic research and associated training activities (Patel and Pavitt, 1994).

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[7] However, they have been critiqued for their pronounced separation of the creation and the selection of innovation.

An RSI approach to innovation policy suggests a focus on the entrepreneurial culture and the level of innovation activity in a region (Fritsch and Mueller, 2007). While overarching national policies will be important, regional development strategies and policy measures need to account for region-specific factors. Factors stimulating entrepreneurship, like regional tax and welfare arrangements as well as general economic development policies are thought to be important (Van Stel and Stunnenberg, 2004). Large businesses can also make a significant contribution to regional development as incubators for spin-offs (Klepper and Sleeper, 2005; Agarwal et al, 2004; Klepper, 2001; Sorenson, 2003). However, precisely how to achieve a balanced combination of both small businesses and incumbent enterprises remains ―still rather unclear‖ in policy terms according to Fritsch and Mueller (2007, 312).

According to Malerba (2002, 29), policymakers pursuing an SSI approach need to:

> "[F]acilitate the self-organisation of the sectoral innovation system within the relevant policy domain."

This involves policy measures on a number of fronts including prioritising investment into basic science and R&D activities, as with other innovation studies approaches. Such broad measures could also include generic and thematic research funding programmes, bridging/linking policies to foster the application of knowledge, and improving science education and the stock of qualified scientists and engineers (Reid and Miedzinski, 2008).

Specifically, in terms of innovation policy, an SSI approach suggests increasing the quantity and efficiency of innovation activities in enterprises, measures boosting investment invest in technological product and process (TPP) and non-technological innovation, support for improved innovation management skills and the promotion of innovation culture (Reid and Miedzinski, 2008). Regarding sectoral innovation policy, measures include improving the organisation of the sectoral innovation system (networks, etc.), increasing the understanding of sectoral-specific drivers and barriers, tailoring general measures to sectoral needs or launch sectoral innovation policy measures, and improving the institutional conditions regulations, IPR, etc.) specific to the sector (Reid and Miedzinski, 2008). Lastly, where the sector is showing signs of spatial clustering, policymakers can attempt to strengthen the linkages between the enterprises and related organisations of a cluster with a view to increasing joint R&D, innovation, export, training, etc. activities and identify and remedy specific institutional, framework, etc. barriers to the development of the cluster (Reid and Miedzinski, 2008).

In terms of TIS/TSIS policy, Bergek et al (2008) suggest that the healthy feedback between system functions is often impeded by “blocking mechanisms”. These include uncertainties of needs among potential customers, inadequate knowledge of relations between investments and benefits, lack of capability and poor articulation of demand, lack of standards, few relevant university programmes for skills and a weak advocacy coalition. Remedying these deficits in policy terms involves increasing user capability, supporting users to increase and diffuse knowledge, supporting experiments with new applications, developing standards, altering research and education and supporting an advocacy coalition (Bergek et al, 2008).

2.3.2 Systems Innovation (SI) / Technological Transition (TT) Heuristics

In the early 1990s, as part of an earlier reaction to the shortcomings of IS heuristics, (chiefly their reliance on structural and functionalist ontologies[8]), a new strand of Innovations Studies emerged: Systems Innovation (SI) heuristics based on quasi-evolutionary theories known as Technological Transitions (TTs). These heuristics include Strategic Niche Management (SNM), Transition Management (TM) and the Multi-level Perspective (MLP).[9]

Each of these heuristics imports social constructivist and relationist assumptions from Science, Technology and Society research (cf. Latour and Woolgar, 1979, Callon, 1980, Callon, 1986, Pinch and Bijker, 1984, Hughes, 1986). Policy problems are framed in terms of actors achieving societal functions (Kemp and Soete, 1992, Kemp, 1994, Kemp et al., 1998a, Kemp et al., 2007a). Analysis is made of the long-term restructuration of heterogeneous socio-technical elements and processes in which markets and institutions are an important part of the broader picture (cf. North, 1990).

However, SI theorists are less interested in normative goals such as sustainability compared to their IS counterparts (Smith et al., 2010). SI heuristics produce micro-level insights about technological niches, regimes, learning and actor networks based on the concept of sustainability transitions, i.e. normative shifts towards the development of more sustainable technologies (cf.Van den Belt and Rip, 1987, Kemp, 1994, Kemp, 1995). The focus in the literature is on public-private sector cooperation

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[8] In sociology in the 1970s and 1980s, the structural functionalist approaches of Parsons (1949, 1951) were critiqued by Giddens (1979, 1984) amongst others.

[9] I devote more space here to SI approaches than IS and SOE because of their importance to my analysis of Technological Transitions with HFCs, which I return to in Chapters 6 and 7.

that may shape the future direction for so-called ‘pathway technologies‘. Government policymakers must make strategic judgements about which technologies to develop. They are encouraged to do this via the technological assessment of technical feasibility, economic opportunities, user demand and competitive advantage over alternative technologies (Kemp, 1994; Kemp et al, 1998).

Insights from Innovation Studies and social constructivism were merged with several new SI/TT heuristics in the 1990s and 2000s. The first was Constructive Technology Assessment (CTA) (Schot and Rip, 1997). Here, a split in Innovation Studies between the processes of technological variation and selection was critiqued. It was argued instead that technologies are shaped simultaneously with their environmental context in a ‘co-evolutionary’ fashion. CTA is underpinned by the idea that paradigm shifts in technology can be steered by national governments (Schot et al., 1994). In policy terms, carrot and stick approaches, like grants for technology testing, are proposed. However, examination of the social, economic, technical and political factors shaping the trajectories of future clean technologies, like hydrogen fuel cells, was then largely ignored in the literature for a decade because of a “largely one-dimensional and instrumental, downstream-consequences risk discourse” (Wynne, 2002, 464).

The evolution of three more SI/TT heuristics - Strategic Niche Management, Transitions Management and the Multi-level Perspective – are outlined below along with a section on the policy implications of their use.

2.3.2.1 Strategic Niche Management (SNM)

In 1994, a new SI/TT heuristic, Strategic Niche Management (SNM), was proposed. This heuristic took shape in the context of policy efforts to help to create more sustainable energy and transport systems (Kemp, 1994, Kemp et al., 1998b). This heuristic is defined as:

> “The creation, development and controlled phase-out of protected spaces for the development and use of promising technologies by means of experimentation, with the aim of (1) learning about the desirability of the new technology and (2) enhancing the rate of application of the new technology” (Kemp et al., 1998b, 186).

SNM examines the social, economic, legal, cultural, and political factors that create conflict with the introduction and expansion of new technologies (Kemp, 1994; Kemp et al, 1998). Actors work to establish a niche in which new technological factors and societal factors can develop and advance together. However, because of the wide range of actors and structures, SNM focuses on potential conflicts when introducing new technologies, a focus that is highly relevant to the development of many radical technologies, including hydrogen fuel cells.

As shown in Figure 5, innovative growth structures in SNM (marked ‘1’), which are based around actors/sectors/firms, are protected in a niche thanks to subsidies and/or other regulatory measures (cf. Nelson and Winter, 1977). Niches are defined by Kemp et al. (2001, 274) as “limited domains in which the technology can be applied.” Niches are important to transitions because they help demonstrate the viability of a new technology, provide financial means for further expansion, foster support from stakeholders, and set in motion learning activities - the development of complimentary technologies and institutional adaptations – which are all key to a technology’s diffusion (Kemp et al., 2001). Park (2009, 70) points out that:

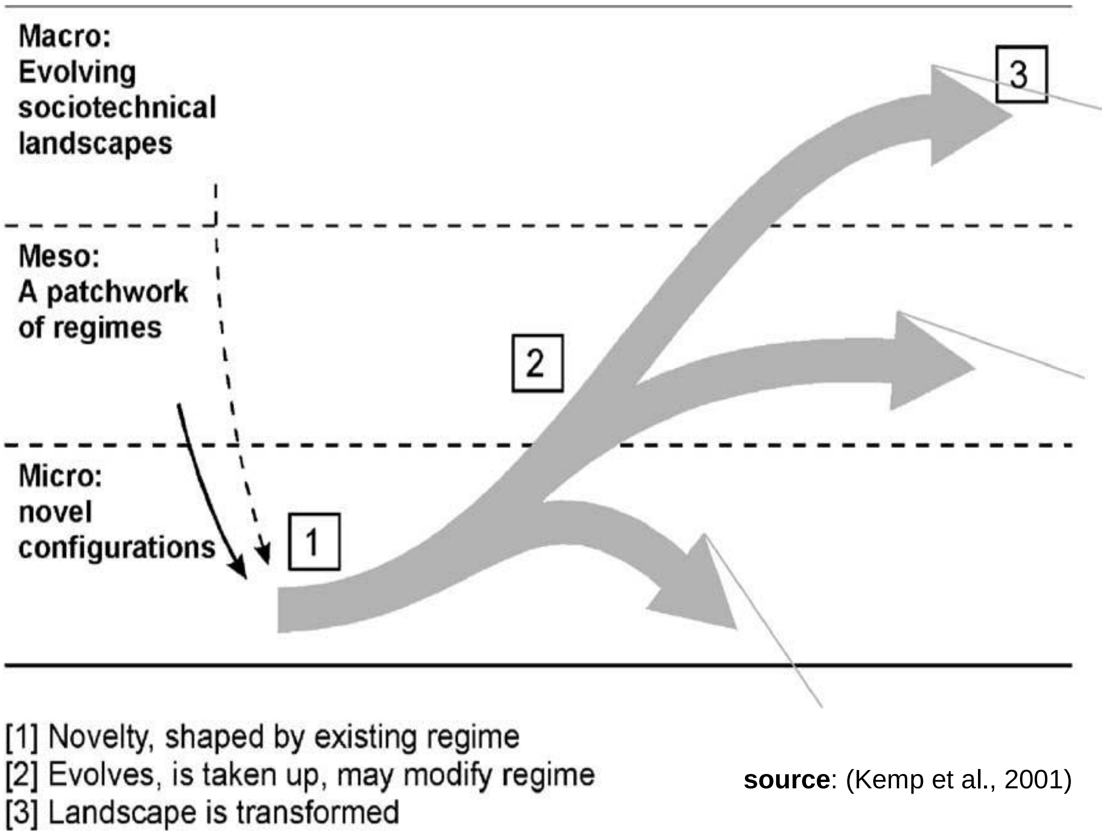
> “From the viewpoint of the technology supplier, the innovation subjects (the technical community developing and supporting specific technologies) that strategically foster new technologies in the niche carry out ‘technology learning’ activities. They also carry out activities to obtain socio-political legitimacy and cognitive legitimacy, which over time may enable their technologies to become the dominant design and socially legitimate, and form policies that support the technologies they are developing.”

Successful innovations are then thought capable of modifying the existing technological ‘regime’ (‘2’ in Figure 5). Georghiou et al. (1986, 30) define a technological regime as:

> “a set of design parameters which embody the principles which will generate both the physical configuration of the product and the process and materials from which it is to be constructed. The basic design parameters are the heart of the technological regime, and they constitute a framework of knowledge which is shared by the firms in the industry.”

With greater success, these innovations that have impacted upon a regime can go on to transform the entire ‘socio-technical landscape’ (‘3’ in Figure 5) but then they lose their niche protection:

> “Once the technology is sufficiently developed in terms of user needs, and



source: (Kemp et al., 2001)

Figure 5: The Dynamics of Social Change at the Different Levels of the Technology-Society Relationship in a Technological Transition

> broader use is achieved through learning processes and adaptations in the selection environment, initial protection may be withdrawn in a controlled way" (Kemp et al, 1998, 185).

Rip (1995) suggests that a socio-technical landscape consists of nodes made up of infrastructural and network technologies where reflexive thought goes into how these technologies function and are handled. These nodes include, for example, 'the office' and/or 'the city' where many (socio-) technologies interact (and induce new innovations): "It is into this landscape that new technologies are introduced, and where [political] alignment [amongst actors] has to be created" (Rip, 1995, 427).

Rennings (2000) points out that SNM's strength is successfully avoiding analytic generalizations via micro-level assessments of the innovation process. The level of analysis is felt to be appropriate for characterising long-term, radical change processes including path-dependencies, irreversibility, transition processes, and discontinuous and unpredictable events.

However, the spatial dimensions are not overtly spelled out. Explicitly, niches begin their evolution on a micro level of analysis, but seemingly this can stretch from a small project to a region or regions filled with firms. Might a whole country or supranational group of countries provide the territorial basis for a niche's evolution? Also, as Loorbach and van Raak (2006, 7) point out:

> "The link between regimes and niche (management) and sustainable development is rather weak in the sense that although SNM focuses on 'sustainable technologies', there is no direct link to research on sustainable development nor are definitions of sustainability made explicit."

The SNM heuristic has therefore been critiqued for the suggestion that SNM researchers' preferences might be determining the degree of sustainability of particular technological options rather than the evidence (Loorbach and van Raak, 2006). Subsequently, a number of Innovation Studies heuristics have been critiqued for implying that innovation – in niches or otherwise - might arise anywhere in economic space (cf. Coenen and Díaz López, 2010).

2.3.2.2 Transition Management (TM)

By the late 1990s, the SNM heuristic evolved into another potentially powerful approach to Technological Transitions (TTs): Transition Management (TM). Like SNM, TM specifically aims to show policymakers how they might 'steer' technological change via available policy levers but specifically tries to avoid ‘transition failures’ (Loorbach and van Raak, 2006, Loorbach, 2007, Kemp et al., 2007b, Loorbach and Verbong, 2012). Given the failure of top-down, command-and-control policies in the past, success depends on joint decision-making and network management where visions and roadmaps hold together networks of stakeholders in a particular technology.

Kemp et al (2007) suggest the problem-structuring methods of Rosenhead and Mingers (2001) may help stakeholders with conflicting frames of reference to discuss shared problem definitions about unsustainable aspects of current systems. Portfolio management overcomes the dilemma of which technologies to support.

2.3.2.3 Multi-level Perspective (MLP)

Such transitions thinking leads to the Multi-level Perspective (MLP), or ‘Kemp-Geels model‘, an expansion of Kemp‘s SNM approach (Geels, 2002, Geels, 2004). Geels critiqued the shortcomings of the SI heuristic, Sectoral Innovation Systems (SISs), saying that it did not provide enough of an understanding of the techno-economic and social aspects of TTs, or ‘sustainability transitions’.

Geels (2011) stresses the special characteristics of sustainability transitions compared to emergent historical transitions: 1) they are goal-oriented or ‘purposive’ given persistent environmental problems (Smith et al., 2005); 2) the involvement of public authorities and civil society is key to addressing public goods and internalizing negative externalities, changing economic frame conditions, and supporting green niches (Elzen et al., 2011); 3) there will be disagreement and debate about the direction of sustainability transitions because it is an ambiguous and contested concept (Stirling, 2009), 4) it is unlikely that environmental innovations will be able to replace existing systems without changes in economic frame conditions (e.g., taxes, subsidies, regulatory frameworks) because most sustainable solutions do not offer obvious user benefits (because sustainability is a collective good) and often score lower on price/performance dimensions than established technologies; 5) they require changes in policies involving politics and power struggles, because vested interests will try to resist such changes, 6) because of their large size and complementary assets, incumbent firms have strong positions regarding the pioneers who often first develop environmental innovations. Geels (2011) suggests that if these characteristics of sustainability transitions mean that actor interactions are between a technology or technologies and policy/power/politics, economics/business/markets, and culture/discourse/public opinion, then innovation theory must address several key points. Sustainability transitions are: 1) multi-dimensional, 2) structural change has distinct dynamics centred on various lock-in mechanisms, e.g. scale economies, sunken investments in machines, infrastructures and competencies, and institutional commitments, shared beliefs and discourses, power relations, and political lobbying by incumbents, and consumer lifestyles and preferences, and 3) such path dependence makes it difficult to dislodge existing systems. As Geels (2011, 25) says of sustainability transitions:

> “The core analytical puzzle is to understand how environmental innovations emerge and how these can replace, transform or reconfigure existing systems.”

As with SNM, the MLP envisages a range of state and non-state actors between niche and regime who pro-actively manage significant social, economic and technical aspects of Technological Transitions. Geels (2002, 1258) suggests:

> “[New socio-technical] configurations that work cannot easily be bounded from the rest of society in a simple and obvious way. Things and skills are part of routines, of patterns of behaviour, of organisations. They work only because they are embedded.”

The one essential difference between Kemp’s and Geels‘ heuristics is that the MLP has two transition levels – technological niches and socio-technical regimes - instead of SNM’s three.

2.3.2.4 Innovation Systems (IS) Heuristics - Policy Implications

With SNM, policymakers need to stimulate the co-evolution of supply and demand to produce desirable outcomes in the short- and long-term. This will not be achieved by laying down requirements, but rather via process management to help steer and keep sociotechnical change on track (Kemp et al, 1998). Instead, SNM offers a concentrated policy effort to develop protected spaces for certain applications of a new technology. This gives it a chance to develop from a demonstration project to one that is actually in use (Kemp et al, 1998). Risk assessment, technology assessment and monitoring of effects can help with the uncertainty associated with long-term system effects of a technology transition. Kemp et al (2007) also suggest that if reactions are required to keep a technological pathway on track this can be aided via flexible designs (Verganti, 1999), adaptive management (cf. Lee, 1993; Walker et al., 2001), the use of portfolios and the use of capital-extensive solutions with relatively short life times (Collingridge, 1980). With the MLP approach, carrot and stick policy approaches - as seen with CTA – such as grants for technology testing are advocated.

2.3.3 Sociology of Expectations (SOE) Heuristics

A third strand, SOE heuristics, also emerged in the mid-1990s as a result of perceived shortcomings with both the emerging IS and SI/TT theoretical approaches. These heuristics are based on ontological crossovers between quasi-evolutionary, social constructivist, and relationist assumptions from Science, Technology and Society (STS) research (van Lente, 1993, Garud and Ahlstrom, 1997, van Lente and Rip, 1998, Borup et al., 2006, Voß et al., 2006, Weber, 2006, Ruef and Markard, 2010, Alkemade and Suurs, 2012). SOE heuristics incorporate approaches from other disciplines including ‘hype cycles’ (Fenn and Raskino, 2008), ‘enactors and selectors’ (Garud and Ahlstrom, 1997) and ‘expectations management’ (McDowall and Eames, 2006a).

SOE heuristics make micro-level contributions to innovation theory and combine quasi-evolutionary notions like path dependence with approaches to power and thus strategy, contestation and access to resources (e.g. van Lente and Rip, 1998, Ruef and Markard, 2010, Bakker et al., 2011). Different technologies are adopted – or diffuse – at differential rates between different places (Rogers, 1962; Freeman et al, 1963, 1965). Advocates of neoclassical economics regard such outcomes at the micro and macro levels of actors and economies respectively as ‘irrational‘. Rosenberg (1976), however, built on early diffusion research and suggested that two factors at the micro level, in particular, that might better help explain it. Firstly, there are varying technological promises (or expectations) made by entrepreneurs, and, secondly, these promises then intersect with the different levels of risk aversion held by decision-makers who may or may not fund further development of the technology.

A social constructivist sociology of expectations (SOE) literature has since developed in this area (cf. van Lente, 1993; Garud and Ahlstrom, 1997; van Lente and Rip, 1998; Borup et al, 2006) in which Rosenberg‘s idealized vision of the interplay between entrepreneurs and decision-makers has been further refined into a heuristic model known as ‘arenas of expectations‘. This approach involves ‘enactors‘ (entrepreneurs) and ‘selectors‘ (decision-makers) as leading actors. As before, the technological promises being made by enactors are continually being constrained and revised by the financial risk aversion of selectors but this is now conceived as taking place within ‘arenas of expectations‘. It is also worth noting that arenas of expectations are not regarded as level playing fields for actors. Negotiations between them are thought to be subject to power relations as characterised in Latour‘s (1987) concept of ‘trials of strength‘ where actor-networks form and try to build a case for a technology by building political legitimacy through the enrolling, aligning and coordinating of other enactors and resources (van Lente, 2012; Alkemade and Suurs, 2012). Visions and roadmaps of potential future developments for a technology are thus considered especially powerful tools for enactors and selectors given their dual ability to assist enactors - by enrolling, aligning and coordinating the support and resources of others – and yet also constrain them (Eames et al, 2006). Expectations thus need to be seen as a key means of linking the micro-economic perspective of actors to the macro-economic perspective of innovation systems, particularly technological innovation systems (TISs). Expectations stimulate the fulfilment of other key processes in technological innovation systems such as the mobilization of resources. This role of expectations is strongest in the earliest phases of the life cycle of a technology which is characterized by uncertainty regarding future performance and possible applications.

Over time, collective negotiations over technological promises, or expectations, have been shown to lead to so-called ‘hype cycles‘ which are rises and falls in the shared expectations that actors have in a technology or group of technologies (Alkemade and Suurs, 2012). Heuristic modelling of this process, also termed the Gartner hype cycle, has been developed commercially by the US information technology research and advisory company, Gartner, Inc. The Gartner hype cycle characterizes the way emerging technologies move from a period of user and media over-enthusiasm for a technology to swift disillusionment with it. However, ultimately, an understanding of a technology's position in the marketplace emerges (Fenn and Raskino, 2008). The Gartner hype cycle attempts to offer a more detailed description of the early stages seen in the broader S-curve model of technological diffusion pioneered by Rogers (1962).

2.3.3.1 Sociology of Expectations (SOE) Heuristics - Policy Implications

In policy terms, SOE heuristics suggest pursuing protective niches so that final research, development and demonstration (RD&D) can be completed and market demand can be met or developed. Very strong positive expectations can assist public and private agencies to create and maintain such technological niches and as such, strong expectations may well ensure that a technology is more positively evaluated (Konrad, 2006; Eames et al, 2006; Alkemade and Suurs, 2012). Shared, or aligned, expectations may reduce the financial uncertainty perceived by selectors (decision-makers). This guides the process of technological change in ways that have been formalized in the private and public sectors of many developed nations via technological foresight/vision reports (e.g. roadmaps) which are now seen as a standard policy tool.

2.3.4 Summary

Since the late 1980s, Innovation Studies' researchers have built on the 'Nelson-Winter-Dosi' innovation heuristic (Dosi, 1988, Dosi et al., 1988). They have pursued research agendas which continually assess and re-assess the strengths and weaknesses of three groups of heuristics based on an evolution from IS to SI and SOE strands of theorizing. Each heuristic has contributed in different ways to improved understandings of the dynamic processes required for normative sustainability transitions. However, the critique of Bruun and Hukkinen (2003) that suggests that evolutionary assumptions central to *all* Innovation Studies heuristics remains unclear, still holds. Specifically, the relationship between agency, structure and the selection environment (i.e. the regime and/or socio-technical landscape) remains contested and needs greater theoretical clarity:

> "[S]ystems-oriented attempts to deal with [agency, structure and selection] replace 'selection' with terms like 'coupling', 'collaboration' and 'learning'. However, they tend to use these terms at a rather aggregate level, *without providing detailed analysis*. Lists of circumstances that are necessary for the formation of a paradigm or a generic system do not explain why a particular system emerged." (Bruun and Hukkinen, 2003, 100, my italics)

Such critiques have led to some improvements in the 2000s and 2010s, but in terms of micro-macro linkage, IS heuristics like the TIS and the TSIS still need to better identify why certain actors pursue particular 'patterned paths' of change, i.e. path-dependent technological pathways (Bruun and Hukkinen, 2003), as I describe in detail in Section 2.4 below. As Faber and Frenken (2009, 467-8, my italics) argue:

> "An important weakness lies in the lack of empirical testing of existing evolutionary models, due to … (too) many parameters. A key challenge … is to *improve the hypothesising of the linkages between the micro and the macro level*."

In summary, ontological differences between the IS, SI and SOE heuristics outlined in this and the previous section mean that epistemological (and hence methodological) fault lines exist between these various heuristics (cf. Carlsson et al., 2002, Edquist, 2004, Coenen and Díaz López, 2010). Such differences are important to be aware of when answering my research questions because these differences impact upon methodological debate in the following thematic areas in the next four sections. These debates further contextualise the ways the Technology-specific Innovation Systems (TSIS) heuristic is applied in this study.

2.4 Thematic Review of Innovation Studies Heuristics

In this section, each heuristic is examined in terms of four analytical themes which emerged from the literature:[10]

1) micro-macro conceptions of actors' agency and structure,
2) system delineation,
3) system indicators, and
4) policy guidance.

This analysis gives a more detailed understanding of the potential weaknesses of Innovation Studies' heuristics in general (while focusing on the TSIS approach in particular). I then illustrate these potential weaknesses with specific knowledge gaps that are in the HFC literature. Then, in Section 2.4, these gaps are used to contextualize my development of four methodological modifications to the TSIS heuristic.

2.4.1 Theme 1: Conceptions of Agency and Structure

Conceptions of agency and structure are directly relevant to Research Questions 1 and 2 and indirectly relevant to RQs 3 and 4 (Text Box 3 in Chapter 1):

1) 'How, when and where has innovation and diffusion of Hydrogen Fuel Cell (HFC) technologies taken place in the UK and Germany?'

2) 'Which socio-technical factors have had the most influence on the nature and pace of HFC innovation and diffusion in these cases and why?'

In general, actors in networks operating at different scales differ dramatically in their relative levels of agency (Coenen et al., 2012). Actors' access to resources

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[10] As with the DoSH study, Innovation Studies heuristics were chosen for their relative success in explaining the social processes of innovation compared to the Rational Choice approach (cf. Lundvall and Johnson, 1994).

differs depending on the strength of their networks. Such differences in power should impact upon any Innovation Studies' analysis.

Giddens (1979, 91) suggests that analysis of agency involves notions of power relations:

> "Power ... is centrally involved with human agency; a person or party who wields power *could* 'have acted otherwise' and the person or party over whom power is wielded ... *would* have acted otherwise if power had not been wielded."

Power can only be exercised by actors who pursue strategies and who are embedded in networks that have resource interdependency (Smith et al., 2005, Christopherson and Clark, 2007). Actor competition which is based on unequal access to resources can therefore be expressed via the relative sizes and structures of rival networks (Markard and Truffer, 2008a). Network operationalization can be conceived of differently, however. IS models use economic sociology (e.g. Granovetter, 1973, Powell and Grodal, 2005). SI and SOE models draw on relationist/social constructivist approaches like Actor Network Theory (Callon, 1986, Latour, 1987, Law, 1992). However networked power is operationalized, though, it has been critiqued for being relatively poorly developed in both IS and SI/TT approaches particularly in terms of i) uneven access to resources and ii) strategies pursued to gain access to resources (Shove and Walker, 2007, Weber, 2007, Avelino and Rotmans, 2009, Lawhon and Murphy, 2012, Truffer and Coenen, 2012). A more realist approach is needed that asks:

> "[What] is the degree of openness of the current economic structure to innovative challenges [?] If politics and economic power combine to suppress enterprise then little can be expected of innovative experimentation." (Metcalfe and Ramlogan, 2008, 440)

IS and SI/TT heuristics therefore struggle with theorizing uneven development:

> "Uneven development is a natural consequence of differential knowledge and of very different instituted ways by which societies correlate the existing knowledge and promote the growth of knowledge ... in many studies, markets and users are simply assumed to be 'out there'" (Metcalfe and Ramlogan, 2008, 439).

This is true of Technological Innovation Systems (TIS) proponents who have sought a systemic view of co-evolving economic structures. This view is based on structuralist and neofunctionalist assumptions about actors, institutions and technology (Suurs, 2009, Geels, 2010). TIS and TSI/TTS studies are therefore not typically overt in their conceptions of power relations. Breukers et al. (2014), for example, cite a series of Dutch biomass TSIS case studies (Hekkert et al., 2007b, Negro et al., 2007, Negro et al., 2008, Suurs and Hekkert, 2009a, Suurs and Hekkert, 2009b) suggesting they require a more sophisticated approach to the contestation between stakeholders of the technologies involved.[11] This suggests that structural change may not be well addressed in TIS/TSIS heuristics, i.e. explanations are not offered for the struggles of emerging innovations against existing regimes (Geels, 2011). In this context, TIS/TSIS case studies risk underplaying the co-evolution of technologies with their institutional structures. They also risk under-conceptualizing the role of new technologies in social transformations (Coenen et al., 2012, Truffer and Coenen, 2012). This occurs when studies by downplay: “user-driven innovation and the pre-competitive technological formation processes where non-market users and broader political context conditions play an important role” (Truffer and Coenen, 2012, 5).

Few TIS case studies attempt micro-level conceptualisations of actors’ behaviour (Markard and Worch, 2009, Coenen and Díaz López, 2010). Exceptions include the study of Wieczorek et al. (2013) on wind power in the UK, Denmark, Netherlands and Germany, which uses Social Network Analysis (SNA) to reveal the relative networked power of actors.[12]

In general, the key problem for TIS studies has been that data gets aggregated to the macroeconomic level in terms of functions. More detailed explanations of strategic behaviour at the individual or project levels are not offered (Bruun and Hukkinen, 2003). This can be due to *ex ante* delineation of technological systems. Such delineation de-emphasizes the importance of power struggles between actors seeking to achieve their strategic ends (see section 2.3.2). There has been similar criticism by Coenen et al. (2012) of the concept of a universal ease of access to resources by actors, the so-called ‘global technological opportunity set’ proposed with the TIS heuristic (Carlsson, 1997, Carlsson et al., 2002).

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[11] Breukers et al (2014) use a stakeholder dialogue approach with event history analysis (EHA) to draw out contested, normative visions from stakeholders in the Dutch biomass sector who are shown to have different levels of agency (and hence power).

[12] SNA can reveal asymmetries of power and is often used in conjunction with Granovetter’s approach to networks. Suurs and Hekkert (2009b, 1006) incorrectly suggest that SNA is “limited in that it detects only network formation.”

In terms of SI/TT approaches and power, there is “no conception of power relations” according to Lawhon and Murphy (2012, 10). This is disputed by Geels (2011, 29) who claims that the MLP heuristic is “shot through with agency” (Geels, 2014). However, in common with IS models, the MLP is generally less powerful in terms of conceptualising the roles and strategies different actors play, how they interact with institutions, and the notions of agency that they may hold (cf. Coenen and Díaz López, 2010).[13] This limitation relates to the materiality of uneven resource distributions:

> "[R]esource endowments explain the development of networks and the innovation potential of actors ... actors and strategy making have received little attention in the conceptualization of niches." (Markard and Truffer, 2008c, 609)

In terms of SI/TT approaches to energy transitions, Simmie (2012, 730) points out that some conceptualisation of local context is required:

> “[T]echnological regimes and economic landscapes play out differently and have different characteristics in different regions. From this perspective it is important to analyse the regional and local geographies of energy transitions.”

Schot (1998) and Späth and Rohracher (2010) have nevertheless highlighted how niche success lies with wider groups. More powerful actors also need to become involved in a new technology in ways that mobilise broader social legitimacy for change (cf. Kern and Smith, 2008, Smith et al., 2010, Geels, 2014).

Social legitimacy and guidance of the search appear to be key elements of IS, SI/TT and SOE approaches to innovation especially in their early phases. In the case of the Transition Management (TM) heuristic, it has been argued that it is naïve to think transition managers' efforts are undertaken in a political vacuum:

> “[T]echniques like those of multi-stakeholder involvement in foresight exercises, or methods of public participation and deliberation are never `neutral' and never evacuated of power and strategic behaviour.” (Shove and Walker, 2007)

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[13] Chang and Chen (2004) cite exceptions including Autio (1997) and Saviotti and Nooteboom (2000).

Lawhon and Murphy (2012) similarly cite developments in TM (Berkhout et al., 2004, Loorbach, 2007) which are claimed to create dialogue in order to counter the unequal distribution of power amongst stakeholders:

> "[Proponents] lack an explanation for how to better account for the *everyday politics* that will inevitably shape socio-technical transition outcomes and their distribution within society ... [They] need more careful consideration of how power is mobilized, referenced, and applied to achieve regime shifts, and who are the winners and losers of these processes." (Lawhon and Murphy, 2012, 364)

The quasi-evolutionary approach of SOE research has distinct implications for notions of agency and structure because actors can anticipate their selection environment:

> "[They] seek to modify selection environments, by voicing expectations or with other moves like forging strategic alliances. The quasi-evolutionary approach, thus, provides us with a model of technological development and competition that is not dependent on spontaneous, blind variation, but instead relies on guided search through different heuristics and on strategic moves to shape the selection environment." (Bakker et al., 2012, 152)

This more formal emphasis on power relations and the strategies that flow from them marks out SOE approaches to agency and structure as more nuanced than IS and SI/TT approaches.

The agency-structure debate is also linked to analyses of causality. Coenen et al. (2012) point to ways that proponents of both TISs and the MLP risk producing false positives in their analyses of causality because of a tendency to use time as an independent variable and so privilege time over space in case study analyses. Suurs and Hekkert (2009b, 1006), for example, describe historical events in a TIS narrative as being linked like:

> "[T]he logic of a plot in a narrative. Events that are part of a plot are not (only) related to each other by an efficient causality (the simple logic of mechanics) but (also) by final and formal causality."

Kern (2012), however, says that while TIS narratives may imply causality between certain events on a timeline, any correlation between them - however derived - does not necessarily mean causation exists. There is therefore a risk of a logical fallacy of *post hoc ergo propter hoc* or 'after this, because of this' when analysing sequences of events where event Y infers cause from earlier event X. More caution is required (cf. Abell, 2004). Coenen et al. (2012, 975) suggest:[14]

> "Introducing space to these analyses [would] contribute to creating better explanations of the timings and sequences of transitions, reducing the problem of the 'causality of time', making more explicit why particular transitions have succeeded or failed."

In this context, TSIS analysis: "[R]isks overemphasizing 'universal' (abstract) mechanisms as causal explanations for innovation at the expense of (real) embedded actor strategies and institutional structures" (Coenen et al., 2012, 970). There is also the suggestion that if causality in TSIS analyses is not strengthened then the transferability of case study results may not be robust. Efforts in this area are advancing with spatial notions being introduced for TIS case studies (Binz et al., 2014) and for SI/TT heuristics (Raven et al., 2012, Späth and Rohracher, 2014).[15]

In terms of conceptions of agency and structure, SOE case studies reveal that reality rarely matches the technological expectations of actors (Alkemade and Suurs, 2012). The disappointments following a downturn in a hype cycle for a technology, i.e. after actors have hyped a technology beyond what can be delivered in a reasonable time frame, are generally less well examined in the SOE literature. An exception includes the HFC study of Ruef and Markard (2010). Similarly, the comparative analysis of the shapes of hype cycle curves as a topic of study is limited (Geels, 2007). There is always a local, regional, national and supranational context to activities in a hype cycle which enriches the details of a case study but does not allow wider conclusions to be drawn (Borup et al., 2006).

In summary, there have been concerns about the IS and SI/TT heuristics' relatively poorly developed notions of agency and structure compared to SOE heuristics. This suggests that, when answering the research questions, some caution is needed with analyses of agency via the TSIS heuristic. Specific knowledge gaps regarding agency and structure for HFC research are explored in the next section.

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[14] Genus and Coles (2008) urge caution with historical accounts from secondary sources.

[15] Binz et al (2014), for example, suggest that tacit knowledge can be 'sticky', i.e. not travel far from where it was created.

2.4.1.1 HFC Research - Knowledge Gaps – Conceptions of Agency & Structure

In the previous section, it was suggested that individual institutions cannot exercise agency alone. Instead, as a strategic response to the uneven availability of resources, relative power is exercised through various contestations of claims within and between actor networks (Markard and Truffer, 2008a). The Innovation Studies literature critiqued in Section 2.3.1 suggests that, in general, innovative activity needs to involve broad regime membership in terms of networks (Smith et al., 2005). Analysis of HFC activity also needs an operationalization of networked power at different levels/scales (cf. Archibugi and Michie, 1997, Bunnell and Coe, 2001, Coenen et al., 2012, Coenen and Díaz López, 2010). HFC-specific insights into knowledge gaps emerge from analysing the HFC studies listed in Table 3 and these are examined below.

At the top of Table 3, there are several references to research based on top-down, rational choice approaches to innovation. These examples of a ‘technology push’ approach suggest the need for, and the means of, achieving a ‘hydrogen economy’ (Bockris, 2002) and a ‘hydrogen highway’ (Al-Ahmed et al., 2010). Such studies are strong on technological determinism, but lack an appraisal of the demand factors that spur state agencies into helping to foster innovation (in varying degrees of partnership with private enterprise depending upon the national economic context). Also, these studies do not assess the nature of structure, i.e. the socio-economic or socio-technical barriers that can hinder the development of a hydrogen economy or highway for actors. Similarly, the ‘technology push and demand pull’ category towards the top of Table 3 includes studies that are cautiously deterministic about what HFCs may achieve when rolled out into the market (e.g. van den Hoed, 2005). These studies recognise the socio-economic constraints of external changes in demand with some (e.g. Dunn, 2002) noting the importance of potential socio-technical barriers to HFC uptake such as the public acceptance of these technologies (cf. Whitmarsh and Wietschel, 2008).

In terms of Innovation Systems’ (IS) research on HFCs, Suurs et al. (2009, 9652) in their research into Dutch HFCs report that:

> “[while the] crude conceptualisation of actor roles ... does help understand why certain actors prefer particular strategies ... [T]he TIS approach could [however] benefit from a more sophisticated actor concept.”

Musiolik and Markard (2011) in their case study of the stationary fuel cell TIS in Germany characterize the historical context in purely functional and temporal terms

Table 3: Innovation Models and Hydrogen Fuel Cell (HFC) Literature

Approaches (oldest first)	**Innovation Models**	**Literature**
Rational Choice	Technology Push	Bockris (2002), Al-Ahmed et al. (2010)
	Demand Pull	Chen et al. (2011)
	Technology Push & Demand Pull	Hoffmann (2001), Dunn (2002), Rifkin (2003), van den Hoed (2005), Hugo et al. (2005), Brey et al. (2007), Murray et al. (2007), Haeseldonckx and D'haeseleer (2011), Gutiérrez-Martín and Guerrero-Hernández (2012)
Innovation Systems (IS)	Innovation Systems (general)	Bleischwitz and Bader (2010), Brown et al. (2007), Ekins and Hughes (2009), Foxon et al. (2005), Markard and Truffer (2008a), Peters and Coles (2010)
	National Systems of Innovation (NSIs)	Liston-Heyes and Pilkington (2004), Mans et al. (2008), Vasudeva (2009), Haslam et al. (2012), Park (2009a),
	Regional Systems of Innovation (RSIs)	Bader et al. (2008), Godoe and Nygaard (2006), Holbrook et al. (2010), McDowall (2010), Madsen and Andersen (2010), Cooke (2013), Tanner (2014), Tanner (2016)
	Sectoral Systems of Innovation (SSIs)	Godoe (2006), Choi et al. (2011)
	Technological Innovation Systems (TISs) / Functions of Innovation Systems	Hekkert and den Hoed (2004), Hekkert et al. (2005), Brown et al. (2007), Bader et al. (2008), Madsen and Andersen (2010), Markard and Truffer (2008a), Musiolik and Markard (2011), Suurs et al. (2009), Nasiri et al. (2013), Andreasen and Sovacool (2015)
Systems Innovation (SI) / Technology Transition (TT)	Strategic Niche Management (SNM)	Lane (2002), Karlström (2005), Agnolucci and Ekins (2007), Agnolucci and McDowall (2007), Ekins (2010), Ekins and Hughes (2010), Park (2010), Park (2011), Park (2013), Ehret and Dignum (2012)
	Transition Management (TM) / Multi-level Perspective (MLP)	Van Bree et al. (2010), Van den Bosch et al. (2005), Farla et al. (2010), Geels (2013), Hodson et al. (2008), Köhler et al. (2009), Köhler et al. (2010), Whitmarsh and Köhler (2010)
Sociology of Expectations (SOE)	Expectations	Budde et al. (2012), Eames and McDowall (2010), Eames et al. (2006), Acs et al. (2002), Hodson and Marvin (2005a), Hodson and Marvin (2010), Hultman and Nordlund (2013), Maack and Skulason (2006), McDowall (2012)
	Enactors and Selectors	Bakker (2011), Bakker (2010a), Bakker (2010b), Bakker et al. (2011), Bakker et al. (2012)
	Hype Cycles	Alkemade and Suurs (2012), Bakker (2010a), Bakker (2011), Konrad et al. (2012), Ruef and Markard (2010)

with little or no overt reference to space. This privileging of time over space perpetuates knowledge deficits in terms of agency in IS analyses (Coenen et al., 2012).

Systems Innovation (SI/TT) approaches include Strategic Niche Management (SNM). The SNM study by Karlström (2005) of the local environmental benefits in monetary terms of using HFC buses in central Gothenburg in Sweden suggests that the leading normative arguments for change are to "improve the environment" (684) and to "[act] as the first step of a long-term transition strategy to a hydrogen economy" (*Ibid.*). This SNM study ignores the importance of actors' agency in determining strategy (cf. Markard and Truffer, 2008b). It also downplays the everyday politics of the contestation between networked groups. As with technology push/pull approaches, this approach ignores the need for policy makers to acquire legitimacy for normative visions of socio-technical change.

Nevertheless, SNM approaches have been used with studies of hydrogen and fuel cells (HFCs) to illustrate the socioeconomic factors which influence external economies of scale, network effects and the behaviours of users (including their expectations for HFC technologies) (Agnolucci and Ekins, 2007, Agnolucci and McDowall, 2007).

Another example of using SNM, shown in Table 3, is the study of Iceland's hydrogen energy policy development (Park, 2011). Because Park knows *post hoc* that certain straightforward technology choices were made in favour of HFCs in the 1990s, there is relatively little elaboration on the state's role in renewable energy technology selection and how it maintained its portfolio of niche technologies, something advocated in SNM theory. Instead, Park enlarges upon some of the policy instruments also associated with TM/MLP - visions and expectations, network development and alignment, policy-making and negotiation - as being key areas for state agencies and other stakeholders to be involved in. Just in terms of visions and expectations, for example, Park (2009b, 10452) notes that "Iceland aimed to be a 'global exemplar'" in HFCs, an aspiration which, for a variety of sociotechnical reasons, has so far failed to take place.

In Table 3, the transition management (TM) study of bottom-up, civic initiatives for fuel cells in transport in Rotterdam of Van den Bosch et al. (2005, 1034) found that:

> "[I]ncremental, feasible innovation steps, which are widely supported by stakeholders … are more effective in terms of budget, time and stakeholder commitment. … small steps encourage learning-by-doing … an important characteristic of transitions".

Van den Bosch et al. (*Ibid.*) conclude that:

> “[A] long-term vision, commitment and a pro-active role of both industry and (local) government are crucial in starting transitions or system innovations. Furthermore, there might be a challenging role for universities and other independent institutes in facilitating stakeholder interactions and mobilizing stakeholders to set up transition projects.”

Since its initial use in Dutch energy policy making at the turn of the century, the use of the transition management (TM) heuristic has become ever more sophisticated (e.g. Kern and Smith, 2008, Smith et al., 2010, Späth and Rohracher, 2010). In one TM study, Farla et al. (2010, 17), for example, cite the boosting of sustainable mobility in the Netherlands in which hydrogen is evaluated against other renewable fuels each with their own costs, benefits and backed up with political lobbying:

> “[O]ur main recommendation to Dutch transition management actors is that – besides the activities at the transition path level – a systemic approach should be taken, in which the interdependencies between the transition paths are critically taken into account and in which possibilities to legitimize sustainable mobility as a whole are exploited.”

This approach is similarly pursued with the multi-level perspective (MLP) where the institutionalized and co-evolutionary relationship between carmakers and consumers, for example, is shown to shape technological pathways to battery–electric vehicles (BEVs) and fuel cell vehicles (FCVs) (Van Bree et al., 2010).

In terms of agency and structure, questions of equity and democracy also arise. The study by Farla et al. (2010, 16) on transitions in Dutch mobility concludes in cautionary terms:

> “The transition management idea to execute small-scale experiments which can be developed into mass markets, seems to be rather difficult for transition paths in which the build-up of new physical infrastructures plays an important role. One reason is the need for large and typically irreversible investments, even for small-scale experiments. This seems to hinder the involvement of small entrepreneurs and newcomers.”

Such knowledge gaps are in line with the critique of Lawhon and Murphy (2012) in Section 2.3.1 above which suggests that SI/TT approaches lack a coherent conception of power relations.

Sociology of Expectations' (SOE) heuristics offer insights into HFC actor agency and the structure they typically encounter. However, there is a knowledge gap with one of these approaches. The study of Bakker et al. (2012) uses the 'enactors and selectors' approach (cf. Garud and Ahlstrom, 1997) in a case study of different technological options pursued by the US Department of Energy's HFC programme. Unfortunately, the aspatial nature of the enactors and selectors approach, as deployed by Bakker, implies that HFC innovation and diffusion could be encouraged to take hold anywhere in space. The empirical evidence of HFC clustering does not support this (e.g. Mans et al., 2008, Bleischwitz et al., 2008, McDowall, 2010). SOE studies show that HFCs have been subject to a number of hype cycles. Bakker (2010a) notes that, in the case of HFC mobility, original equipment manufacturers (OEMs) in the auto industry were deliberately involved in the hyping process in the late 1990s. This was regarded as necessary to attract attention, create legitimacy and so find further funding. It was a process that helped to create a global blowout in 'hydrogen hype' in 2001. In this context, Ruef and Markard (2010) suggest that SOE heuristics could avoid potential knowledge gaps in their analyses of socio-technical change by foregrounding the "broader societal and political" aspects of their case studies.

In the next section, I examine how concerns with the system delineation of Innovation Studies' heuristics are illustrated with knowledge gaps in the understandings about HFCs.

2.4.2 Theme 2: System Delineation

Systems approaches to innovation have been criticised for their delineation or where the analytical boundaries are drawn for their case studies (Weber, 2007). System delineation directly impacts upon Research Question 3 and indirectly on RQs 1, 2 and 4 (Text Box 3 in Chapter 1):

3) 'Based on answering RQs 1 & 2, are there research suggestions that would add and enrich existing theoretical and methodological approaches in Innovation Studies?'

There is no right or wrong way to delineate system boundaries as they depend on a study's research question(s) (McKelvey, 1997). Many distinctions turn out to be blurred and overlapping (Fløysand and Jakobsen, 2011, 3). In terms of IS delineation, Markard and Truffer (2008c) highlight three broad delineation distinctions:

1) descriptive - which typically introduces the need for spatial levels of activity, e.g. NSIs and RSIs (cf. Bergek et al., 2005),

2) conceptual - which suggests that readily quantifiable system components will interact closely (cf. Carlsson et al., 2002), and

3) key determinants of innovation - which appear to boost or block system functions (Johnson and Jacobsson, 2001, Edquist, 2004).

In terms of descriptive delineation, Coenen and Díaz López (2010, 1150) state that:

> "It is important to consistently consider the boundaries of the innovation system in order to avoid an explosion of possible factors and drivers for innovation. However [do not] isolate the system from its environment ... Every system of innovation is situated within a certain context."

In descriptive delineation, the socially-constructed territorial borders used are only ever loosely defined (cf. Carlsson and Stankiewicz, 1991, Cooke et al., 1997, Edquist, 1997, Edquist, 2004, Kaufmann and Tödtling, 2001, Carlsson et al., 2002, Metcalfe and Ramlogan, 2008). Case study evidence typically reveals that heterogeneous actors embedded in networks make links with each other between and across hierarchical levels of activity (Hodson et al., 2010). Dual knowledge flows for innovation activities arise, which involve localized learning embedded in local nodes or clusters as well as global knowledge networks made up of 'international epistemic communities', corporate networks of multinational companies (MNCs) or temporary proximity and face-to-face interaction at international trade fairs and conferences (cf. Healy and Morgan, 2012, Heidenreich, 2012a, Heidenreich, 2012b). As Binz et al. (2014, 139) state:

> "Scrutinizing these interconnected relational dynamics has been ignored so far by TIS research, but [has] become one of the hallmarks in the so-called relational turn in economic geography."

The TIS heuristic is not the only IS approach to be unclear about how such multi-scalar approaches to knowledge/learning flows are meant to be operationalized (cf. Archibugi and Michie, 1997, Bunnell and Coe, 2001). The National Systems of Innovation (NSI) heuristic does not explain the manifest ability of MNCs based *outside* a country's stated physical borders to influence innovative activity *inside*. The use of a national container, for example, via descriptive delineation, impacts upon analyses that can be made, as Bunnell and Coe (2001, 583) suggest:

> "The system or scale as 'container' effectively means the relative neglect of broader networks that support innovation in particular locales".

This means that for certain territorial heuristics, such as NSIs and RSIs, the activities of actors (firms) – from small- and medium-sized enterprises (SMEs) to MNCs – need to be better differentiated, as they have very different roles in the global economy. MNC R&D headquarters are unevenly distributed across space and are powerful attractors for SMEs. MNCs, for example, benefit from knowledge spillovers by exploiting new ideas and niche markets (Audretsch and Feldman, 1996). According to Simmie (2005, 800):

> "The combination of these activities of different types of firm helps to explain why both they and innovation are so often concentrated in a limited number of localities."

As studies suggest, new technologies typically start in specific local environments while the knowledge networks they become embedded in tend to cross national boundaries (Metcalfe and Ramlogan, 2008, Truffer and Coenen, 2012). Thus, as formal distinctions between domestic and foreign firms have become more problematic, debate has continued about whether and in what ways the NSI concept still makes sense, given the globalisation of business and technology and the integration of national and regional economies into supra-national bodies (Freeman, 1995, Archibugi and Michie, 1997, Cantwell, 1995, Patel and Pavitt, 1994, Patel and Pavitt, 2000, Liu and White, 2001, Chang and Chen, 2004, Balzat and Hanusch, 2004, Carlsson, 2006, Metcalfe and Ramlogan, 2008).

Regarding systems delineation with the sectoral systems of innovation (SSI) literature, Coenen and Díaz López (2010, 1151) warn about boundary setting of the system before data is gathered:

> “Due to [a] state of emergence, there is considerable technological and market uncertainty. How markets will develop and which users will adopt the technology is still an open-ended question. *Ex-ante* boundary setting of the system may therefore miss out on important factors and actors driving innovation.”

With the TSIS heuristic, there is debate over the appropriate level of analysis (Jacobsson and Johnson, 2000, Carlsson et al., 2002, Bergek et al., 2005, Markard and Truffer, 2008c, Truffer and Coenen, 2012). National boundaries have typically been the “‘natural’ yet implicit” TIS system delineation (Coenen et al., 2012, 972). Currently, TIS case studies follow four delineations of which ‘technology’ has been the most numerous in its use by researchers:

i) product,
ii) technology,
iii) multi-product (‘competence bloc’),
iv) a set of related firms (vertical/horizontal) developing a particular technology.

Coenen et al. (2012, 970) feel that all TIS approaches offer “spatially undifferentiated entities” where the overall technological boundary is “a little ambiguous” (Coenen and Díaz López (2010, 1152) in terms of geography and sectoral embeddedness.[16] In a criticism linked to analyses of agency and structure, Coenen et al. (2012, 970) feel that this undermines confidence in TSIS analyses:

> “Without explicitly elaborating why actors in particular TISs choose to pursue their activities in particular regional and national contexts, it is very difficult to isolate individual success factors … In general, technological systems’ structures (actors, institutions, networks) highlight resources, competencies and synergies provided by actors operating in specific locales or regions, while often overlooking that these local resources are produced in much wider economic, business, political and organizational networks, hierarchies and markets … [A] spatially naïve TIS concept runs the risk of obscuring simple, place-specific causal relationships behind a more general systems analysis, that in turn lacks explanatory power.”

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[16] Note that in the case of certain TIS studies, e.g. Negro et al (2007), system delineation expands over time as the TIS grows raising further questions about comparisons between systems.

In response to such concerns, Coenen et al. (2012) and Binz et al. (2014) propose a relational and multi-scalar treatment of space for TSIS studies based on post-structural approaches to economic geography (cf. Foucault et al., 1991, Murdoch, 2006). This avoids any *a priori* scalar boundaries and hierarchies that come with system delineation (cf. Boggs and Rantisi, 2003, Bathelt and Glückler, 2003, Sunley, 2008, Fløysand and Jakobsen, 2011, Allen, 2011).

In the case of SI/TT heuristics, there are critiques about the system delineation of the socio-technical approach (Smith et al., 2005, Geels and Schot, 2007, Markard and Truffer, 2008c). A narrow delineation centred on nations is the primary context within which regimes and niches are situated (Hodson and Marvin, 2010, Smith et al., 2010). According to Fløysand and Jakobsen (2011, 9):

> “This prevents socio-technical transition scholars from conceptualizing the spatial variety and complex interdependencies that result in geographically specific forms of institutional embeddedness within regions and places.”

In SI/TT approaches, the different levels where innovation activities occur – niches (micro), regimes (meso) and landscapes (macro) - are not geographical scales. Scale is not explicitly conceptualized in these heuristics (Lawhon and Murphy, 2012, Coenen et al., 2012).[17] Scales tend to get conflated in SI/TT studies. This reveals that there is: “Insufficient recognition that niche-regime interaction is mediated through complex scalar processes”(Coenen et al., 2012, 973). As with IS approaches, a narrow system delineation in SI/TT studies may well miss key factors contributing to an understanding of agency:

> “The agency enjoyed by any group of actors, and the associated power relations, can only be understood in relation to other actors. This suggests that an agency-based approach to understanding regime transformations must extend beyond the usual bounds to consider the basis, nature and bounding of regime *membership*.” (Smith et al., 2005, italics in original)

Simmie (2005) cautions, however, that all possible actions for any actor (firm) nor the number of actors involved in the governance of a particular locality cannot be known:

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[17] Others have highlighted scales beyond and below niche/regime levels (Hodson and Marvin, 2010).

> "It is therefore virtually impossible to analyse precisely what has led to the path dependency of a given firm or place" (Simmie, 2005, 800).

Overall, this section shows that there are a number of theoretical concerns about system delineation for all Innovation Studies heuristics. These concerns arise from the way research questions are posed. They can be addressed by recognising the nature of socially-constructed boundaries, the importance of networks and considering the mismatch between geographical and relational space. For the two most widely used Innovation Studies models of innovation, Technological Innovation Systems (TISs) and the Multi-level Perspective (MLP), work has begun to resolve these concerns (Coenen et al., 2012, Raven et al., 2012, Binz et al., 2014). This includes a multi-scalar MLP that explicitly incorporates spatial scale (Murphy, 2015, Truffer et al., 2015). There is also recognition that there is a strong 'distance decay' function for the tacit dimensions of knowledge, i.e. 'stickiness' (Howells, 1999, Howells, 2002).

Specific knowledge gaps regarding system delineation with HFC research are explored in the next section.

2.3.2.1 HFC Research - Knowledge Gaps – System Delineation

In the previous section, it was suggested that there is no right or wrong way to delineate system boundaries as they depend on a study's research question(s). In descriptive delineation with IS approaches, socially-constructed territorial borders are loosely defined and suggest a lack of clarity with operationalizing multi-scalar approaches to knowledge/learning flows of HFC-specific insights into knowledge gaps emerge from analysing the HFC studies listed in Table 3 and these are examined below.

In terms of the critique about boundaries and territory with National Systems of Innovation (NSIs), Foxon et al. (2005, 2131) note in their study of HFCs (and three renewables) in the UK that:

> "[M]ost technology for demonstration [is] being sourced from overseas ... [and hopes for future market activity come] mainly as a result of significant collaboration and strong international knowledge networks within the sector."

This point is in line with research in business studies and economic geography referred to in Section 2.3.2 above. This research attempts to quantify the dynamics and importance of embeddedness of firms, chiefly small- and medium-sized enterprises (SMEs) and multinational corporations (MNCs) in national and regional economies (cf. van Stel and Stunnenberg, 2004, Heidenreich et al., 2011, Heidenreich, 2012b) a potential knowledge gap for IS heuristics when contextualising case studies involving globalisation.

The critique in Section 2.3.2 regarding the need to enhance local (spatial) context in analyses (Coenen et al., 2012), suggests here that there are potential knowledge gaps in analyses due to the aspatial nature of SI/TT and SOE heuristics. These approaches assume that, in the case of HFCs, innovation could take place anywhere in national economic space. For example, the Transition Management (TM) analyses of Van den Bosch et al. (2005) and Farla et al. (2010, 16) privilege time over space while other empirical case studies nevertheless show that local context and/or space do matter in terms of delineation (e.g. Agnolucci and Ekins, 2007, McDowall, 2010, Park, 2011).

In the next section, I examine how concerns with the system performance of Innovation Studies' heuristics are illustrated with knowledge gaps in the understandings about HFCs.

2.4.3 Theme 3: System Performance

Innovation Studies heuristics have been critiqued for offering a range of models but no testable theories which have predictive powers (Fagerberg, 2003).[18] In order to boost the conceptual rigour of this evolving body of research, efforts at improving methodological consistency have been suggested. This theme in the Innovation Studies literature directly impacts upon Research Question 3 and indirectly upon RQs 1, 2 and 4 (Text Box 3 in Chapter 1):

3) 'Based on answering RQs 1 & 2, are there research suggestions that would add and enrich existing theoretical and methodological approaches in Innovation Studies?'

Ways of improving methodological consistency include further standardisation of approaches to system delineation, choices of system components, as well as consistent analysis of the perceived nature of these components' interactions. In the light of the spatial turn in Innovation Studies, more agreement on quantitative and qualitative system indicators would improve the transferability of case study results

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[18] Fagerberg (2003, 143) suggests: "some cross-fertilization with the more formal evolutionary theories [is required]".

and lead to theoretical formalisation. However, proponents of SI/TT and SOE heuristics, with their social constructivist assumptions, disagree and argue that only measures of technological expectations give meaningful insights into system performance (Alkemade and Suurs, 2012).

Technology distance indicators or bibliometric and patent analyses are widely used as quantitative indicators of system performance but they have their shortcomings (cf. Acs et al., 2002, Becheikh et al., 2006, Peters, 2009, Mairesse and Mohnen, 2010). They can miss the economic performance associated with the use of knowledge (Carlsson et al., 2002). Instead, best-practice studies of performance measures (e.g. Furman et al., 2002) have led to more standardized indicators for innovation (Fløysand and Jakobsen, 2011). Spatial and temporal benchmarks from longitudinal analyses can also help policymakers highlight systemic problems within sectors in terms of how a system is developed (Coenen and Díaz López, 2010). However, even if better performing socio-technical configurations emerge from a transition, measuring actual process outcomes is rarely the focus of such research studies (Coenen et al., 2012).

In terms of improving the measurement of TIS system performance, eleven functional indicators were advanced (Rickne, 2000, Rickne, 2002) while Liu and White (2001) suggested five. Carlsson et al. (2002) suggested identifying i) the level of analysis in terms of whether a technology or a product is the focal point, and ii) the maturity of the system. If a technology or knowledge field is the focus of a TIS study, then the generation and diffusion of knowledge will be the key function to measure performance. If a product is the focal point of a TIS study, Carlsson et al. (2002) suggested that diffusion rates or market shares should be leading indicators, except in the case of the very early emergence of a TIS (Markard and Truffer, 2008c). Successful entrepreneurship of innovations is regarded as a direct result of feedback with the TIS's functional performance. However, this approach to performance risks downplaying the relative importance of a TIS's institutional context. Markard and Truffer (2008c) feel that external institutions which slow the innovation process down are simply regarded as blocking mechanisms in the TIS approach (cf. Klein Woolthuis et al., 2005). Instead, they argue, such institutions may be more influential in terms of overall system performance:

> "[T]he systems approach runs the risk to miss influential processes because the review of the environment is less systematic. In a similar vein, novel technologies or products that emerge in competing innovation systems and thus affect the

> innovation under study may be neglected in the analysis." (Markard and Truffer, 2008c, 610)

Of the range of potential methodological improvements suggested for TISs, Carlsson et al. (2002) felt that system performance measurement needs most attention. This then led to a significant evolution of the TIS heuristic with the advent of the TSIS heuristic (Hekkert et al., 2007a, Bergek et al., 2008, Suurs, 2009).

Conceptually, the TSIS heuristic imports a more neofunctionalist approach into existing evolutionary, structural and functionalist assumptions underpinning TIS models. TSIS system performance is measured by quantifying positive and/or negative feedback between seven functions of innovation systems': market formation, entrepreneurial experimentation, influence on the direction of search, resource mobilisation, knowledge development and legitimation (Hekkert et al., 2007a). The approach is based on the principle of cumulative causation (Myrdal and Sitohang, 1957). As Suurs (2009, 26) notes:

> "System functions are likely to interact with each other, and as they do, a cumulative causation process may be set in motion that directs the TIS through its 'formative stage' into a 'take-off' stage ... In the ideal case, the TIS will develop and expand its influence, thereby propelling the emerging ... technology towards a stage of market diffusion."

TSIS system delineation is similar to that of TISs. TSIS data is "quasi-quantitative" (Kern, 2012, 300) and gathered on the system's functional performance via Event History Analysis (EHA). EHA is typically a project-level (micro-level) methodology which logs innovative events longitudinally in order to produce qualitative event narratives (Allison, 1984, Van de Ven et al., 1999, Poole et al., 2000).[19] Section 3.3.1.1 in Chapter 3 describes the use of EHA in this thesis and in TSIS studies. Unlike EHA used by Van de Ven, Poole and colleagues, however, TSIS analyses *aggregate micro-level data to the meso and macro levels*. As with TISs, social processes associated with each function can be mutually reinforcing, but only in certain combinations: virtuous and vicious (i.e. positive and negative) feedback loops. These loops are termed 'motors': e.g. 'motors of change' (Hekkert et al., 2007a),

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[19] More than one researcher is required in this method to check the qualitative event and narrative interpretations in order to avoid systematic bias.

‘motors of innovation’ (Suurs and Hekkert, 2009b), and ‘motors of sustainable innovation’ (Suurs and Hekkert, 2012).

By contrast, the approach to performance indicators for SI/TT and SOE heuristics is different because of their social constructivist assumptions. As Bakker (2011, 4) indicates:

> “[A]ny technological option [in a constructivist framing] … may have different meanings and purposes to different actors … [Thus] the notion of technological performance is problematized and can no longer be understood unequivocally … To say that a winning technology was, in hindsight, the better performing option does not do justice to the complexity of the competition and the process of variation and selection.”

Variation and selection via SOE notions of agency and structure leads to data gathering focused on the expectations and (linked) strategies of actors. A critique of SI/TT and SOE heuristics is the degree to which case study results are transferable.[20] As Genus and Coles (2008, 1440) put it:

> “There is... a question mark over the definition, conceptualisation and verification of transition paths within transition research. It is unclear whether a new, unique transition path can or should be identified for each new case study - as it appears at the moment, or whether there are generalities of some kind, universalities prevalent across cases.”

Overall, performance indicators are very important for all Innovation Studies heuristics given the desire to produce more robust and testable theories. The indicators described here suggest that, for the proponents of the TSIS heuristic, functional indicators have largely been settled on and subsequent efforts – i.e. post 2007/8 - have been more focused on case studies which proponents require to move towards theoretical formalism and policy utility. Nevertheless, I propose two additional indicators in Sections 2.4.1.and 2.4.2 – organisational funding and geographic location - in the belief that they will contribute to more robust and testable theorising.

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[20] This concern underpins Saxenian’s work (1985, 1996) in economic geography on the hi-tech regional cluster around Silicon Valley and Route 128 in California.

The next section further explores my critique of Innovation Studies approaches in terms of policy.

2.4.4 Theme 4: Policy Guidance

Policymakers need to decide how, when and *where* to deploy resources to encourage the growth of a healthy HFC innovation system. In terms of the evolving theorising in Innovation Studies about agency, Fagerberg (2003, 153) suggests: “[T]here is a lot of unfinished business … [which] implies that one cannot draw very firm conclusions on policy matters.” The theme of policy in the Innovation Studies literature directly impacts upon Research Question 4 which is shaped by answers to RQs 1, 2 and 3 (Text Box 3 in Chapter 1):

4) ‘What are policy options that follow on from answering RQs 1, 2 & 3?’

A rational approach to policy assumes that social problems are solvable. In reality, they may be ‘wicked’ or even ‘super-wicked’, i.e. intractable (cf. Rittel and Webber, 1973, Levin et al., 2012). In terms of theory building for transitions, Innovation Studies approaches suggest that state-led innovation management, especially for radical innovations, is required (Hillman et al., 2011). This is not thought of as a control problem but rather one of: “[O]rchestrating a highly complex, uncertain and probabilistic process of collective action in a systemic context.” (Smits et al., 2010, 10). Questions about why states should support research, development and demonstration (RD&D) go back to Nelson (1959) and Arrow (1962). Policy prescriptions for sustainability transitions are more recent and the learning activities of societal actors have been added to that of governmental actors. In this context, Grin and Loeber (2006, 215) suggest: “Learning ... may hold the key to enabling mutually shaped, collective change.” Learning is now regarded as more collectivist than individualist and better accounts of the links between agency, structure, learning and societal change exist (Grin and Loeber, 2006). Theorizing about transitions has also moved away from suggesting that state actors can single-handedly effect an entire transition, but they still retain very important roles (Mazzucato, 2013). In the context of short-termism in the private sector, the state can:

> “[P]erform various roles from facilitating to directing, depending on the stage of the transition. Key roles early on in transitions ... [are] to mould the agenda for change, build shared long-term visions across society and to create opportunities

> for learning about the substance and process of change.” (Genus and Coles, 2008, 1439)

This encourages policies that optimise trust, creativity and proximity in clusters around resource advantages (which include knowledge spillovers) (Dankbaar and Vissers, 2009). Nevertheless, a variety of political, cultural and other unanticipated factors – operating at different levels - can constrain state agency.

In this context, the user-friendliness of Innovation Studies policies and the expectations of their users have been critiqued. Policymakers tend to regard heuristics as simple, functional toolkits to deploy in a techno-economically deterministic manner without difficulty (Lundvall, 2007, Metcalfe and Ramlogan, 2008, Voß et al., 2009, Hodson and Marvin, 2010, Lawhon and Murphy, 2012). There is an assumption within policy circles that systems’ approaches can be “constructed, governed and manipulated” (Fløysand and Jakobsen, 2011, 4). Lawhon and Murphy (2012, 6) argue that there is a “lack of critical reflexivity with regard to who participates in, and the politics of, transition management activities”. Metcalfe and Ramlogan (2008, 443) warn that, because of the uncertainty of the process, evolutionary policy making needs to be more reflexive about policy actors’ roles and expectations:

> “The growth of knowledge changes the actors involved so that learning effects continually shift the relation between policy cause and innovative effect ... Thus, the evolutionary policy maker is ... adaptive ... [and] as boundedly rational as the agents that are the policy target."

Uneven development is of key importance to policymakers at the local, regional and national levels. Finding the causes of uneven development has been central to Innovation Studies since Freeman’s 1960s case studies (cf. Fagerberg et al., 2007). Economic Geography also has much to offer in this context (Howells, 1999, Howells, 2002, Morgan, 2004, Asheim and Gertler, 2005). A systemic form of regional lock-in has been identified, for example, which results in a place-dependent form of path dependence (Morgan, 2013). As outlined in Section 1.4.6, different levels of lock-in – functional, cognitive and political – exist (Grabher, 1993):

> “[T]he state must take the initiative for *unlocking* the process, either by orchestrating the restructuring of traditional industries or by attracting new enterprise … the state actually shapes the structure of the space economy in

> multiple ways – by what it does *and* by what it chooses not to do." (Morgan, 2013, 320, italics in original)

Morgan (2013) echoes the definition of power of Giddens (1979) who suggests the state ought to have a central role in innovation and industrial policy. Nevertheless, early evidence for state-led policy efforts via Innovation Studies heuristics has been mixed (Hendriks, 2009, Voß et al., 2009, Kern and Howlett, 2009).

Policy makers in Sweden and the Netherlands have pursued Sectoral Systems of Innovation (SSI), Strategic Niche Management (SNM), Transition Management (TM) and TIS approaches (cf. Malerba, 2002, Edquist et al., 2004). This includes specific policies for knowledge creation, R&D financing, networking, intellectual property rights, technology transfer, skills and public procurement (Coenen and Díaz López, 2010). However, innovation policy is made up of an integrated package of industrial and trade policies which produce new local capabilities and new global market opportunities. This means that: "policies for creative destruction must stray beyond a narrow concern with innovation systems." (Metcalfe and Ramlogan, 2008, 444). Systemic tools are needed for Innovation Studies heuristics that permit the selection of a policy mix across the innovation cycle (Coenen and Díaz López, 2010).

Of the IS heuristics, TIS models have been similarly oriented towards informing policy makers but have been felt, in general, to be relatively non-user-friendly (Sharif, 2006, Truffer and Coenen, 2012). Edquist et al. (2004), Klein Woolthuis et al. (2005) and Chang and Chen (2004) have highlighted the need for better policy guidance for putting the TIS approach into practice. The Swedish agency for innovation systems, VINNOVA, has pursued the TSIS approach since the 2000s. Bergek et al. (2008) responded to the critique about user friendliness with the suggestion that healthy feedback between system functions is often impeded by blocking mechanisms. These include uncertainties of needs among potential customers, inadequate knowledge of relations between investments and benefits, lack of capability and poor articulation of demand, lack of standards, few relevant university programmes for skills and a weak advocacy coalition.[21] Remedying such concerns in policy terms involves increasing user capability, supporting users to increase and diffuse knowledge, supporting experiments with new applications, developing standards, altering research and education and supporting an advocacy coalition (Bergek et al., 2008). Regarding agency and power, however, Smith et al. (2005, 1503) point out

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[21] Negro et al (2007) have suggested learning from a typology of seven 'system failures' for TISs.

that even the *possibility* of successful policy intervention in socio-technical regimes may be presumptive:

> "This 'functionalist' perspective masks important difficulties in the practice of governance. The construction of consensus tends to be presumed as unproblematic; the role for informed dissent in innovation can be overlooked ... Questions of trust, partnership and coalition building in processes of change are rarely considered."

In terms of SOE heuristics, there has been a growth in the expectation-building industry in which 'experts' and 'promissory' agencies (consultancies and professional forecasters) have a central role in managing the technological expectations of particular fields (Konrad et al., 2012, van Lente, 2012). This is thanks to a range of expectation-building tools such as technology forecasting and assessment, backcasting, roadmapping, scenarios methods and foresight (Pollock and Williams, 2010, van Lente, 1993). Hence, expectations are thought to play a decisive role in the governance of technical change (i.e. in terms of increasing agency). This involves coordinating and shaping innovation and transition processes in ways outlined by Smits et al. (2010) above, but in an even more distinct way:

> "[G]overnance by expectations feeds back on the governance of expectations" (Konrad, 2010, 4)

While expectations research is undertaken at a variety of public policy levels and in some corporations, relatively little work has been done on public policy-making and corporate strategies which arise from forecasting exercises. This means that:

> "[I]t is not clear to what extent *de facto* governance overlaps with the intentions of these governance 'tools'." (Konrad, 2010, 3)

In sum, a critique of policy guidance based on Innovation Studies' theorising involves the recognition that, once the gaps and limitations in the theoretical approaches are demarcated, uncertainties in applying these heuristics – i.e. in terms of policy - still need to be worked through (cf. Fagerberg, 2003). The empirical evidence suggests that a cautious, nuanced approach to the agency of networked actors is required in order to avoid heavy-handed, top-down policy prescriptions at all levels (Giddens, 1979, Smith et al., 2005, Hendriks, 2009, Voß et al., 2009). Huge uncertainties exist in Innovation Studies' approaches to the governance of transitions including whether or not wicked and super-wicked problems are 'solvable' at all.

Examples from the HFC literature that illustrate such knowledge gaps are examined in the next section.

2.3.4.1 HFC Research - Knowledge Gaps – Policy Guidance

HFC studies in Table 3 are briefly reviewed here in terms of the policy advice that stems from two of the thematic critiques in previous sections: 1) conceptions of agency and structure, and 2) system delineation.[22]

In policy terms, a rational choice study by Dunn (2002), for example, advocates state involvement in RD&D for HFCs (technology push) and public-private partnerships in greening energy infrastructure (demand pull). However, the assessment by Chen et al. (2011) of the optimal patent strategy for the global fuel cell industry solely reflects demand-pull policy advice regarding securing intellectual property protection.

In the first Innovation Systems (IS) category in Table 3 there are two detailed articles on HFC policy shown (Bader et al., 2008, Bleischwitz and Bader, 2010) each of which relate to social constructions of scale (cf. Hodson et al., 2010, Coenen et al., 2012), Here, there is implicit recognition of different levels or scales in the European policy space, for example, but no means of operationalizing a multi-scalar approach (cf. Archibugi and Michie, 1997, Bunnell and Coe, 2001). This risks uncertainty and knowledge gaps based on analyses of agency and structure through de-emphasizing the role of networks and local context in policy prescriptions.

In the TIS category in Table 3, Suurs et al. (2009) pursue their neofunctional analysis of the Dutch HFC sector between 2004 and 2008. The focus of their analysis on the drivers of, and barriers to, change for actors, institutions and technologies within the sector. They claim that the linear model of innovation is still the dominant approach for many policymakers, a clear gap in analytical approaches. To advance with HFCs in the Netherlands, Suurs and Hekkert (2009b) suggest parallel system developments in policy are more appropriate: developing visions, using technological assessments in conjunction with policy development, facilitating learning and communication, procuring HFC technologies and regulating niche markets. However, as I indicate in Section 2.3.4, to achieve a more sophisticated policy analysis, IS proponents need to go beyond a narrow concern with innovation systems (Metcalfe and Ramlogan, 2008). Systemic tools are needed for a number of Innovation Studies

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[22] Matters relating to system performance are considered implicit within each study.

heuristics that permit the selection of a policy mix across the whole HFC innovation cycle (cf. Coenen and Díaz López, 2010).

There are policy implications of IS heuristics' approaches to system delineation. Encouraging the clustering of hi-tech enterprises has been pursued in developed nations for over thirty years. However, the study by Mans et al. (2008, 1384) offers a cautionary note in an analysis of self-declared HFC clusters within an NSI framework in the Netherlands:

> "Just labelling a cluster is not expected to be enough … [C]luster policies … [need] to include incentives for the cluster partners to actually function as a cluster … Stimulating cooperation can be done by anticipating on initiatives arising in the market, and subsequently facilitating these initiatives by assuming the role of broker in the exchange of knowledge."

In this example, spatial aspects of innovative activity are both explicit and implicit. The geographical boundary in which the Dutch NSI fits is made explicit in geographical terms. However, the social processes underpinning key systemic and functional aspects of innovation taking place in these Dutch clusters, such as learning and the maintenance of trust, for example, are only implicit and this risks promoting knowledge gaps around important socio-technical and socio-spatial processes at the micro-level. For example, a distance decay function (cf. Howells, 1999) is in evidence with social interactions centred on HFC clusters.

The RSI category in Table 3 contains HFC literature that includes a focus on encouraging the healthy growth of European HFC clusters (e.g. Bader et al., 2008).[23] This is to be achieved via the boosting of functional activities such as knowledge transfer and coordination. In terms of the economic geography of these HFC clusters in Europe, Madsen and Andersen (2010, 5380) report that: "[G]eography and cluster aspects seem to matter in establishing a European H2FC technology innovation system". However, which systemic processes are linked to clustering is not made clear, an example of uncertainty and a knowledge gap linked to policymaking about socio-technical and socio-spatial processes.

As with technology push/pull approaches from Rational Choice, the SI/TT approach of Karlström (2005), with its HFC buses case study from Sweden, ignores the need for policy makers to acquire legitimacy for normative visions of socio-

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[23] The RSI approach is generally used as an analytical tool to direct regional innovation policy and is more holistic than the cluster approach (Bleischwitz et al, 2008).

technical change. This is a knowledge gap about policy stemming from the analysis of agency and structure.

In the next section, I summarize my critique of Innovation Studies' heuristics which includes the knowledge gaps illustrated by research into HFCs before presenting methodological modifications to the TSIS heuristic in my conclusions in Section 2.4.

2.4.5 Summary

In summary, how serious are the potential weaknesses with Innovation Studies' heuristics as illustrated by the knowledge gaps in the HFC literature? Compared to heuristics based on the Rational Choice approach, Innovation Studies' models have had relative success in offering improved understandings of the social processes of innovation (Fagerberg and Verspagen, 2009, Markard et al., 2012). The thematic review of the Innovation Studies literature in this section reveals that there are many different ways to approach sustainability transitions. The seven ontologies reviewed suggest varied approaches to system stability and change, with very different reasons cited for system changes. While the typology of ontologies helps with an understanding of the theoretical orientations of the various sustainability transition heuristics, there are epistemic fault lines between them (Carlsson et al., 2002, Edquist, 2004, Coenen and Díaz López, 2010). This is where a range of uncertainties and knowledge gaps begin to emerge (cf. Fagerberg, 2003). These epistemic differences mean networks and power are conceived of differently amongst different Innovation Studies heuristics. This means that notions of agency and structure, and hence how to gain access to unevenly distributed resources, for example, also vary significantly (Peters and Coles, 2006, Peters and Coles, 2010).

In terms of the degree of concern based on this critique, this section reveals that conceptualisations of agency and structure for the Innovation Systems (IS) and Systems Innovation (SI/TT) heuristics struggle with the micro-macro problem (Callon and Latour, 1981, Wiley, 1988, Tsekeris and Lydaki, 2011). This is evidenced in relatively poorly developed conceptions of actors' power relations, their strategies and their access to an unevenly distributed set of resources (Breukers et al., 2014). Such gaps, however, have been circumvented by some researchers, like those pursuing Technological Innovation Systems (TISs) and Technologically Specific Innovation Systems (TSISs), who aggregate micro-level activity at the meso- and macro-levels (cf. Bruun and Hukkinen, 2003). However, in broad terms, what is less well known about such an approach is whether or not empirical, case study data consistently offer a valid approximation of the reality that the TIS/TSIS heuristics seek to describe. There may well be hybridised or completely alternative heuristics that fare better.

Another way of bypassing the micro-macro problem, for example, is via a relational approach from economic geography. This may have equivalent or better empirical validity to the TIS/TSIS approach (Coenen and Díaz López, 2010, Coenen et al., 2012, Binz et al., 2014), but as yet is not more widely tested. In terms of HFC case studies and conceptions of agency and structure, an uneven availability of resources linked to asymmetries of actor power is typically revealed. Here, the delineation of innovative activity requires broad knowledge of network membership (cf. Malerba, 2002, Malerba, 2004, Smith et al., 2005). More sophisticated actor concepts have also been suggested. These need to include the activity of state agencies *and* partner actors: investing in R&D, facilitating/organising knowledge networks, developing industry visions, using technological assessment (TA) in conjunction with policy development, procuring HFC technologies and regulating niche markets (Choi et al., 2011, Suurs et al., 2009). Similarly, with HFCs and beyond, an operationalization of knowledge networks at different spatial levels is still required (cf. Archibugi and Michie, 1997, Bunnell and Coe, 2001, Coenen et al., 2012, Coenen and Díaz López, 2010).

Similarly, system delineation is shown to be a concern for all Innovation Studies heuristics due to the way research questions are posed. This can be solved by recognising the nature of socially-constructed boundaries, the importance of networks and theoretically tackling the mismatch between geographical and relational space as suggested above (Coenen et al., 2012, Binz et al., 2014). For the two most widely used Innovation Studies models of innovation, Technological Innovation Systems (TISs) and the Multi-level Perspective (MLP), theoretical research has begun to resolve these deficits (Coenen et al., 2012, Raven et al., 2012, Binz et al., 2014) but it remains unclear whether or not such approaches will prove theoretically robust. *Ex ante* boundary setting has been identified as problematic (Coenen and Díaz López, 2010, Markard and Truffer, 2008c, Weber, 2007). In the HFC literature reviewed here, delineation (based on the choice of the level of analysis) is typically only part of a study’s methodological discussion. When it comes to practical questions, like gauging both the local influence and the global reach of multinational companies (MNCs) on a national HFC TIS, for example, where analytical ‘containers’ may seem artificial, further theoretical elaboration may be required if more meaningful guidance is to be offered to policy makers regarding HFC-specific policies.

Indicators of system performance are shown to be problematic given the shortcomings of some indicators and the seeming impossibility of finding definitive ones that can be agreed on. Also, SI/TT and SOE advocates with their social constructivist assumptions suggest that a solely quantitative approach to indicators of system performance may be erroneous. Only measures of technological expectations, they say, can give a meaningful insight into system performance (Alkemade and Suurs, 2012). Thus, epistemic differences involve rival methodologies and produce possibly irreconcilable uncertainties about what is gained and lost with different approaches.

Finally, and linked to all of these areas of critique, the quality of policy guidance stemming from Innovation Studies' heuristics has so far been uneven in the countries where it has been tried, i.e. the Netherlands and Sweden. It remains early days for policies based on Innovation Studies' heuristics, but early Transition Management (TM) efforts in the Netherlands generally did not go as expected (Kern and Smith, 2008, Kern and Howlett, 2009, Hendriks, 2009, Voß et al., 2009).

Overall, Section 2.3 has established that there are epistemic differences between the various Innovation Studies' heuristics. These differences are based upon the ontological choices made by researchers and are shown to lead to emphases (and de-emphases) of certain aspects of agency and structure for actors in terms of the ways that innovative activity and its diffusion are theorized. My critique covers four themes and is supported by evidence of knowledge gaps in the HFC literature. I feel that my analytical concerns about the TSIS heuristic, in particular, justify the four methodological suggestions made in Section 2.4 below which are expanded in Chapter 3.

2.5 Thematic Review: Conclusions

At the start of Chapter 1, I stated that the reasons why hydrogen fuel cell (HFC) innovative activity begins to take off in one country (or one region or locality), but not in another, are not well understood. I have used this chapter to identify key knowledge gaps about HFC innovation and diffusion (Activity 1 from Text Box 4). I began by exploring the implications of different ontologies relevant to Innovation Studies heuristics (cf. Geels, 2010). I then critiqued the use of these heuristics via four interlinked and emergent themes in the literature covering: 1) micro-macro conceptions of actors' agency and structure, 2) system delineation, 3) system indicators, and 4) the quality of policy guidance.

Ultimately, with this chapter, I conclude that methodological concerns for the TSIS heuristic can be divided into the following categories: 1) the reliance on aggregating micro-level data to the meso- and macro-levels, 2) the innovation system itself being regarded as the causal agent of change, 3) the lack of a regional 'container' for analysis, and 4) the lack of predictive powers. From this theoretical critique, I then established specific knowledge gaps in approaches to HFC innovation and diffusion.

This analysis has allowed me to: 1) refine my research questions which are highlighted in Text Box 3 in Chapter 1, 2) make changes to the TSIS methodological framework which is based on a variant form of Event History Analysis (cf. Hekkert et al., 2007a), and 3) answer my research questions and complete my outstanding activities. Having developed the critique above, the sections below outline why I decided to pursue four methodological modifications to the TSIS heuristic in this study (which are more fully developed in Chapter 3).

2.5.1 Extended Coding - Organizational Funding

In terms of concerns regarding conceptions of agency and structure, the Functionalist approaches to innovation of the TSIS heuristic involve aggregating micro-level data to the meso- or macro levels (as outlined in Table 2). With the TSIS methodology, I have shown that there is a clear trade-off to be had. There are analytical gains made from the functional analysis at the aggregated meso- and/or macro-levels, but there are also potential losses in finer-grained understandings of the socio-technical processes at work at the micro-level (cf. Van de Ven et al., 1999, Poole et al., 2000). Such losses risk underemphasizing the importance of the relative power relations of actors and individuals in networks (cf. Avelino and Rotmans, 2009, Geels, 2011). Similarly, potential asymmetries of power, and hence the relative agency of different actors, is evidenced over time in contestations over technological choices at key technological 'branching points'. These points, when examined in detail, illustrate the socio-technical processes at work (Foxon et al., 2013).

I conclude therefore that it is preferable in methodological terms to triangulate the functionally aggregated data from the TSIS approach with more fine-grained interview material at the project level, i.e. the micro level, and to deploy that interview material overtly in the TIS event narratives (in ways that TSIS studies do not do). Without some analysis of project-level and/or individual-level data, the aggregation of data used in the TSIS approach means that key epistemological concerns remain, i.e. "What is the relationship between individual cognition and collective cognition?" and "How do firms 'think'?" (Fagerberg, 2003, 152).

To overcome these concerns, my methodological proposals based on this chapter's review includes extending the variant EHA approach of Hekkert et al. (2007a) by coding each TIS event for the organizational funding status of the projects linked to events. This coding covers ownership, whether public, private or public-private. This added coding will help to assess actors' relative agency via an indication of the nature and strength of their networked power relations (see Section 3.3.1.3 of Chapter 3 for full details of this coding indicator). In my TIS event narratives for the

UK and Germany, I will also provide micro-level text boxes in several places which expand the aggregated narrative event data. These expanded narrative descriptions cover episodes which, *in hindsight*, were important branching points in HFC socio-technical pathways.

My approach to extending the coding of EHA in the case of researching HFCs is underpinned by an examination of some selected literature on the role of the public sector in the next sub-section. I then return to the other conclusions from my literature review.

2.5.1.1 Role of the Public Sector in Innovation

As outlined in Section 1.3 in Chapter 1, there was a rise in numbers of HFC public-private partnerships (PPPs) in the EPSRC SUPERGEN XIV DoSH data starting in the 1990s. This rise suggested that extending the coding of EHA to include organisational funding might be a useful indicator of agency and hence sustainable change for this study. There is a historical - and contested - context for public sector involvement in innovation theory and policy (e.g. Freeman, 1974, Rodrik, 2013, Mazzucato, 2013). Such debate, outlined here, impacts on my analysis of HFC innovation in the UK and Germany chiefly in my analysis and conclusions in Chapters 6 and 7.

In the late 1980s, the principles of sustainable development were outlined in the Brundtland Report (WCED, 1987). Many EU member states, including the UK and Germany, responded with more cooperative approaches with their private sectors in order to achieve greater environmental policy integration. This shift in environmental policymaking involved combining traditional top-down regulatory approaches with cooperative arrangements and legally non-binding voluntary agreements. As an approach to neoliberal environmental governance, ‘new’ environmental policy instruments (NEPIs) emerged from the contestations between public and private actors in policy networks (and at various institutional levels from the local to the supranational). In this context, public private partnerships (PPPs) are one NEPI that has become increasingly popular since the 1990s. State actors wanting to become more pro-actively involved in supporting RD&D for clean technologies are still keen to ensure reduced exposure to the financial risks involved (cf. Hodge and Greve, 2005, Mazzucato, 2013, Verhoest et al., 2015).

In this thesis, I define an HFC PPP as a state mechanism specifically designed to leverage private investment, create a contract, spread financial risk, gain off-balance-sheet financing, and increase innovation in the design, construction and operation of HFC RD&D-, infrastructure- and manufacturing-based projects. My empirical evidence from the UK and Germany suggests that such arrangements range from efforts by the state to:

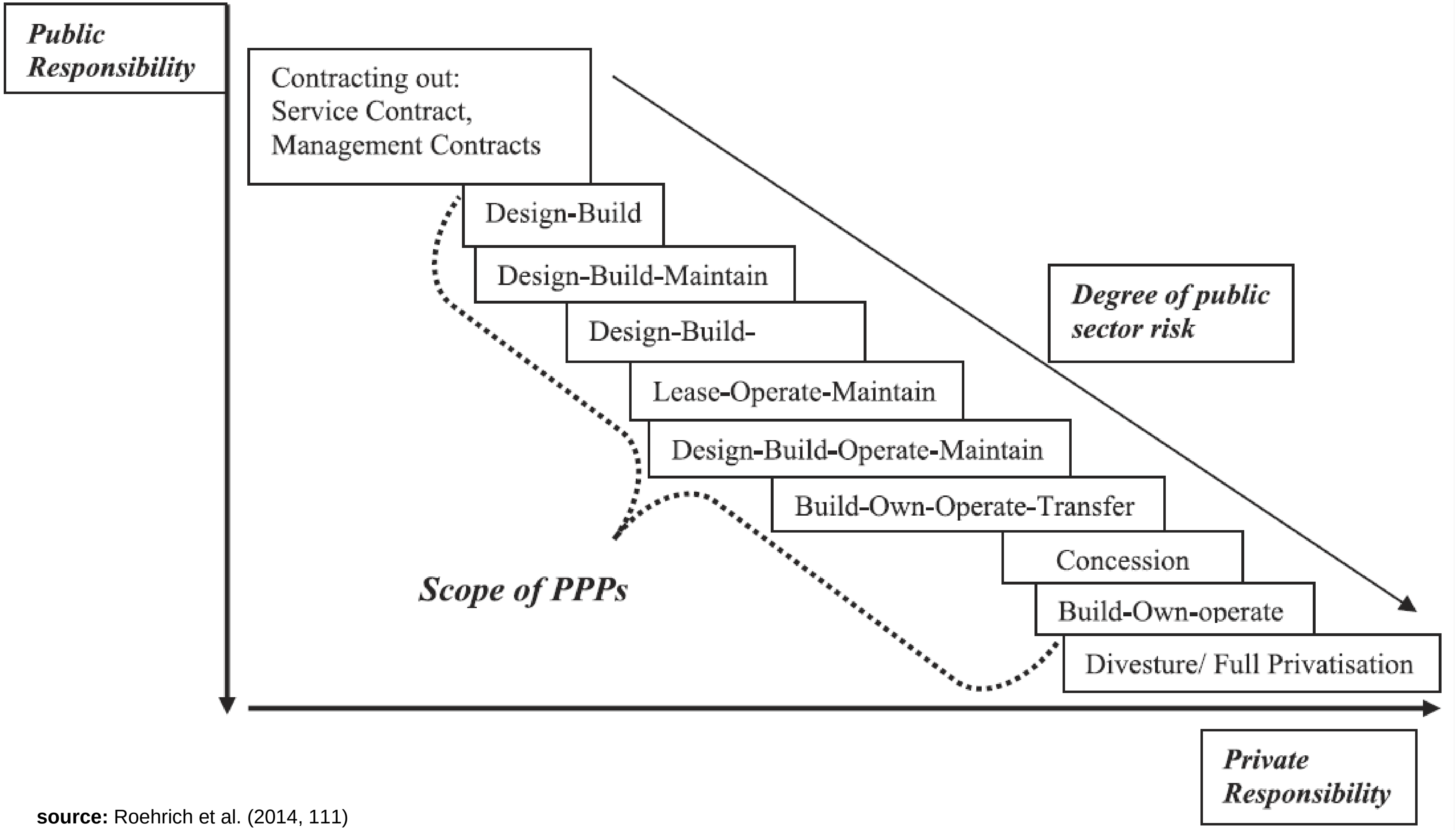
1) support knowledge exchange and leverage corporate investment in HFCs in specific places,
2) contract out the provision of specific services via HFC applications,
3) enter joint ventures (JVs), and,
4) enter strategic partnerships in which JV actors more pro-actively assist the state in achieving long-term policy goals (cf. Skelcher, 2005).

As the HFC data from the UK and Germany reveals in Chapters 4 and 5 respectively, PPP activity at three levels of governance – regional, national and supranational - varies within and between these two countries (cf. Verhoest et al., 2015). In general terms, these differences can be characterised in terms of differing national approaches to market mechanisms (cf. Hall and Soskice, 2001) – see Section 2.5.2.1 below - and, more specifically, in terms of the levels of risk that HFC actors working in a range of industrial sectors are prepared to accept (cf. Mörth, 2007).

As shown in Figure 6, mutual agreement on the shared levels of risk determines the scope of each PPP. For example, low levels of state risk at the top left of Figure 6 reveal PPP arrangements for service provision. This includes state actors contracting out. Conversely, at the bottom right of Figure 6, private involvement is much increased, public sector risk has increased, and state actors are operating as facilitators only (cf. EC, 2004). PPP arrangements for a service provision, like energy supply, may involve complete divestiture to the private sector, and in the case of infrastructure provision, concessions and ‘build-own-operate’ arrangements may be witnessed.

My empirical evidence on HFC activity from Germany and the UK suggests that there are four main forms of public-private activity. These are illustrated in Table 4 and Table 5:

- **public leverage** – measures include funding patents and attracting actors to invest in regional sites/clusters, e.g. business parks, university science parks, and enterprise zones, where knowledge spillovers are hoped for (cf. Mans et al., 2008).



source: Roehrich et al. (2014, 111)

Figure 6: Scope of Public-Private Partnerships in Terms of Public Sector Risk

Table 4: Typology of HFC Public-Private Partnerships (PPPs) in Germany and the UK

	Public Leverage	Contracting-Out	Joint Ventures	Strategic Partnering
Purpose from State Perspective	i) Create conditions attractive to private sector investment. ii) Foster sectoral development in specific locations.	i) Achieve cost reductions, efficiency gains and quality improvements in public services. ii) Reduce the workforce management responsibilities of public managers.	i) Deliver projects where government has commonality of interest with business or not-for-profits. ii) Enable government to gain access to private capital off the public balance sheet. iii) Transfer risk to the private sector.	i) Enable government to gain significant cost and business process gains over the medium to long term. ii) Integrate business and not-for-profit actors into the public policy process.
Mechanism	Government prepares land for industrial development, provides tax breaks, and offers subsidies, e.g. capacity payments for electricity generation.	Provision of public service under contract by business, not-for-profit or any other agency, often utilising competitive tendering against the existing public provider.	Contract between government and private partners covering relative financial contributions to RD&D, design, capital works and subsequent costs.	Long-term and open-ended relationship between public and private actors based on trust and mutuality rather than formal contract.
Partner Relationships	Government seeks to attract business partners who will invest in RD&D generally but also in specific locations typically in need of economic regeneration.	Public.	i) Government commissions and specifies the project outcomes, and commits to repaying costs. ii) Private partner finances RD&D, design, marketing, and/or builds, and/or manages, and/or operates facilities.	May include elements of contracting-out, franchising and/or joint venture.
Funding	Public	Public purchaser. Private or not-for-profit supplier.	Private, with government refunding costs over the long term.	Public, but may include private.
Timescale	Medium term. Open-ended.	Short-, medium- and long-term. Fixed period contracts.	Long term. Fixed-term contract.	Long-term. Open-ended, relational contract.

based on: Skelcher (2005)

Table 5: Examples of HFC PPPs Based on the PPP Typology in Table 4

	Public Leverage	Contracting-Out	Joint Ventures	Strategic Partnering
German Examples	In 2009, the **North Rhine-Westphalia Fuel Cells and Hydrogen Network (NBW-NRW)** created a high-tech cluster policy. The Land has been undergoing a long-term economic transformation away from its traditional energy industry. Using a range of incentives, the cluster policy was designed to encourage HFC RD&D by encouraging local and multinational HFC actors to locate there.	Between 1980 and 2008, the **Ministry of Defence (BMVg)** procured HFC-powered air-independent propulsion (AIP) for diesel-electric submarines. A range of project partners helped de-risk the overall investment. This included national actors such as the state shipyard Howaldtswerke-Deutsche Werft (HDW) and Siemens, and foreign ones including Ballard Power Systems (based in Canada).	The **Solar Wasserstoff Bayern (SWB)** Solar-Hydrogen-Project was a demonstration project in Bavaria which ran from 1986 to 2000. The aim was to make a technical assessment of AFC, PAFC and PEM fuel cells for different applications. SWB was funded by the federal government, the Bavarian state, and private companies based in Bavaria, including Bayernwerke AG (later E.ON), BMW and Linde AG.	In 2009, the **H_2Mobility** project began with the signing of a Memorandum of Understanding (MOU) between the federal government and eight automotive and energy multinationals. This long-term, strategic PPP was designed to bring HFC vehicles to the marketplace through investment in vehicles and infrastructure. This PPP is also hoped to help the German state meet low-carbon policy commitments.
UK Examples	In 2009 and 2010, the **Department for Business, Innovation and Skills** and the **Department of Energy and Climate Change** designated the North East, West Midlands and South Wales regions as Low Carbon Economic Areas. Financial support for R&D into low carbon vehicles was offered.	From 1959 to the present, the Admiralty (later, **the Ministry of Defence**) has had a long-term contract with CJB Developments Ltd. (and its successors) to provide electrolysers. This HFC technology has provided fresh water, oxygen and a source of electricity on board all of the UK’s nuclear submarine fleet since 1962.	**Energy Conversion Ltd. (ECL)** was formed in Sunbury-on-Thames in 1961 by the non-departmental government body, the National Research Development Corporation (NRDC). This joint venture consisted of BP, British Ropes, GKN and the NRDC. BP saw the new HFC 'engine' as another outlet for oil, GKN for its electrochemical prowess, and British Ropes simply wanted to diversify.	In 2002, the Greater London Authority launched the **London Hydrogen Partnership** (LHP). The LHP strategically aligns public and private actors, legitimises HFCs, facilitates knowledge transfer and de-risks investment with the overall aim of establish a regional hydrogen economy. The long-term aspiration is to contribute to carbon reduction targets and boost the regional economy.

- **contracting-out -** measures are designed to support investment in RD&D in energy supply and its infrastructure. Examples include contracts and contract payments for energy generation in deregulated energy markets.

- **joint ventures** – JVs are typically undertaken for a very specific HFC RD&D project, marketable application or infrastructure project, and

- **strategic partnering** – this is in evidence where private JV actors (who may also be benefitting from public leveraging) are encouraged to become involved in the delivery of state policy objectives.

From the state's perspective, the purpose for each form of HFC PPP is shown in the top row of Table 4. This suggests an increasing sophistication in partnership mechanisms and relationships moving from public leverage on the left to strategic partnering on the right. There are also shifts in the mix of public and private funding as well as typical time scales from the medium- to the long-term.

Based on Table 4's typology, some HFC PPP examples from the German and UK TIS narratives are given in Table 5. Public leverage includes a range of support from state funding for HFC patent sales to offering financial incentives to invest in specific locations. In terms of the latter, the state- funded North Rhine-Westphalia Fuel Cells and Hydrogen Network is shown in Table 5 to have created a high-tech HFC cluster policy. In the UK, Table 5 shows that, in 2009 and 2010, the Department of Business, Innovation and Skills and the Department of Energy and Climate Change made appeals to automotive actors to invest in the North East, West Midlands and South Wales regions after designating them as Low Carbon Economic Areas. Examples of contracting-out shown in Table 5 include the German Ministry of Defence's procurement of HFC-powered air- independent propulsion for diesel-electric submarines. Similarly, the UK Ministry of Defence has had a long-term contracting-out PPP since 1959 to supply submarine electrolyser technology. Examples of joint ventures (JVs) shown in Table 5 include the Solar Wasserstoff Bayern Solar-Hydrogen-Project. An early UK JV was Energy Conversion Ltd. formed in Sunbury-upon-Thames in 1961 by the National Research Development Corporation (NRDC), a non-departmental government body involved in promoting HFC patents. Finally, Table 5 shows examples of strategic partnering PPP activity including Germany's H_2Mobility project and the London Hydrogen Partnership.

2.5.2 Extended Coding - Geographical Location

In terms of concerns regarding agency and structure, Functionalist approaches also suggest that the social system itself is the causal agent of change. As discussed in the literature review above, the TSIS approach uses a modified form of EHA to suggest causation between events, i.e. the occurrence of event Y implies the occurrence of an earlier event X (Hekkert et al, 2007). However, as Kern (2012) indicates, this is not formal causation as TSIS proponents claim. Coenen et al. (2012) argue that the TSIS heuristic risks overemphasizing apparently universal functional mechanisms as causal explanations for innovation. The key socio-technical processes at work over time, they point out, are grounded in real, place-dependent actor activity linked to institutional structures. By factoring in the spatial dimensions of innovative temporal events, improved spatio-temporal understandings of the causality of HFC innovation and diffusion will arise (cf. Coenen et al., 2012).

I conclude, therefore, that the ways that HFC innovation and diffusion are analysed via the TSIS approach should be altered to better reflect the spatial dimension to activity on the ground (cf. Hacking and Eames, 2012). A theoretical solution to this problem appears unlikely because the meso- and macro-levels of analysis of the TSIS heuristic are dictated by the neofunctional ontology (cf. Geels, 2010). However, narrative sections based on *project-level* EHA (Poole et al., 2000, Van de Ven et al., 1999) can be expanded, at least in places, to avoid the risk of underemphasizing or even missing socio-spatial processes which impact upon socio-technical analyses with HFCs.[24]

Based on the development of my critique in this chapter, my methodological proposal to overcome concerns about causality is, as in Section 2.5.1 above, to extend the variant EHA approach. I do this by adding data from a new indicator for events - geographical location - to the overall TSIS analysis. Through data triangulation, this extended coding will ground the temporal TSIS analysis with a place-dependent context for actor activity which remains linked to institutional structures (see Section 3.3.1.4 of Chapter 3 for full details of this coding indicator). In my analysis of causality with HFCs, I also triangulate spatial data in the event narratives for the UK and Germany. For example, while the uneven availability of resources *over time* is typically self-evident in HFC case studies, the closely-linked unevenness of resources *in space* is less well theorized. Coenen et al. (2012, 970) make a key observation when they suggest that with the TIS heuristic: “Don’t obscure

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[24] The use of qualitative interviewee results in the TIS narratives is another way to avoid losing the micro-level insights of HFC actors.

simple, place-specific causal relationships behind a more general systems analysis [because] … Without explicitly elaborating why actors in particular TISs choose to pursue their activities in particular regional and national contexts, it is very difficult to isolate individual success factors". My additional coding for geographical location will permit analysis of dynamic change with HFC activity in these spatial contexts, particularly at the regional level which is not currently theorized as a 'container' of analysis in the TSIS heuristic.

Note also that an important spatial differentiation between the UK and Germany concerns the ways that capitalism is practiced as I describe in the next sub-section. I return to these points in Chapters 6 and 7.

2.5.2.1 The Varieties of Capitalism Approach

As I mentioned briefly in Section 1.4.5, the EPSRC SUPERGEN XIV DoSH study indicated that there were distinct national differences in the ways capitalism was practiced between the UK and Germany. In terms of encouraging HFC innovation and diffusion, the typical forms that PPPs have taken in Germany and the UK appear to depend in large part on historic approaches of actors to the governance of financial risk. As Skelcher (2010, 299) suggests:

> "[T]he key task in developing the governance of PPPs is less to do with their financial probity, and more with aligning their mode of operating to … fundamental democratic values."

Germany, as a coordinated market economy (CME), has a long history of firms working with each other and with other actors including the federal state, regional states and trade unions (cf. Hall and Soskice, 2001). Such CMEs, which also include Japan, Sweden and Austria, for example, rely more heavily on non-market forms of interaction. When it comes to PPPs, German industrial actors therefore retain a degree of scepticism towards public management reforms based on business models (given the history of consensual decision-making on social and industrial matters) (cf. Trampusch, 2006).

The UK, by contrast, as a liberal market economy (LME) is similar to the United States, Canada, Australia, New Zealand and Ireland, for example, and has a history of firms coordinating their activities via hierarchies and market mechanisms (cf. Hall and Soskice, 2001).[25] The UK has developed considerable experience with the use of PPPs thanks to its neo- liberal political and economic consensus.[26] There are therefore potentially significant differences between Germany and the UK in general economic terms and, specifically, in terms of the former's largely public sector-centred approach to innovation via PPPs compared with the latter's predominantly market-centred PPP approach (cf. Lember et al., 2014b).

The Varieties of Capitalism approach suggests that because of different national approaches via a range of institutions, state power is exercised in different ways (Mikler, 2009). In terms of space and place, this suggests that there are:

> "different propensities for change and how change occurs … [T]his has implications for non-economic outcomes, such as addressing environmental externalities, because these are directly related to national variations in the institutional basis of capitalist relations of production" (Mikler, 2009, 32)

As Nieuwenhuis and Wells (2015) point out, the Varieties of Capitalism approach has evolved from an initial focus on the strategic behaviour of multinational corporations regarding national differences in labour resources to a more nuanced appreciation of differences of space, place, scale and socioeconomic characteristics such as systems of political representation. This means that:

> "even if there is a process of global economic integration … the outcomes are not uniform or indeed simply predictable … [T]o some degree firms are embedded in their localities, in the cultural and social practices that surround them, and in the institutional, legal and regulatory frameworks that may be more or less specific to place" (Nieuwenhuis and Wells, 2015, 12).

The varieties of capitalism approach has been critiqued for its relatively narrow focus on institutions. According to (Jessop, 2014, 48) this means proponents:

1) can neglect the interrelationships between distinct families of capitalism,
2) focus on factors internal to a given type of capitalism via macroeconomic indicators,

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[25] The UK experience is also underpinned by established norms regarding property rights and legal compliance (Skelcher, 2010).

[26] Defence contracts reveal the most complex forms of cooperation with the private sector in both countries.

3) do not relate short- or medium-term cyclical performance to longer-term dynamics
4) tend to assume that all varieties of capitalism are analytically equal, i.e. they just happen to occupy different places on a continuum, in a two-dimensional property space, or in a more complex, n-dimensional matrix.

Generalisations can result in Varieties of Capitalism analyses which suggest that one type of capitalism is superior to others over time (whilst competitive pressures force less successful regimes to wither). Jessop (2014, 49) suggests that this:

> “sometimes leads to prescriptive remarks on the efficiency and desirability of a neoliberal turn or, less often, the ability of a coordinated market economy to avoid the worst aspects of its more crisis-prone, inequality-generating (neo)liberal counterpart.”

I will return to these points about the Varieties of Capitalism approach again in the comparative analysis of the national TIS narratives in Chapter 6 and in my conclusions in Chapter 7.

2.5.3 Extended Delineation – Broader Actor Network Membership

The critical literature review also suggests that asymmetries of power between actors are not always made clear in theoretical terms in the TSIS heuristic. In the case of HFC actors, greater numbers should be included in broader network membership (cf. Smith et al., 2005). This includes the activities of the state, its agencies and *all* partners in public-private partnerships (PPPs). Also, broad actor inclusion in such networks is required because explanations of the nature of causation between events in Innovation Systems’ (IS) heuristics is not straightforward (cf. Coenen et al, 2012, Kern, 2012). For these reasons, another methodological revision is to draw on interviews with a larger group of individuals than is typically seen with TSIS case studies. Thanks to the data from the EPSRC DoSH study, I have ensured that interviewees’ backgrounds are broader than simply HFC scientists and entrepreneurs. In the DoSH study, for example, I also concentrated on individual actors involved in the broader delivery of infrastructure, including local planning authorities. This qualitative interview material is triangulated here with other data sources and cited directly in the HFC TIS event narratives for each country (which is not typically seen with the TSIS heuristic’s approach to case studies).

2.5.4 Extended Level of Analysis – Regions

System delineation was identified as problematic in the critical literature review due to *ex ante* boundary setting (Coenen and Díaz López, 2010, Markard and Truffer, 2008c, Weber, 2007). The literature indicates that, when it comes to practical questions like gauging both the local influence and the global reach of MNCs on a national HFC TIS, for example, the aggregated analytical 'containers' used in the TSIS heuristic, like nations and sectors, may seem somewhat artificial. More importantly, however, is that once the events are coded for geographical location (see Section 2.5.2), analysis of dynamic change can be made at the regional and sub-regional levels – reinforcing the potential impact of space and place on my analysis of agency and structure – something which the TSIS approach currently lacks.

2.6 Summary

In this chapter, I have achieved Activity 1 from Text Box 4. I have used a critical literature review of all Innovations Studies' heuristics to establish what the gaps are in the knowledge base regarding HFC innovation and diffusion activity. This review has helped me to refine my research questions described in Chapter 1. It has given me an assessment of the scope for enhancing the methodological approaches of the TSIS heuristic. The methodological tools that will help me to overcome the knowledge gaps that I have identified are more fully explored in Chapter 3. Finally, this review lets me complete my remaining activities by presenting data in Chapters 4 to 5 and offering analysis in Chapters 6 and 7. Overall, it is clear that this critical literature review is of key importance to every chapter of this thesis and determining the nature of HFC innovation and diffusion in the UK and Germany.

In the next chapter, the methodological choices that I made with my HFC case study material are described in more detail. My approach involves using the TSIS heuristic, but with the addition of the methodological extensions described here.

Chapter 3: Methodology and Methods

3.0 Introduction

In this chapter, I describe how I achieved research Activities 2, 3 and 4 (see Text Box 4 in Chapter 1). Activity 2 is to characterize hydrogen fuel cell (HFC) innovative activity via two case studies from the UK and Germany between the 1950s and 2012. Activity 3 is to identify the factors that have influenced the dynamic nature of HFC innovation and diffusion through comparisons between the two countries. Activity 4 is to make an assessment of how effectively the Technologically-specific Innovation Studies (TSIS) heuristic captured the nature of the patterns of HFC innovation and diffusion. Throughout the remaining chapters, that assessment is made at TSIS heuristic's meso- and macro-levels of analysis which is dictated by its neofunctional ontology (cf. Geels, 2010). Below, I describe and justify the use of a neopragmatic research design (Tashakkori and Teddlie, 2003, Plano Clark and Creswell, 2011) which is informed by innovation theory (Hekkert et al., 2007a). This input from Innovation Studies involves analysing the case study evidence for sustained positive feedback between HFC Technological Innovation System (TIS) functions and, hence, for the beginnings of transitional change associated with this clean technology sector. Using this approach in the empirical chapters, HFC technologies are shown to coevolve with institutions over time. There is branching along certain technological pathways - and not others - depending upon structural barriers and enablers encountered by HFC actors. Case study data comes from material that I collected for the EPSRC's Supergen XIV Delivery of Sustainable Hydrogen (DoSH) consortium between 2011 and 2013 and from data that I collected solely for this thesis between 2014 and 2015.

In Chapter 1, I stated that the reasons why HFC innovative activity begins to take off in one country (or one region or locality), but not in another, are not fully understood. In Chapter 2, I identified the specific nature of knowledge gaps about HFC innovation and diffusion (Activity 1 from Text Box 4). I achieved this analysis by applying four interlinked and emergent critical themes from a range of interdisciplinary literatures to HFC research papers. I concluded Chapter 2 suggesting four methodological modifications to the TSIS approach (which are detailed further in this chapter):

1) national HFC Technological Innovation System (TIS) event narratives are coded for the organizational funding status of the projects linked to events –

this data is then triangulated with other sources to overcome concerns about conceptions of agency and structure linked to power relations,

2) national HFC TIS event narratives are coded for geographical location – this data is then triangulated with other sources to overcome concerns about conceptions of agency and structure linked to causality (as well as the lack of analysis at the regional and sub-regional levels in the TSIS heuristic),

3) interviewees were selected from the prior DoSH study from a broader range of actors in HFC networks (beyond researchers and entrepreneurs) than seen in other TSIS studies – this was to allay concerns about conceptions of agency and structure related to causation and *ex ante* system delineation,

4) text boxes are to be used in national HFC TIS event narratives at technological branching points – citing and sourcing micro-level (i.e. project-level) material more overtly in the analysis than in standard TSIS analyses offers broader insights into conceptions of agency and structure of HFC actors involved in socio-technical contestations.

In terms of the structure of this chapter, I begin in Section 3.1 by detailing how and why a neopragmatic research design was arrived at for this study. In Section 3.2, I examine the philosophical nature of pragmatism and neopragmatism and indicate what the implications are of a neopragmatic methodological framework for the analysis of HFC innovative activity. In section 3.3, I describe how my data production, analysis, and outputs link together. I do this via a route map graphic which links three tracks of research activity to an integration point. There are two quantitative datasets covering the national HFC TIS event timelines and national lists of HFC actor information. A third dataset is qualitative and involves 49 interviews from HFC individuals in the UK, Germany and from the EC (Brussels in Belgium). Results are then reported in Chapters 4 and 5, covering the UK and German case studies respectively. Comparative analysis of this data is given in Chapter 6. Chapter 7 concludes with my so-called ‘warranted assertions’ (see Section 3.2.1 below) about the uneven nature of HFC innovation and diffusion within and between these two countries.

A description of the process of searching for a research design - which establishes how my data gathering and analysis are structured in later chapters – is given in the next section.

3.1 The Search for a Research Design

Finding a research design appropriate for this comparative UK-German study began with my research questions (as set out in Text Box 3 in Chapter 1 and at the top of Figure 4). Understanding uneven development is central to Innovation Studies' approaches and a comparative case study approach is typical (e.g. Freeman, 1987, Nelson, 1993). My research questions are about the nature of uneven development. They are linked to my five activities with this study (Figure 4 in Chapter 1). To complete research Activities 2 and 3, I drew on the analysis in my critical literature review (Chapter 2). The key methodological challenges were: 1) finding a research design that allowed me to draw on data produced for a different study that had different research questions, and 2) making methodological adjustments to an existing theoretical approach to innovation (the TSIS heuristic). In the end, I pursued a neopragmatic research design which ensures fuller data and theory integration than most mixed methods studies. I did this for two main reasons: 1) long-standing practical concerns about whether researchers using mixed methods designs manage to get the most from their data, and 2) my need for data *and* theoretical triangulation. I explore these points in the next two sections below.

3.1.1 Critique of Mixed Methods Designs

In this section, I identify concerns with mixed methods research designs in order to contextualize my choice of a neopragmatic mixed methods design.

Some mixed methods researchers struggle with true integration of their data, i.e. the ability to look at phenomena from varied perspectives and offer enhanced understandings through triangulation (Jick, 1979). As Feilzer (2010) indicates, much mixed methods research presents its analysis through the presentation of data from different methods alongside each other. Findings are then discussed individually. In this way, most empirical mixed methods researchers are unable to go beyond the "forced dichotomy of quantitative and qualitative methods and data" (Feilzer, 2010, 10). This lack of integration suggests that mixed methods researchers may not always be making the most of the data they collect.

Instead, Howe (1988, 15) points out that qualitative methods evolve and remain compatible with quantitative methods:

> "At the level of epistemological paradigms, philosophy of science has moved on, into a … 'postpositivistic' era. Questions about methodology remain, but they ought not [to] be framed in a way that installs abstract epistemology as a tyrant or that presupposes the moribund positivist- interpretivist split."

Some social science researchers engaged in the mixed methods' debate advocate dropping mixed methods completely:

> "Mixing methods is wrong, not because methods should be kept separate but because they should not have been divided at the outset" (Gorard, 2007, 1)

Howe (1988, 15, my italics), as suggested above, rejects the 'incompatibility thesis' which suggests quantitative and qualitative methods are not compatible:

> "At the levels of design, analysis, and interpretation of results, quantitative and qualitative researchers differ chiefly in the assumptions they are willing to make and how much attention they pay to 'experience-near' data …The existence of two sets of methods entails at most that *having more than one set of tools is useful*."

Another point of critique of mixed methods approaches, according to Giddings and Grant (2007, 58), occurs when assumptions about particular methods – qualitative or quantitative - are not made explicit:

> "[T]he ensuing analysis may contain unprocessed contradictions … [We] found that where there was a lack of goodness of fit between findings, the qualitative [methods] took the back seat in order to preserve the 'integrity' of the study's conclusions ... qualitative findings are all too easily relegated to the position as 'handmaiden' of quantitative ones."

This point is echoed by Denzin and Lincoln (2011, 7):

> "Mixed methods presume a methodological hierarchy with quantitative methods are at the top and qualitative methods are relegated to a largely auxiliary role in pursuit of the technocratic aim of accumulating knowledge of what works."

Denzin and Lincoln (2011, 246) also identify other concerns about the use of mixed methods research designs which include: "cost, superficial methodological bilingualism, and an entanglement in superficial philosophical debate."

To solve these concerns, Symonds and Gorard (2008) suggest social science researchers should firstly:

> “[Focus] ... on the quality of our actual research techniques, the resulting data and on how that data is used, no matter whether this involves one or more sets or types”.

Then, by bringing quantitative and qualitative findings together, Bryman (2007, 9) says *effective triangulation* between them has:

> “the potential to offer insights that could not otherwise be gleaned … [E]ven when a fusion of the two sets of findings was not envisioned at the outset of a project, it may be valuable to consider whether the findings suggest interesting contrasts or help to clarify each other.

For all of the reasons above, I became interested in using a neopragmatic mixed methods design in which the means of triangulating between datasets and theoretical approaches are overt. However, I also considered using a case study methodology, as I describe in the next section.

3.1.2 Critique of Case Study Designs

With the EPSRC’s DoSH study, my use of case studies followed a comparative national approach where Technology Innovation Systems’ (TIS) event histories were set within the broader TSIS analytical framework. As stated in Section 1.4.3 in Chapter 1, the specific needs of this thesis are different to that study. Early on, I nevertheless considered using the case study methodology of Yin (1984). Yin’s definition of a case study has appeal to the examination of co-evolutionary processes. It refers to examining a “contemporary phenomenon in its real-life context” and making investigations where “boundaries between phenomenon and context” are not clearly demarcated (Yin, 1981, 59). However, as Evans (2011, 61) points out:

> “[T]he case study method requires fundamental rigour at the level of first principles. Because there is no set ‘method’, there is no set ‘model’ that can be used without fundamental interrogation of the research field, the research questions or the theories which underlie the research enquiry. This need to ‘build from scratch’ each individual research project … means that it is not the simplest method to employ.”

Also, while Yin’s case study methodology is rigorous and very widely used, I needed a research design that could handle analysis from triangulating a wide range of data types in the case studies *and* make comparative methodological analyses based on using additional indicators which extend the TSIS approach. I also noted that the same judgement can be made of Flyvbjerg's case study approach, which I also considered because of its qualitative rigour and case study depth (cf. Flyvbjerg, 1998, Flyvbjerg, 2006).

I concluded from this review of case study research designs that the best way to achieve my later research activity (Activities 2 to 4 in Text Box 4 in Chapter 1) was to pursue a more integrated neopragmatic design (see below).

In the next section, I describe the nature of neopragmatism in more detail and outline the implications for this study.

3.2 Neopragmatism

A neopragmatic research framework allows me to avoid privileging quantitative over qualitative data (or vice versa) and to triangulate all data sources as well as theoretical approaches from Innovation Studies (as described in Section 1.4.3) (cf. Hekkert et al., 2007a). This type of research design means that I ultimately make 'warranted assertions' (see Section 3.2.1 below) about the nature of HFC innovation and diffusion in Chapter 7, i.e. working conclusions based upon a range of triangulated sources which give me relatively high levels of confidence.

Neopragmatism makes use of the most appropriate methods (i.e. 'what works') from both positivist and postpositivist ('interpretivist' or 'constructivist') epistemologies. Mixing inductive and deductive reasoning, the neopragmatic approach to mixed methods includes 'abductive' reasoning. This reasoning is based on the "expertise, experience, and intuition of researchers" (Wheeldon and Åhlberg, 2012, 117). Neopragmatism espouses the use of a set of tools rather than offering an ontological worldview (Biesta, 2010). Its philosophical roots go back to the work of several classical pragmatists, chiefly Dewey (1903), James (1907 / 2014) and Peirce (1904 / 1997). For them, the inter-subjective nature of the observer and the observed encourages the testing of intuitions theoretically and empirically. Tentative explanations and hypotheses, based on the best information at hand, will:

> "emerge through the research process and can be developed and/or tested using methods that are either quantitative, qualitative, or a mix of both" (Wheeldon and Åhlberg, 2012, 117).

Neopragmatism ought to have appeal to Innovation Studies' researchers because, in Dewey's theory of knowledge, the formation of routines, or 'habits', is a key learning process (Dewey et al., 1938 / 2008). This idea is very similar to the Nelson-Winter-Dosi model of innovation which is advocated by Neo-Schumpeterians (Nelson and Winter, 1982, Dosi, 1982). Dewey felt that habits were the basis for the transmission of know-how and cultural tradition. He proposed a framework that "starts with *interactions* – or as he later preferred to call it, *transactions* – taking place in nature" (Biesta, 2010, 106, italics in the original). From this, an actor's external environment is conceived of as "a moving whole of interacting parts" (Dewey, 1929, 232). Objects such as R&D prototypes, for example, can be considered more than just 'things'. Rather they are "events with meaning" (Dewey, 1925 / 1958, 240). Dewey therefore had a non-dualistic approach to knowledge and placed as much emphasis on the meaning of events as their causality. This emphasis means pragmatism represents a potential shift away from deterministic causality.

A neopragmatic methodological approach therefore appears useful for mixed methods investigations into how technological 'objects' interact with their external environment, i.e. in a non-linear and co-evolutionary way. In Dewey's theory of knowledge, there is the expectation that contestation via competing realities/worldviews will occur (Dewey, 1903). Amongst a range of data types, pragmatism can incorporate micro-level qualitative interview data. Such data can reveal meaning, motivation, power, strategy and networks as seen with Sociology of Expectations (SOE) approaches from Innovation Studies. There is also a key point of crossover with SOE heuristics - Dewey's suggestion that knowledge is about 'inference' or expectations of the future. As Biesta (2010, 109) states: "Knowledge is in part a reaction to something distant in time or place. Because [it] is a step into an unknown future, it is a precarious journey. Inference always involves uncertainty and risk." On this point, I noted in Chapter 2, for example, that advocates of SOE heuristics suggest that technological expectations alone are the key to understanding the co-evolutionary dynamic behind innovation system change, not functional approaches (Alkemade and Suurs, 2012).

For these reasons, I judged that my methodological framework, which needs to be informed by innovation theory, should also draw on recent reinterpretations of Dewey's theory of knowledge. I outline in the next two section the practical methodological implications stemming from neopragmatic approaches that are relevant to the data production and analysis in this study.

3.2.1 Implications of a Neopragmatic Approach on Data Production

As suggested above, a neopragmatic research philosophy suggests a number of practical positions with methodological implications for this thesis:

> “Pragmatists supplant coherence and correspondence with criteria such as accuracy, scope, simplicity, consistency, and comprehensiveness … and contend that basing theory choice on these criteria entails not that science is irrational, but that scientific rationality simply does not fit the positivistic (i.e. mechanistic) account.” (Howe, 1988, 15)

I highlight these in turn below.

Firstly, the research questions being asked are regarded as more important than the methods because there will always be a range of methods that can be drawn on (Morgan, 2007). Secondly, pursuing a pragmatic philosophy means no research method is considered better than any other (cf. Biesta, 2010). Instead:

> “We have to evaluate the results from our research studies in terms of how good a job we did in selecting, using and integrating all the available methodological tools.” (Tashakkori and Teddlie, 2010, 811)

Table 6 shows the methodological implications of mixing positivism with interpretivism/constructivism into pragmatism’s ‘third way’. Thirdly, in terms of a pragmatic research philosophy, notions of ‘truth’ and ‘reality’ should be abandoned. Instead, pragmatism:

> “[places] its emphasis on *shared meanings* and *joint action* ... on actual behaviour (‘lines of action’), the beliefs that stand behind those behaviours (‘warranted assertions’), and the consequences that are likely to follow from different behaviours (‘workability’) … [There is an emphasis] on 'what difference it makes' to believe one thing versus another or to act one way rather than another.” (Morgan, 2007, 68)

A neopragmatic research design merges truth and inquiry together where correspondence to an external world is no longer relevant. As Boyles (2006, 7-8, my italics) indicates:

Table 6: Neopragmatism: Implications for Research Practice

Worldview / Element	**Positivism**	**Post-positivism (also ‘Interpretivism’ / ‘Constructivism’)**	**Neopragmatism**
Ontology (the nature of reality)	**Singular reality** (researchers reject or fail to reject hypotheses)	**Multiple realities** (researchers provide quotes to illustrate different realities)	**Singular and multiple realities** (researchers test hypotheses and provide multiple perspectives)
Epistemology (the relationship between the researcher and what is researched)	**Distance and impartiality** (researchers objectively collect data on instruments)	**Closeness** (researchers visit participants at their sites to collect data)	**Practicality** (researchers collect data by ‘what works’ to address research questions)
Axiology (the role of values)	**Unbiased** (researchers use checks to eliminate bias)	**Biased** (researchers actively talk about their biases and interpretations)	**Multiple stances** (researchers include both biased and unbiased perspectives)
Methodology (the process of research)	**Deductive** (researchers test an a priori theory)	**Inductive** (researchers start with participants’ views and build ‘up’ to patterns, theories and generalizations)	**Combining** (researchers collect both quantitative and qualitative data and combine them)
Rhetoric (the language of research)	**Formal style** (researchers use agreed-on definitions of variables)	**Informal style** (researchers write in a literary, informal style)	**Formal or Informal** (researchers may employ both formal and informal styles of writing)
Innovation Studies Approach	**Innovation Systems (ISs)** (e.g. National Systems of Innovation, Technologically Specific Innovation Systems)	**Systems Innovation (SI) / Technology Transitions (TT) / Sociology of Expectations (SOE)** (e.g. Strategic Niche Management, Transition Management, Multi-level Perspective, Hype Cycles, Enactors and Selectors and Expectations).	**This Study**

based on: Author and Plano Clark and Creswell (2011, 42)

> “The point [of pragmatic research] … is the interdependency of truths and the processes of inquiry … [I]dealists and realists are misguided when they describe epistemology as [a] way of determining knowledge. ‘Knowledge’ is not the focal point of epistemology for Dewey … ‘[K]nowing’ is … [B]y ‘knowing’ Dewey means inquiry in a world that is not static … into things ‘lived’ by people. He means experimenting with solving problems such that *the action entailed in the solving of problems is inquiry itself and [is] warranted in the assertions made about the solved problem when it is solved* (where ‘solved’ is understood as temporal and a portal to further inquiry).”

In this context, Dewey emphasizes the dynamic nature of ‘knowing’ when he rejects traditional epistemologies and defines ‘warranted assertions’ as the key to arriving at conclusions when using pragmatic analysis:

> “[’Warranted assertions’ are] preferred to the terms *belief* and *knowledge* [as] it is free from the ambiguity of these latter terms, and it involves reference to inquiry as that which warrants assertion. When knowledge is taken as a general abstract term related to inquiry in the abstract, it means ‘warranted assertibility.’ The use of a term that designates *potentiality rather than an actuality* involves recognition that all … conclusions of … inquiries are parts of enterprise that is continually renewed.” (Dewey et al., 1938 / 2008, 8, my italics)

A neopragmatic methodological approach, as outlined in Table 6, also stresses practicality: there is no single and reliable way of acquiring valid knowledge (i.e. no claims to ‘truth’) about the observed universe. ‘What works’ is about finding the best way(s) of addressing the research questions.

Fourthly, in the list of practical implications of a neopragmatic research design, it should be made clear in studies when each type of data – whether quantitative or qualitative or both - is being drawn on in analysis. Fifthly, with this research philosophy, the focus of neopragmatic studies is ultimately on the consequences of the research in terms of contributions to debates about theory and policy.

With this thesis, I have reflected at every stage of data production about issues of data compatibility and, with the analysis, the signposting of where data has come from and how it is has been processed within the datasets.

In the next section, I examine in more detail what a neopragmatic research design means for the presentation of results and analysis in Chapters 4 to 7. In Chapter 7, I reevaluate my use of this methodological framework.

3.2.2 Implications of a Neopragmatic Approach for Results and Analysis

The neopragmatic research design that I employ allows my analysis to involve:

- **data transformation** – quantifying a significant amount of qualitative interview data (49 interviews) (cf. Tashakkori and Teddlie, 1998) – this is not seen in TSIS studies for example,

- **data consolidation** - merging *time-dependent and space-dependent* data to create an expanded dataset – this is not seen in TSIS studies (Louis, 1982, Onwuegbuzie and Teddlie, 2003),

- **data triangulation** - significant amounts of coded interview material crossed-checked with quantitative case study material – this is indicative of the depth of analysis,

- **data comparison** – comparison of qualitative and quantitative data/findings (Onwuegbuzie and Teddlie, 2003), and

- **warranted assertion analysis** – iteratively reviewing all qualitative and quantitative data to yield meta-inferences (Smith, 1997).

Of these methods, data triangulation is particularly important. Initially, text was drafted to provide a more integrated narrative from all sources. However, this was rejected because of research question 3: “Are there research suggestions that would add and enrich existing theoretical and methodological approaches in Innovation Studies?” In this thesis, I therefore provide further evidence for the limits to the TSIS model even when once I have modified it with some extra indicators. I will therefore show the shortcomings of the TSIS’s quantitative and quasi-quantitative approach in order to then pursue the methods above to offer a more integrated narrative picture of the quantitative and qualitative material via data triangulation.

The final analytical implication of pursuing a neopragmatic approach is that it permits me, as a researcher, to get close to the social processes being studied. For two and a half years I worked as an ‘insider’ in the UK community of HFC academic researchers through my work on the EPSRC DoSH study. In order to interpret and appropriately describe the social processes at work in both Germany and the UK, I also actively sought critical distance from the activities of the individuals and actors that I have learned from. This critical distance involves recognizing my own normative approach to social and technological change via the tenets of sustainable development.

Ultimately, ‘what works’ is a neopragmatic research design that produces warranted assertions about the empirical nature of HFC innovation and diffusion based on triangulating the three datasets. These assertions reveal the differences that individuals’ and actors’ actions made, or did not make, in the context of different innovative behaviours. These actions particularly relate to activity at technological branching points between transition pathways where individuals collectively agree to change direction and pursue another solution in order to overcome technical hurdles (cf. Morgan, 2007, Foxon et al., 2013).

In the next section, I describe how I use this methodological pluralism to convert the data I drew on into specific datasets and outputs before being triangulated at an integration point.

3.3 Data Production

This section describes the methods I used to produce the datasets and outputs which I integrated and later analyzed. I developed and pursued a route map in which quantitative and qualitative data on HFC actors was collated for both countries and turned into datasets and outputs (see Figure 7).[27] The interview data was triangulated with the national narrative event data to make the two case study narratives richer. These broad quantitative and qualitative routes to data production are examined in more detail in the next two sections respectively. The case study results for the UK and Germany are reported in Chapters 4 and 5 respectively.

As I indicated in section 1.4.3 in Chapter 1, my research design was informed in several key places by the TSIS approach to innovation with its seven ‘functions of innovation’ (cf. Hekkert et al., 2007a). I did this because my work for the EPSRC DoSH study which concluded in 2013 (Contestabile et al., 2013) yielded the greater part of the data pursued here. As with the DoSH study, the choice of the TSIS approach was also made for this thesis because evidence from case studies had only just begun to validate this promising approach to theorising innovation (Hekkert and Negro, 2009). Wherever a grey box is marked ‘Informed by TSIS Approach’ in Figure 7, a dashed line is linked to particular boxes which represent research activity.

The next section covers the production of quantitative data for this thesis.

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[27] This included the forty nine interviews from the DoSH study. See the anonymized list of interviewees in Appendix A which records the actor that each individual represented.

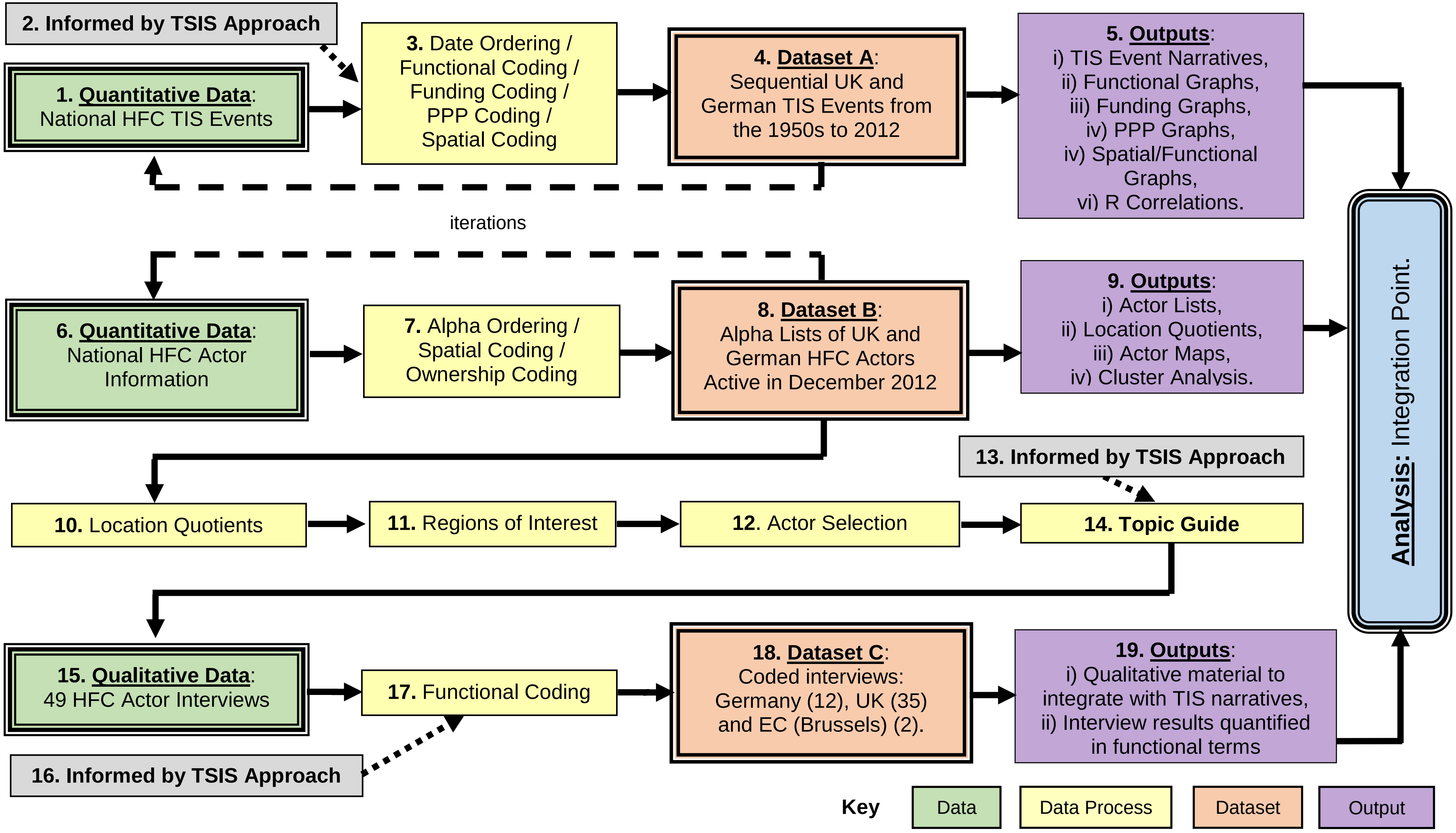

Figure 7: Outline Route Map of Mixed Methods Data Production for this Thesis

3.3.1 Quantitative Approaches

The quantitative data for this study include:

1) HFC TIS Events,
2) HFC Actor Lists,
3) Organizational/funding data related to 1), and
4) Spatial data related to 1) and 2).

As I described in Chapter 1, data initially came from the EPSRC DoSH study (2011-2013). The HFC TIS events dataset and the HFC Actor Lists were further updated iteratively in 2014 and 2015 with events going back to the 1950s. The routes to quantitative data production are described in the next two sections.

3.3.1.1 Production of HFC TIS Event History Narratives

As Allison (1984) indicates, events are chosen as the unit of measurement in Event History Analysis (EHA) because they represent distinct qualitative change compared to what came before. This type of change occurs at a specific point in time. In terms of analysis, the implication of this approach is that:

> "the best way to study events and their causes is to collect *event history* data … a longitudinal record of when events happened to a sample of individuals or collectivities … [It] should … include data on possible explanatory variables." (Allison, 1984, 9)

EHA is widely used in the social sciences. When applied to innovation, for example, a major empirical study conducted in Minnesota by Van de Ven et al. (1999) defines four key elements as part of its longitudinal EHA process approach:

> "*Innovation* is defined as the introduction of a new idea, the *process of innovation* refers to the temporal sequence of events that occur as people interact with others to develop and implement their innovative ideas within an institutional context. *Events* are instances when changes occur in the innovation ideas, people, transactions, contexts or outcomes while an innovation develops over time. *Change* is an empirical observation of differences in time on one or more dimensions of an entity." (Van de Ven et al., 2000, 32, italics in original)

With the Hekkert et al. (2007a) methodology for the TSIS heuristic, Van de Ven and colleagues' methodological approaches are cited. Hekkert et al. (2007a) modify the EHA methodology to accommodate a neofunctional ontological perspective (as examined in Section 1.4.3). On this basis, Hekkert et al. (2007a, 427-428) suggest that innovation-related TIS events should include, for example:

> "workshops on the technology, the start up of R&D projects, expressions of expectations about the technology in the press, announcements of resources that are made available, etc."

It is worth noting that the EHA approaches of the Minnesota studies and TSIS studies do not overtly record the spatial context in which events occur. I identified this as an important methodological deficit in Chapter 2 (see Section 2.5.2). I have therefore included additional codes to each event covering its geographical location in terms of town, city, region/Land and nation, or 'external' if an influential event occurs outside of the national boundary of the HFC TIS. These new codes are part of my 'extended indicators' (see Section 3.3.1.3 below).

In thinking about the later case study chapters on the UK and Germany, it is also worth noting that the ability to capture events from secondary sources did change somewhat over time. This greater availability of sources led to something of a bias towards an increasing numbers of HFC events from the 1990s onwards (at a time when the global number of HFC events began to rise significantly). Nevertheless, the empirical evidence from the UK and Germany in Chapters 4 and 5 shows that HFC TIS events in the 1950s and 1960s occurred at distinctly lower rates compared to the 2000s and 2010s, a trend that such a bias could not mask. It is also worth noting that different events mean different things to different actors given the evolving contestations over the legitimacy of different HFC technologies. The TSIS and extended coding do offer a way of categorising the functions of events that remains relatively constant over the long time frame and between these two countries and so permit comparisons of like with like.

In Figure 7, data gathering for the national HFC TIS narratives began with event selection shown in Box 1. Just over half of the TIS events were sourced from the online journal *Fuel Cells Bulletin* (FCB).[28] The German search terms used were 'German' and 'Germany'. The FCB resulting articles provided coverage of HFC

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[28] From 1998, FCB has been comprehensive in covering RD&D developments from around the world.

activity in all sectors of the German economy from road transport to shipping to heating, energy storage, aerospace, recreational and the military amongst others. The UK search terms used in FCB were 'UK', 'United Kingdom', 'Britain', 'British', 'England', 'English', 'Scotland', 'Scottish', 'Wales' and 'Welsh' covering events in similarly broad sectors. With the German event searches, there will have been a degree of skewing to the reporting of German events given that English-language source material was almost solely sought. Some under-reporting of the contents of German-language-only professional journals and German press articles was clearly inevitable. This is because I am not a German speaker. However, almost all of the post-1990s secondary source material was in English (including academic journals). I was able to talk with German HFC researchers and interviewees about my analysis of the TIS events pre- and post- the 1990s to ensure the German narrative was well-grounded. Cross-checks were also made on the broad sweep of the German TIS narrative both with English-language HFC academic papers and PhD theses from German researchers in the 2000s and 2010s (e.g. Ehret, 2004). Early German events, for example, were largely dominated by contextual information gleaned from patent filings (e.g. Eduard, 1958, Winsel and Justi, 1960) and corporate publications (e.g. Daimler-Benz, 2007a, Daimler-Benz, 2007b). The early UK case study material was somewhat richer and more varied. This was largely because of access to Bacon's patents and publications given his relatively high profile in the history of UK science (e.g. Bacon, 1954a, Bacon, 1954b). As with Germany, literature in the 2000s and 2010s (e.g. Eisler, 2009, Wilson, 2012) suggested some contemporary sources that could be accessed and reviewed (e.g. Bacon, 1969, Bacon and Fry, 1973). Throughout, the events discovered for both countries were selected without any privileging for known later developments.

The remaining half of the total event data – i.e. the portion not from *FCB* - came from patent searches with the World Intellectual Property Organization*,* the US Patent Office, Google Patents and a wide range of secondary sources, chiefly for events prior to FCB's coverage which started in 1998. Once set for 'GB' or 'DE', patent search words were 'fuel cell' *and* 'hydrogen'.[29] Further secondary sources include: i) academic research, ii) grey literature, iii) corporate historical documents, iv) state policy documents, v) corporate and university press releases and vi) web page data.

Overall, in this thesis, I use the modified approach of Hekkert et al. (2007a) to EHA to record the dates that individual TIS events occur on (including the dates that

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[29] Patents selected were only those successfully filed. Each was ordered in Excel by *initial* filing date.

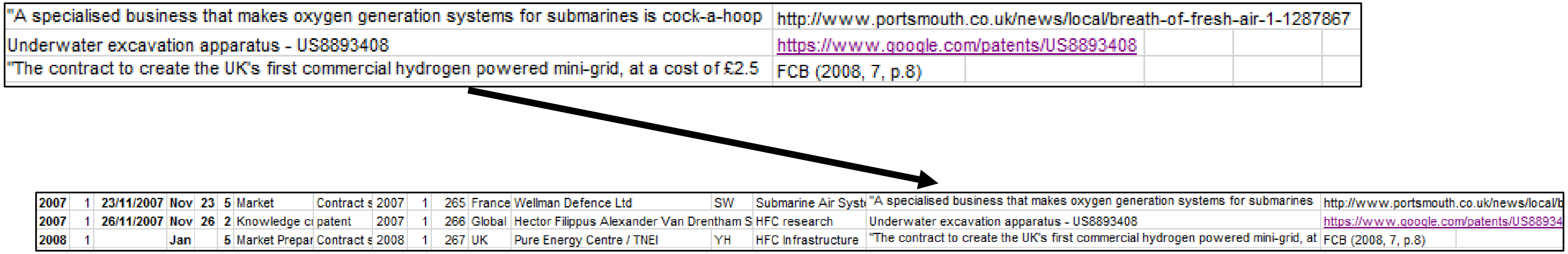
projects and other activities begin and end on) (see Section 3.3.1.3 below). In terms of event selection, I pursue the definition of 'event' of Van de Ven et al. (2000), outlined above, and I include examples drawn from secondary sources as per the suggestions of (Hekkert et al., 2007a). However, a more comprehensive list of all 'Event Categories' emergent in the secondary source data is shown in my coding frame given in Table 7 further below. In terms of the quality of secondary source material, typical events included, for example:

1) Marketing activity - the sales of HFC energy storage devices are sometimes reported in the news media and/or grey literature. In Figure 8, the first item enlarged from the UK TIS events database is news of engineering firm Wellman Defence's newest HFC contract going ahead in 2007. In this case, I found reference to the event, which would later be coded as 'market' activity (TSIS function 5), in local news reports in the Portsmouth press. That citation was added to the UK events database in this case. However, post-1998, most HFC contracts were recorded in *Fuel Cells Bulletin* (FCB). FCB was the source, for example, for the third item in Figure 8, news of sales of a hydrogen-powered mini-grid.

2) Knowledge development - patent registrations were largely drawn from online international patent offices chiefly the World Intellectual Property Organization, the US patent office and the European Patent Office and cross-referenced. A handful emerged from a check of the Google Patents online search engine. The second highlighted item in Figure 8 is an HFC patent for underwater equipment.

As indicated above, these examples are illustrative of the quality/validity of the sorts of secondary source material that was logged into the national TIS event history databases. In terms of Event History Analysis, Abell (1984, 310) indicates that two sets of secondary source material are compiled and analysed in a process of creating 'comparative narratives':

1) Explaining why a sequence of events occurs, when agency has played a necessary though not necessarily sufficient role, the context-specific action(s) which brought the events about must be described.
2) Other actions, by the same or other actors, which gave rise to the sequence of events, need describing and explaining.



"A specialised business that makes oxygen generation systems for submarines is cock-a-hoop	http://www.portsmouth.co.uk/news/local/breath-of-fresh-air-1-1287867
Underwater excavation apparatus - US8893408	https://www.google.com/patents/US8893408
"The contract to create the UK's first commercial hydrogen powered mini-grid, at a cost of £2.5	FCB (2008, 7, p.8)

2007	1	**23/11/2007**	**Nov**	**23**	**5**	Market	Contract s	2007	1	265	France	Wellman Defence Ltd	SW	Submarine Air Syst	"A specialised business that makes oxygen generation systems for submarines	http://www.portsmouth.co.uk/news/local/b
2007	1	**26/11/2007**	**Nov**	**26**	**2**	Knowledge c	patent	2007	1	266	Global	Hector Filippus Alexander Van Drentham S		HFC research	Underwater excavation apparatus - US8893408	https://www.google.com/patents/US88934
2008	1		**Jan**		**5**	Market Prepar	Contract s	2008	1	267	UK	Pure Energy Centre / TNEI	YH	HFC Infrastructure	"The contract to create the UK's first commercial hydrogen powered mini-grid, at	FCB (2008, 7, p.8)

Figure 8: Selected Secondary Source Entries in the UK TIS Events Timeline

3) This process generates a story or narrative comprising a set of interrelated actions. In writing a narrative, an explanation of the original event/sequence is given.
4) When it comes to comparing (explaining) the occurrence of two or more events/sequences, comparisons are made between two or more narratives - comparative narratives – are made.

Once a time-limited HFC event was first identified and placed in the national TIS event history, sometimes a second or even a third secondary source would be found and also referenced. This part of the process raised my confidence in the analysis of the events as I turned them into emergent narratives. The neopragmatic methodological approach was also useful as it involves the overt recognition of bias/contestation in the secondary source material (see 'Axiology' in Table 6). Above all, with the narratives, I sought coherence given the wide range of historical secondary sources used. There could be no direct equivalence amongst the patents, academic papers, press articles, corporate news releases, and so on, but each narrative was built up and made coherent via a process involving all such types of secondary sources (to a greater or lesser extent depending upon availability). Each individual secondary source was therefore used to build up support for the existence and nature of a myriad of socially-constructed and time-delimited 'events'. As the two TIS narratives emerged, I was then able to identify the rises and falls in HFC hype cycles on the basis of the rate of change of event numbers over time (cf. Fenn and Raskino, 2008). As I describe in my analysis in Chapter 5, external landscape-level events like an oil crisis typically result in a period of HFC hype. e.g. the hype cycle in Germany between 1974 and 1984.[30]

I recognise that, at one level, it might be possible to critique the EHA method used here for producing a 'lopsided' outcome between the two national narratives, i.e. like is *not* being compared with like. However, as this sub-section makes clear, it was not possible to create these narratives in a strictly comparative way given the variety of secondary sources reviewed. Instead, the purpose of the exercise is to make a virtue of the different qualities of the different sources of data as they shape the comparative narratives (Abell, 1984).

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[30] As Chapters 4, 5 and 6 show, these periods of hype, when the number of events rises and falls over time, are roughly coincident for 1959 to 1968, 1998 to 2004 and 2006 to 2012. However, one global period of hype was expressed differently in the two countries: between 1974 and 1984 there was a period of HFC hype in Germany, but not in the UK, the reasons for which are explained in Chapter 4.

With the events date ordered, they were then coded, as I describe in the next section.

3.3.1.2 Coding TIS Indicators

In terms of the coding of the TIS events, I do not claim to be an ‘objective’ observer. I acknowledge that there are competing positions on HFCs. I also recognize that there is potential for selection bias occurring with me as sole researcher. Box 3 in Figure 7 shows that date-ordered events for both countries were coded for TSIS function, organizational funding and geographical location. I describe my approaches to each of these below.

Initially, when coding the TIS events in terms of their functions, I examined the coding frame of Hekkert and Negro (2009) (Table 7). I made the generic nature of this coding frame, which was designed for renewable energy technologies, more HFC-specific by incorporating emergent content from the qualitative interview material and the TIS events. The resulting HFC-specific coding frame is shown in Table 8. The TIS events were then dated and coded with a TSIS function – 1 to 7 – depending upon the relevance of the event to each aspect of HFC innovation and/or diffusion. Then the event was coded a second time with a +1 or -1 to see whether it represented a ‘positive’ or ‘negative’ contribution to innovation and/or diffusion, i.e. a likely barrier or enabler of future change in the TIS. Overall, my approach to EHA is very similar to that of Hekkert and Negro (2009), as suggested in Table 9.

3.3.1.3 Coding Extended Indicators: Organizational Funding

As described in Chapter 1, extended coding for event funding and PPPs was introduced in this thesis because of the thematic topics that emerged in the data that I gathered for the EPSRC DoSH study.

3.3.1.4 Coding Extended Indicators: Geographical Location

After coding for TSIS function, Box 3 in Figure 7 shows that each event had its precise location and region/Land added from its address data. The locations offered a code for region and a town/city. With all coding complete, another sample section of the database is shown in Figure 9. TIS codes are on the left in blue (+/-, 1-7), spatial codes are in the middle in green and organizational codes are on the right in orange. The narratives in Chapters 4 and 5 include relatively few of the references included for every event because the sheer number is so high.[31]

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[31] Full details of all references gathered for the TIS narratives are on an attached CD.

Table 7: Coding Operationalization of System Functions for Generic 'Renewables'

System Functions	Event category	Sign / value
Function 1: Entrepreneurial activities	Project started Contractors provide turn-key technology Project stopped Lack of contractors	+1 +1 -1 -1
Function 2: Knowledge development	Desktop-, assessment-, feasibility studies, reports, R&D projects, patents	+1
Function 3: Knowledge diffusion	Conferences, workshops, platforms	+1
Function 4: Guidance of the search	Positive expectations of renewable energies; Positive regulations by government on renewable energies Negative expectations of renewable energies; Negative regulations by government on renewable energies	+1 +1 -1 -1
Function 5: Market formation	Positive expectations of renewable energies; Positive regulations by government on renewable energies Negative expectations of renewable energies; Negative regulations by government on renewable energies	+1 +1 -1 -1
Function 6: Resource mobilisation	Subsidies, investments Expressed lack of subsidies, investments	+1 -1
Function 7: Advocacy coalition	Lobby by agents to improve technical, institutional & financial conditions for technology Expressed lack of lobby by agents; Lobby for other technology that competes with particular technology; Resistance to change by neighbours (NIMBY attitude)	+1 −1 −1 −1

source: Hekkert and Negro, (2009)

Table 8: Coding Frame for System Functions for Hydrogen Fuel Cell (HFC) TIS Events (Author’s Design)

System functions	**Event category**	**Sign / value**
Function 1: **Entrepreneurial activities**	Commercial HFC project started/product distributor signed/order made/product delivery made/product available;	+1
	Components/resources (supply chain) agreement made;	+1
	HFC product/demonstration started/planned/distributor signed/order or training made/service agreement;	+1
	Public and/or private demonstration of HFC applications;	+1
	HFC product standards approval;	+1
	HFC portfolio expansion/office/merger/production site opening;	+1
	HFC portfolio divestment/office closing;	-1
	HFC product/demonstration stopped;	-1
	Commercial HFC project stopped/distributor lost/orders cancelled.	-1
Function 2: **Knowledge development**	Desktop-, assessment-, feasibility studies, reports;	+1
	HFC R&D project started/continues (includes prototyping, lab/field trials, pilots);	+1
	HFC-related patent(s) granted/licensed/sold;	+1
	Patent expires;	-1
	HFC R&D project stopped.	-1
Function 3: **Knowledge diffusion**	Formation of HFC-specific conferences, workshops, platforms, professional networks;	+1
	Signing MOU / VA agreement on HFC R&D (also includes subsequent partner addition);	+1
	Termination of MOU / VA agreement (also includes partner withdrawal);	-1
	Termination of HFC-specific conferences, workshops, platforms, professional networks.	-1

Table 8: **Coding Frame for System Functions for Hydrogen Fuel Cell (HFC) TIS Events (Author's Design)**

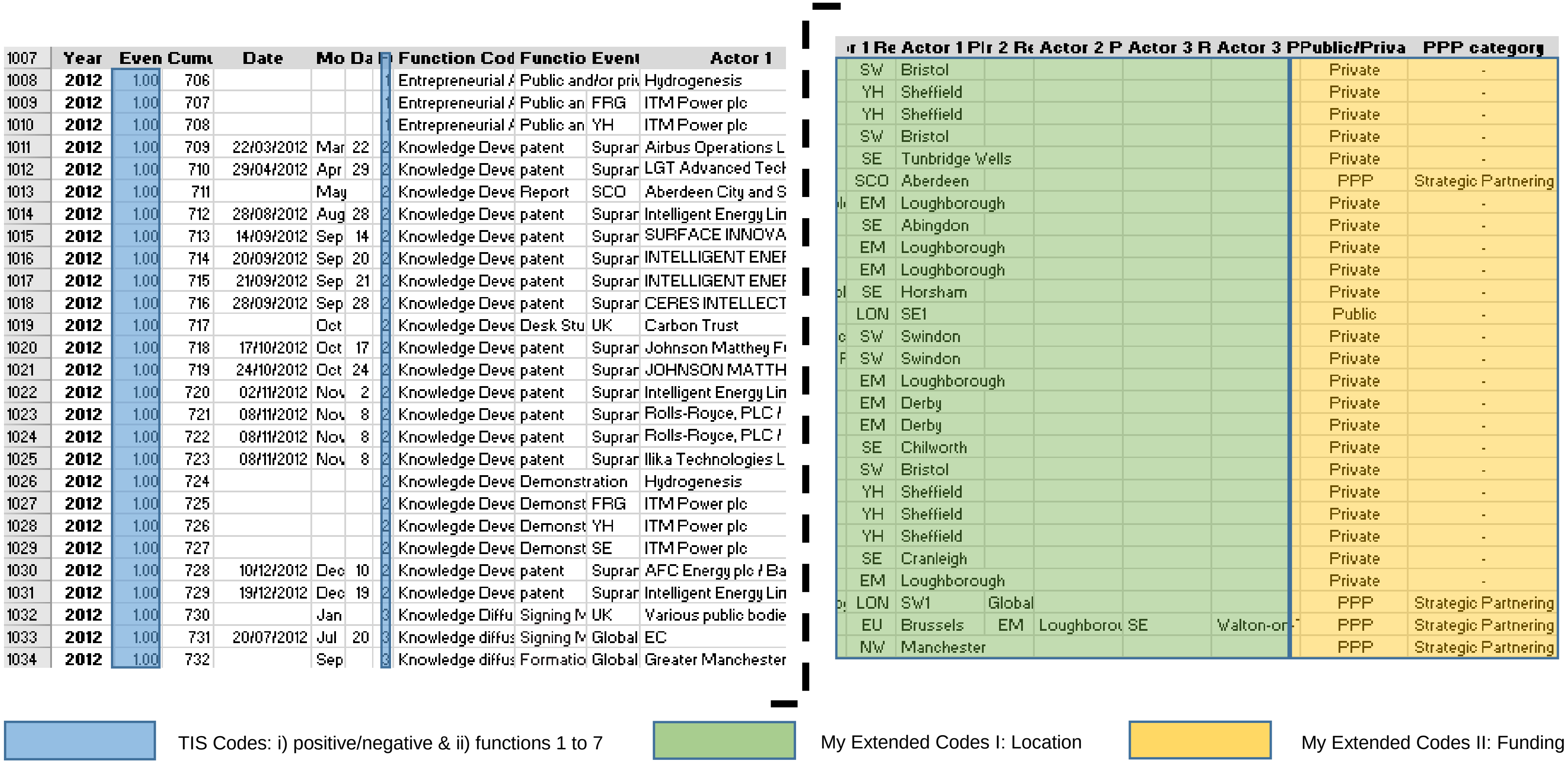
System functions	Event category	Sign / value
Function 4: **Guidance of the search**	Energy regulations/policy targets that encourage the development of the HFC TIS;	+1
	Environmental and safety standards that help to guide HFC R&D;	+1
	Positive expectations/promises/roadmaps of HFC technologies;	+1
	Negative expectations/promises/roadmaps of HFC technologies;	−1
	Expressed lack of environmental and safety standards;	−1
	Expressed lack of energy regulations/policy targets.	−1
Function 5: **Market formation**	HFC-specific market instruments: e.g. feed-in rates, tax exemptions;	+1
	Corporate/state commitment to higher HFC production volumes;	+1
	Actor/network(s) agree(s) coordination/market/service standards;	+1
	Signing/extending MOU / VA agreement on HFC infrastructure (includes subsequent partner addition);	+1
	Termination of MOU / VA infrastructure agreement (also includes partner withdrawal);	-1
	HFC product passes comparative benchmark (e.g. range), environmental and/or safety standards;	+1
	Expressed lack of corporate/state commitment to higher HFC production volumes;	-1
	Expressed lack of HFC-specific market instruments.	-1
Function 6: **Resource mobilisation**	State subsidies/investor; private/long-term/'angel' investments;	+1
	Access to a skilled workforce	+1
	Access to material factors;	+1
	Expressed lack of access to material factors;	-1
	Expressed lack of access to a skilled workforce and material factors;	-1
	Expressed lack of state subsidies, private investments, long-term/angel investments.	-1

Table 8: **Coding Frame for System Functions for Hydrogen Fuel Cell (HFC) TIS Events (Author's Design)**

System function	**Event category**	**Sign / value**
Function 7: **Advocacy coalition**	Lobbying by agents to improve technical, institutional & financial conditions for HFCs;	+1
	Expressed lack of lobbying by agents;	−1
	Lobbying for other technology that competes with HFCs;	−1
	Resistance to change - competing industry and/or project/prototype neighbours (NIMBYism).	−1

Table 9: Comparison of Approaches to Event History Analysis (EHA) Narratives

EHA Methodological Aspect	Hekkert and Negro (2009)	This Study: German-UK HFC Activity
Data Sources	Secondary data including newspapers, magazines, reports and professional journals.	Secondary data including academic, professional, grey and journalistic literatures, and web sites (corporate, academic and governmental).
Database	Database storage of events.	Database storage of events (Excel).
Event Classification	Generic renewable event classification scheme produced inductively and iteratively.	Specific HFC event classification. Scheme produced inductively and iteratively.
Event Labels	Events labelled as positive (+1) or negative (−1) in terms of a neutral observer examining the diffusion of the technology.	Events are labelled as positive (+1) or negative (−1) in terms of a *non-neutral* observer examining the diffusion of the technology.
Event Classification Verification	Classification scheme and event categories are verified by another researcher. Differences in the coding results of the researchers are analysed and resolved.	Classification scheme and event categories are verified by another researcher. Differences in the coding results of the researchers are analysed and resolved.
Event Weighting?	No. The events are not weighted since the importance of an event is not known beforehand.	No. Events were selected without any privileging for known later developments.
Outputs	The narrative is complemented with and illustrated by several pictures in which the events are plotted over time.	The narratives are complemented with and illustrated by several graphs in which the events are plotted longitudinally.



1007	Year	Even	Cumu	Date	Mo	Da	F	Function Cod	Functio	Event	Actor 1
1008	**2012**	1.00	706				1	Entrepreneurial A	Public and/or priv		Hydrogenesis
1009	**2012**	1.00	707				1	Entrepreneurial A	Public an	FRG	ITM Power plc
1010	**2012**	1.00	708				1	Entrepreneurial A	Public an	YH	ITM Power plc
1011	**2012**	1.00	709	22/03/2012	Mar	22	2	Knowledge Deve	patent	Supran	Airbus Operations L
1012	**2012**	1.00	710	29/04/2012	Apr	29	2	Knowledge Deve	patent	Supran	LGT Advanced Tech
1013	**2012**	1.00	711		May		2	Knowledge Deve	Report	SCO	Aberdeen City and S
1014	**2012**	1.00	712	28/08/2012	Aug	28	2	Knowledge Deve	patent	Supran	Intelligent Energy Lin
1015	**2012**	1.00	713	14/09/2012	Sep	14	2	Knowledge Deve	patent	Supran	SURFACE INNOVA
1016	**2012**	1.00	714	20/09/2012	Sep	20	2	Knowledge Deve	patent	Supran	INTELLIGENT ENEF
1017	**2012**	1.00	715	21/09/2012	Sep	21	2	Knowledge Deve	patent	Supran	INTELLIGENT ENEF
1018	**2012**	1.00	716	28/09/2012	Sep	28	2	Knowledge Deve	patent	Supran	CERES INTELLECT
1019	**2012**	1.00	717		Oct		2	Knowledge Deve	Desk Stu	UK	Carbon Trust
1020	**2012**	1.00	718	17/10/2012	Oct	17	2	Knowledge Deve	patent	Supran	Johnson Matthey Fu
1021	**2012**	1.00	719	24/10/2012	Oct	24	2	Knowledge Deve	patent	Supran	JOHNSON MATTH
1022	**2012**	1.00	720	02/11/2012	Nov	2	2	Knowledge Deve	patent	Supran	Intelligent Energy Lin
1023	**2012**	1.00	721	08/11/2012	Nov	8	2	Knowledge Deve	patent	Supran	Rolls-Royce, PLC /
1024	**2012**	1.00	722	08/11/2012	Nov	8	2	Knowledge Deve	patent	Supran	Rolls-Royce, PLC /
1025	**2012**	1.00	723	08/11/2012	Nov	8	2	Knowledge Deve	patent	Supran	Ilika Technologies L
1026	**2012**	1.00	724				2	Knowlegde Deve	Demonstration		Hydrogenesis
1027	**2012**	1.00	725				2	Knowlegde Deve	Demonst	FRG	ITM Power plc
1028	**2012**	1.00	726				2	Knowlegde Deve	Demonst	YH	ITM Power plc
1029	**2012**	1.00	727				2	Knowlegde Deve	Demonst	SE	ITM Power plc
1030	**2012**	1.00	728	10/12/2012	Dec	10	2	Knowledge Deve	patent	Supran	AFC Energy plc / Ba
1031	**2012**	1.00	729	19/12/2012	Dec	19	2	Knowledge Deve	patent	Supran	Intelligent Energy Lin
1032	**2012**	1.00	730		Jan		3	Knowledge Diffu	Signing M	UK	Various public bodie
1033	**2012**	1.00	731	20/07/2012	Jul	20	3	Knowledge diffus	Signing M	Global	EC
1034	**2012**	1.00	732		Sep		3	Knowledge diffus	Formatio	Global	Greater Manchester

	r 1 Re	Actor 1 Pl	r 2 Re	Actor 2 P	Actor 3 R	Actor 3 P	Public/Priva	PPP category
	SW	Bristol					Private	-
	YH	Sheffield					Private	-
	YH	Sheffield					Private	-
	SW	Bristol					Private	-
	SE	Tunbridge Wells					Private	-
	SCO	Aberdeen					PPP	Strategic Partnering
l	EM	Loughborough					Private	-
	SE	Abingdon					Private	-
	EM	Loughborough					Private	-
	EM	Loughborough					Private	-
ol	SE	Horsham					Private	-
	LON	SE1					Public	-
c	SW	Swindon					Private	-
F	SW	Swindon					Private	-
	EM	Loughborough					Private	-
	EM	Derby					Private	-
	EM	Derby					Private	-
	SE	Chilworth					Private	-
	SW	Bristol					Private	-
	YH	Sheffield					Private	-
	YH	Sheffield					Private	-
	YH	Sheffield					Private	-
	SE	Cranleigh					Private	-
	EM	Loughborough					Private	-
o;	LON	SW1	Global				PPP	Strategic Partnering
	EU	Brussels	EM	Loughborou	SE	Walton-on-	PPP	Strategic Partnering
	NW	Manchester					PPP	Strategic Partnering

Figure 9: Example Section of UK HFC TIS Events Database with Coding Highlighted

3.3.1.5 Dataset A Outputs

The TIS event data in a single Excel spreadsheet then formed Dataset A (Box 4 in Figure 7) which permitted the production of sequential UK and German TIS events from the 1950s to 2012 totalling 844 and 1,791 events respectively. Box 5 in Figure 7 shows that these event lists permitted a range of outputs and analysis including:

i) TIS event narratives,
ii) graphs of functional activity over time,
iii) graphs of funding over time,
iv) graphs of private and PPP activity over time,
v) graphs showing functional activity broken down spatially, and
vi) correlation matrices showing Spearman's rank correlation coefficients between tallies of functional and PPP activity via an online program that uses the statistical software package 'R'.[32]

The data and graphs of functional activity over time permit TSIS analysis of 'motors' of sustainable change (cf. Van de Ven and Poole, 1995, Van de Ven et al., 2000) in which evidence for potential positive and negative feedback loops between functions is evaluated (cf. Suurs, 2009). Suurs and Hekkert (2012) present a typology of four motors:

1) the Science and Technology Push Motor,
2) the Entrepreneurial Motor,
3) the System Building Motor, and
4) the Market Motor.

Each motor is thought to have dominant system functions – F1 to F7 - and dominant interactions between these functions. Structural drivers and barriers are then said to contribute to the emergence, retention and decline of each motor. External events also impact upon the development of the motors (Suurs and Hekkert, 2012). Whilst there are distinct advantages in using the motors above, particularly as a developmental sequence with longitudinal event histories, there is also a potential downside. As I cited in Chapter

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[32] The Spearman's test was chosen on the online site 'Statistical tools for high-throughput data analysis' (http://www.sthda.com/english/rsthda/correlation-matrix.php) For each variable, the annual data results were divided up by region and were placed into one single string of results in Excel for comparison.

1, Coenen et al. (2012, 970) suggest that TSIS analysis: "[R]isks overemphasizing 'universal' (abstract) mechanisms as causal explanations for innovation at the expense of (real) embedded actor strategies and institutional structures".

3.3.1.6 Production of Actor Lists

Quantitative data production for this study also involved the compilation of alphabetical actor lists. This covered information on HFC innovative actors who were active, i.e. in business or fully funded, in December 2012 (Box 6 in Figure 7). I produced the actor list dataset (Box 8 in Figure 7) via the reinterrogation of the online memberships of state-led, professional and academic networks for the EPSRC DoSH study. I also made specific searches for actors known to be active thanks to information in secondary source material which informs the historical event narratives. This data includes the actor's name, its type of HFC activity, ownership details, network membership, and estimated employee numbers. Professional HFC membership lists are largely maintained by significant public-, private- and public-private bodies. Many source lists overlapped and these were cross-checked. When actor checks were undertaken, the data tallied with the membership lists. The actor lists were weeded several times for primary actors claiming to have a professional 'interest' in HFCs but who had not undertaken HFC-specific activity such as RD&D or had any HFC component production experience as far as could be ascertained. Finally, in 2014, I cross-checked these weeded actor lists for both countries with my colleague at University College London (UCL), Will McDowall. This systematic checking of HFC actor details gave me a high degree of confidence that the German and UK national actor lists were up-to-date and accurate for the baseline date of December 2012.

With spatial data added (Box 7 in Figure 7), actors' geographical distributions were calculated. This analysis involved using a Geographical Information System (GIS) - ESRI's ArcGIS desktop software package - to plot actors' spatial locations from their postcodes (which were converted into latitude and longitude coordinates). These data, held in the same Excel files, were then imported into ArcGIS. Using purchased maps from the DoSH project covering the sixteen German Länder and the twelve UK regions (including Northern Ireland, Scotland and Wales), snapshots of the geographical concentrations of HFC innovative activity for both countries were revealed. These distributions were tested for spatial autocorrelation to see if clustering was occurring.

3.3.1.7 Dataset B Outputs

The most active regions in each country were also calculated from Dataset B (outputs ii, iii and iv in Box 9 in Figure 7). Clustering of HFC actors has obvious policy implications which are discussed in Chapter 7. Clustering is a socio-economic process which would indicate a degree of positive feedback in HFC actors' search for access to resources (cf. Mans et al., 2008). I initially applied employment location quotients (LQs) via Excel. An employment LQ is a way of measuring the relative contribution of one specific region to a whole country for a particular employment sector (cf. Isserman, 1977, Moineddin et al., 2003). This analysis was initially undertaken early on in the DoSH study as a rough, reflexive guide to which regions had the most number of actors and potentially the greatest degree of innovative activity. More precise results were calculated late in the DoSH study using the mapping software ArcGIS. This data was further refined for this thesis with the updating of the actor lists in 2014 and 2015 and with new ArcGIS outputs.

HFC employment LQs were calculated for each UK nation and region and for each German Land using the following equation (cf. Isserman, 1977, 34):

$$LQ_i = \frac{E_{ir}}{E_{in}} \Big/ \frac{E_r}{E_n} \, .$$

Here:

LQ_i = HFC employment location quotient in region/Land *i*
E_{ir} = total HFC employment in region/Land *i*
E_{in} = total employment in region/Land *i*
E_r = total HFC employment in the country
E_n = total employment in the country

The LQ ratios for each state/region permitted a ranking in terms of how over- or under-represented a state or region's HFC activities were in December 2012 compared to the rest of the country as a whole. The LQs helped initially to indicate where HFC activity is likely clustering – any result over 1.0 is more concentrated than the average – although without other data sources it is not certain that meaningful interaction between actors is necessarily taking place. When supported by other data indicating the level and nature of actor interactions, this made the LQs a potentially useful ‘rough and ready’ policy tool in terms of where to consider distributing public and private funds for HFC activity (Moineddin et al., 2003).

However, more precise cluster analysis was undertaken once the updated actor lists of firms and research centres became available. The Multi-Distance Spatial Cluster Analysis tool (based on Ripley’s K function) was used in the ArcGIS software to reveal the significance of the clustering of these two actor groups, on their own, over a range of distances. Ripley’s K function outputs in ArcGIS reveal observed K function values in red alongside expected K values in blue. If the former is higher than the latter (and beyond confidence boundaries) then the spatial distribution of this one group of actors is more clustered than a random distribution.

In order to judge the significance of the clustering distributions of both sets of actors, their geographical data was analysed in Stata14’s statistical software using the Interpoint Distance Distribution (IDD) package (Tebaldi et al., 2011). This particular tool makes use of a ‘Mahalanobis distance’, or ‘M statistic’, between the distributions of two sets of points. This analysis shows if both distribution patterns are correlated with each other in a statistically significant way. Stata14 IDD outputs used here include chi^2 and Monte Carlo runs (cf. Tebaldi et al, 2011). The resulting correlations do not imply causation between these variables and needed to be interrogated further alongside other data to allow me to make warranted assertions.

In summary, the initial LQ results helped me to select the regions of interest in each country with the DoSH study (Box 11 in Figure 7). This analysis was later refined iteratively with the newer actor list data in 2014 and the ability to plot and analyze actor locations in ArcGIS and Stata14. Having outlined the quantitative data production, I examine the production of qualitative data in the next section.

3.3.2 Qualitative Approaches

The steps that I pursued in terms of qualitative data production in the DoSH study are outlined in the sections below. The qualitative interview material (Box 15 in Figure 7), when coded and turned into outputs, revealed competing actor rationalities and perspectives which were later triangulated and integrated with the quantitative data. I note that quantitative data alone cannot indicate whether meaningful HFC clustering is taking place in Germany or the UK, for example. For this reason, qualitative data was gathered not only for evidence of seven functions of innovation, but also for any emergent evidence of other social processes linked to face-to-face networking, learning and knowledge spillovers.

3.3.2.1 Research Ethics

Before qualitative data gathering began, a statement of ethical practice was completed and submitted to and approved by the Welsh School of Architecture's (WSA's) School Research Ethics Committee. Respondents were then provided with a participant information sheet and asked to sign a consent form before the interview started. This offered confidentiality to all interviewees. Only their code names were used in the dataset. Meaningful quotations were used whilst maintaining every effort to ensure confidentiality. Interviewees were permitted to withdraw from the research at any time.

3.2.2.2 Topic Guide

With the DoSH study, I had felt that grounded theory was too open-ended a methodological approach given the large number of contributors and relatively limited time frame (cf. Suddaby, 2006). The forty-nine in-depth interviews drawn on in this thesis were therefore conducted in a semi-structured way using a topic guide based on the seven system functions of Hekkert et al. (2007a) (see Appendix B).

In interview, participants were asked to indicate what they considered to be the enablers and barriers to 'healthy' HFC innovative activity. Each discussion covered a broad range of subject areas relevant to the contributor's area of expertise. However, I aimed to elicit at least one response per function concerning their future expectations about HFCs. I wanted to know whether this was regarded by the interviewee as positive, negative or neither. Whilst insights into the nature of existing outcomes were pointed to by interviewees, much of these discussions also centred on how expectations for HFCs in the future were, in their opinion, being helped or hindered by institutions, structures, processes and the distribution of resources.

As indicated in the topic guide shown in Appendix B, interviewees were also prompted to discuss the activities of their actor in terms of networked links at a variety of levels from the supranational, to the national and the regional/local (cf. Hodson et al., 2008, Hodson and Marvin, 2010).

3.3.2.3 Actor Selection

Forty-nine in-depth interviews were conducted for the EPSRC DoSH study, each lasting between thirty and seventy minutes (Box 15 in Figure 7). This large variation in the length of interviews, in spite of fairly standard questions, occurred because of the varied nature of the interview contexts: phone interviews were typically shorter and face-to-face interviews were typically longer. Each contributor was selected on the basis of the identification of the leading Land/region of HFC activity in both countries via the LQs and ArcGIS results which showed which areas had the greatest concentrations of actors. Some interviews, however, were based in less-active regions in order to provide a balance. Also, while distant from the most active Länder/regions, certain contributors' roles within the TIS system were important at the national level. Nobody refused to be interviewed and I had few concerns over understanding or interpreting words in interviews with those for whom English was not their first language because all German and EC interviewees were fully bilingual/multilingual. Similarly, a range of additional individuals representing the interests of local government, central government, funding bodies, NGOs, multinationals, small-to-medium-sized enterprises (SMEs), and others, were also considered and approached for interview alongside those on the HFC actor lists in order to ensure the input of HFC stakeholders from wider economic, business, political and organizational networks, hierarchies and markets (Point 3 in the Section 3.0 above) (cf. Ruef and Markard, 2010, Coenen et al., 2012).

Thirty-seven interviews were undertaken with individuals in the UK, chiefly because this is where the focus of Chapter 7's policy recommendations lie. Ten interviews were undertaken with individuals from Germany, and two with individuals from the European Commission in Brussels. Subject to the availability of interviewees, as balanced a mix of actors as possible was sought in terms of function, hierarchy and location. Some of the interviews in both countries were recorded face-to-face, but most were recorded on the phone. All were transcribed and coded.

3.3.2.4 Interview Analysis in NVivo

Each interview recording was sent to a transcriber. The interview manuscripts were returned in Microsoft Word format and corrected by hand before being entered into the qualitative analysis software package NVivo. This software package was chosen for the EPSRC DoSH study for two main reasons. Firstly, there was the question of manageability. The number of interviewees was significantly larger than I had previously encountered. This meant that my ability to search the dataset manually for thematic interview material could be compromised without such a resource. Secondly, there was the need for flexibility. Initially, with the DoSH study, there had been an expressed desire by the PI, Prof. Malcolm Eames, to analyze the qualitative data in a quantified form. We both recognized that this could only be done using a software package with advanced analytical options. Choosing to use NVivo simultaneously added to my levels of confidence in the triangulation of warranted assertions (as well as the potential depth of description) and helped with reporting conclusions to a wide range of audiences given these relatively large datasets.

3.3.2.5 Interview Outputs

Micro-level qualitative comments covering the perceptions and experiences of individuals were made available for analysis. Approaches based on expectations (e.g. Borup et al., 2006), with their social constructivist framing, suggest that different individuals will have competing logics and rationalities for their activities in the same operational space (cf. Murdoch and Abram, 2002). As highlighted in Chapter 2, this contestation is something which certain quantitative approaches alone are unlikely to reveal given concerns about the loss of meaning in aggregate data. The interview data were therefore further analysed in NVivo for emergent themes. This was done according to an analytical inductive approach that involved collating similarities in 14 broad response categories. These responses form a range of quotations illustrative of interviewees' competing logics about HFC innovative activity in the broader context of the seven functions of Hekkert et al. (2007a).

The qualitative dataset of interviews also contains quantified data of the positive and negative statements made with respect to the seven functions of innovation by all 49 interviews (Hekkert et al., 2007a). This macro-level material was quantified in NVivo and then tabulated in Microsoft Excel. It reveals where the interviewees were generally in agreement or in disagreement in terms of the functional aspects of each country's HFC TIS.

In summary, for Section 3.3's description of data production, I have described the ways that the three data production routes – two quantitative and one qualitative – were integrated, justified and illustrated (see Figure 7).

3.4 Conclusion

In this chapter, I identified leading concerns about mixed methods which include struggling with true data integration, making the most of data and privileging one form of data over another. I tackled these concerns as I described my methodologies for achieving Activities 2 and 3. In order to characterize HFC innovative activity in two case studies from Germany and the UK *and* identify the factors that have influenced the dynamic nature of this innovation and its diffusion, I justified in Sections 3.1 and 3.2 the choice of a neopragmatic research design (cf. Tashakkori and Teddlie, 2003, Plano Clark and Creswell, 2011). The methodological pluralism of neopragmatism outlined in Sections 3.2 is informed by innovation theory (as described in Section 1.4.3) (cf. Hekkert et al., 2007a). Neopragmatism incorporates a distinct research philosophy, methodology and methods based upon reinterpretations of 'what works' in pragmatism (cf. Dewey, 1925 / 1958, Dewey et al., 1938 / 2008, Howe, 1988). I presented in Section 3.3 a route map for the quantitative and qualitative data production. This helped produce a number of rich and extensive datasets, the results of which are reported in the next two chapters for the UK and Germany respectively.

The relative merits of neopragmatic approaches were critiqued above (cf. Denzin and Lincoln, 2011). However, my decision to pursue a pragmatic research design was based on the need for flexibility and scope. I needed the flexibility to incorporate case study data collected for a previous investigation undertaken for the EPSRC's DoSH consortium between 2011 and 2013 plus data collected solely for this thesis in 2014 and 2015. I also needed the scope to go beyond a straightforward case study methodology. This is because I need to satisfy Activity 3 which involves an assessment, made in Chapter 7, of how effectively the TSIS heuristic captures the dynamic co-evolution between HFC technologies, actors and their associated institutions from the empirical data.

Chapter 4 – Evolution of the UK Hydrogen Fuel Cell (HFC) TIS

4.0 Introduction

In this chapter, I present the results of using a neopragmatic research design informed by the TSIS approach along with my four methodological modifications which will help achieve Activity 2. Activity 2 involves: “characterising HFC innovative activity in the UK and Germany between the 1950s and 2012 via two case studies that draw on qualitative and quantitative data and are informed by innovation theory” and describing “events and processes in terms of *how*, *when* and *where*” (Text Box 4 in Chapter 1).

In Chapter 1, I stated that attempts to mitigate and/or adapt to climate change involve decarbonising the energy use of individual nations. In this context, hydrogen fuel cells (HFCs) are a disruptive technology with the potential to help policy makers decarbonize national, regional and local energy systems (Hardman et al., 2013). Some Innovation Studies researchers suggest that innovation with HFCs can happen anywhere, but researchers in Economic Geography disagree because the reasons why HFC innovative activity ‘takes off’ in one country (or one region or locality), but not in another, are not fully understood. This situation matters to policymakers who have limited budgets for their approaches to industrial policy. In Chapter 2, I highlighted the specific knowledge gaps in the literature about the nature of HFC innovation and diffusion. I then identified four areas of concern associated with the Technologically-specific Innovation Systems (TSIS) heuristic (cf. Hekkert et al., 2007a) and proposed four methodological modifications to help overcome the concerns that I found. These modifications include two extended indicators for Technological Innovation Systems (TIS) events, organizational funding and geographical location, and the use of a broader number of actors linked to known HFC networks plus project-level text boxes at technological branching points in the national HFC TIS event narratives. The latter illustrates the nature of more finely-grained analysis that the TSIS heuristic, with its neofunctional approach, lacks. In Chapter 3, I proposed a neopragmatic research design that is informed by the TSIS approach and includes the four methodological modifications. Chapter 3’s assessment of methodology and methods therefore adds confidence to my analysis of the socio-technical processes at work with HFCs than if I was only using a design based on the TSIS heuristic, as was the case with the EPSRC’s DoSH study.

In this chapter, the methodological modifications I have made to the TSIS approach give me greater levels of confidence in my warranted assertions made by the end of the chapter. These assertions then feed into analysis and discussion in Chapters 6 and 7.[33] In the sections below, I produce a sectoral narrative timeline of HFC innovation and diffusion events in the UK HFC TIS between 1954 and 2012. Enablers and barriers to HFC innovation are identified along with other insights into the dynamic co-evolution of HFC technologies in the UK HFC TIS. 1954 was chosen as the starting point for the UK TIS events narrative. The year was when the leading UK HFC researcher, Francis Thomas 'Tom' Bacon, filed his first highly influential patent for an alkaline fuel cell (AFC) known as the 'Bacon Cell' (Bacon, 1954b). December 2012 was selected as the end date for the timeline because that was when primary source data gathering for the EPSRC DoSH study ended in both countries. Insights from the UK HFC TIS event narrative, along with those for Germany from Chapter 5, feed into Chapter 6's comparative country and regional analysis and Chapter 7's methodological and policy discussions.

In terms of the structure of this chapter, I give a brief overview of the distinction between the methodologies employed with the TSIS approach and my extended indicators in Section 4.1. In Sections 4.2 and 4.3, I triangulate all of my data into two detailed TIS narratives covering two emergent periods, i.e. data- rather than theory-driven:

1) 1954 to 1994 – Gradual Technological Development, and
2) 1995 to 2012 – Commercial Orientation.

These two time periods are divided where a significant upswing in HFC TIS events in both countries begins to occur (which is mirrored in rising event numbers globally). Both periods cover HFC activity in three industrial sectors which have exhibited the greatest number of TIS events in the dataset:

a) Defence and Aerospace,
b) Transport,
c) Stationary Power.

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[33] Additional analysis was made because the DoSH study suggested that TIS event funding and territory were likely influencing the socio-technical processes at work.

Finally, in section 4.4, I give my warranted assertions on the UK case study based on all of the data presented in this chapter.

4.1 Overview of the UK HFC TIS Narrative

As outlined in Chapter 3, I assembled the UK HFC TIS narrative via the compilation of 844 secondary source events (cf. Hekkert et al., 2007a). Events were defined in Section 3.3.1.1 as "instances when changes occur in the innovation ideas, people, transactions, contexts or outcomes while an innovation develops over time [and change] is an empirical observation of differences in time on one or more dimensions of an entity" (Van de Ven et al., 2000, 32). The TIS events narratives for Periods 1 and 2 cover a long time span. The justification for this approach is two-fold: firstly, technological transitions typically take a very long time to occur (Geels, 2002, Geels, 2004), and, secondly, certain social processes like cumulative causation and path dependence are suspected to be at work and it is not possible to be confident which events (and when and where they occurred) will be significant later on (Event History Analysis suggests one should not privilege 'key' events from a post-hoc position).

The next two sections recap the event coding and describe the use of text boxes with the narrative.

4.1.1 Event Coding of the UK HFC TIS Narrative

Each event was coded in terms of whether the HFC activity made a positive or negative contribution to innovation and diffusion.[34] Events were also coded for the seven TSIS functions based on my modified coding frame (Table 8):

Function 1: Entrepreneurial activities
Function 2: Knowledge development
Function 3: Knowledge diffusion
Function 4: Guidance of the search
Function 5: Market formation
Function 6: Resource mobilisation
Function 7: Advocacy coalition

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[34] Note that several TIS events which get coded in terms of their negative influence on innovation and diffusion, and which occur at the same time, will push the TIS function tallies into minus numbers.

To further investigate whether HFC innovation and diffusion had been affected by patterns of TIS event ownership and territory, extra coding of the TIS events dataset was undertaken. As described in Chapter 3, this extra coding identified:

1) the type of funding for each event, i.e. 'public only', 'private only', 'public and private (no partnership)' and 'public-private partnerships' (PPPs),
2) the degree to which 'private only' activity involved JVs,
3) the PPP type - based on the typology in Table 4 in Chapter 2, and
4) the town/city and region where events took place.

Quantitative results for this extended TSIS approach are presented graphically in the TIS event narratives in Sections 4.2 and 4.3 below and in the Appendices.

4.1.1 Text Boxes in the UK HFC TIS Events Narrative

In the TIS event narratives for Periods 1 and 2 in the UK – Sections 4.2 and 4.3 respectively - the co-evolution of HFC technologies is broken into the defence and aerospace, transport and stationary power sectors. As stated in Section 1.2 of Chapter 1, these sectors were chosen because they represent some of the most prominent early demonstration activity in the UK. Subsequently in the timelines, these sectors also became the most active areas of HFC innovation.

Where I put text boxes into the national TIS event narratives in both periods, my level of analysis is disaggregated from the normal meso- and macro-level approach of the TSIS heuristic to the project level (i.e. the micro level). Within these text boxes I draw on the source material to characterise more fully something of the contestations over HFC activity. At the micro-level, the text boxes typically reveal how actors and individuals seek to access resources that are embedded in particular places. These contestations, and those within and between teams over technological choices, reveal themselves to be more clearly subject to the influence of power relations and expectations (Avelino and Rotmans, 2009, Bakker et al., 2011, Alkemade and Suurs, 2012). Ultimately, this project-level source material offers further insights into the socio-technical processes at work which might otherwise be missed when such data is aggregated using the TSIS approach's modified Event History Analysis (EHA) methodology.

Finally, the TIS events in the narratives in both periods have their spatial context – both geographical and relational – and this is given greater emphasis than in TSIS studies.

The next section gives the TIS events narrative for Period 1 which runs from 1954 to 1994.

4.2 Period 1: 1954 to 1994 - Gradual Technological Development

In this section, I outline the leading structural elements of the TIS events narrative. This includes the institutions, technologies, actors and actor networks which further contextualise the co-evolution of HFCs in the UK. 1954 to 1994 was a period when state regulation of energy, industry and the environment became increasingly coordinated in the UK. As well as Bacon's first HFC patent being filed, 1954 also marked when the UK Atomic Energy Authority (UKAEA) was formed (see Table 10 for national-level legislation influencing the HFC selection environment in the UK)[35]. The UKAEA's activities included the large-scale production of hydrogen: since the 1950s nuclear power has been linked to expectations by some HFC advocates for a future hydrogen economy.[36]

Overall, the low-levels of HFC TIS events in Period 1 – shown annually and cumulatively in Figure 10 and Figure 11 - can be characterized by the 'technology push' approach to innovation (cf. Nemet, 2009, Hacking, 2013).[37] As Figure 10 shows, a small bubble of international TIS event activity occurred between 1957 and 1968. I refer to this as 'hype A'. It was dominated by:

a) entrepreneurial activity (F1) peaking at four events in 1957 (Figure 12), and
b) knowledge development (F2) peaking at 11 events in 1963 (shown on the left-hand side of Figure 13).

There was also some low-level knowledge diffusion (F3) (Figure 14), market formation (F5) (Figure 16) and resource mobilisation (F6) (Figure 17). This picture of hype A suggests some limited functional diversity in the UK. The TIS narrative in Section 4.2 reveals that some HFC RD&D actors received state support via: i) public leverage (of

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[35] Policy instruments were identified in a comprehensive fashion when cited in material from all sources. These instruments include regulations, taxation and incentives.

[36] Concorde was also approved in 1954 arguably squeezing out RD&D funding for electric vehicles (EVs) and HFCs in Period 1 (Carter, 1971, Edgerton, 1996).

[37] The TIS event history data coded by function is tabulated in Appendix D.

Table 10: Period 1 (1954-1994) - National Legislative Acts Affecting HFC Innovation and Diffusion in the UK

Act / Policy Instrument	Aim	Impact Summary on HFC TIS
UK Atomic Energy Authority Act (HMG, 1954)	Create a single authority responsible for the UK's entire civil and military nuclear program.	This Act created a potential source of hydrogen linked to long-term prospects for a hydrogen economy. But, until the 1980s, significant financial resources, which could have been spent more widely on other energy RD&D, went into nuclear fission and fusion.
Clean Air Act (HMG, 1956)	Encourage industrial consumers of coal to re-evaluate their fuel choices.	The Act raised the prospect that governance of air pollution could be achieved. It indicated to actors that further regulations were likely. Innovators then stressed the low or no-emissions characteristics of certain applications. The Clean Air Act was updated in 1968 and 1993.
US-UK Mutual Defence Agreement (HMG, 1958)	Increase integration of the UK and US militaries particularly regarding nuclear technology transfer.	On the back of this agreement, a niche HFC application went into production: a cabin life support unit based on an AFC electrolyser. This innovation, based in part on US technology and in part on Bacon's work, was largely kept secret and the technology only diffused once (in the 1960s).
Continental Shelf Act (HMG, 1964)	Open up the North Sea to oil exploration.	As oil and gas deposits were identified and brought ashore between the 1960s and 1980s, the sense of urgency that emerged after each oil crisis amongst energy planners in Whitehall (in terms of security of supply) abated. This negatively impacted renewables and HFC RD&D.
Science and Technology Act (HMG, 1965)	Counter low levels of industrial productivity.	By turning the UK's academic research councils into autonomous civil research agencies with a new remit to engage industry, public-private funding of HFC RD&D took place in the 1960s.
Industrial Expansion Act (HMG, 1968)	Counter low levels of industrial productivity.	The activities of the Ministry of Technology ('Mintech') expanded further into industry. There were attempts to drop big defence projects in favour of small-scale civilian energy and transport projects (including HFCs). Mintech was broken up by the Conservative government in 1970.

Table 10: Period 1 (1954-1994) - National Legislative Acts Affecting HFC Innovation and Diffusion in the UK

Legislative Act / Policy Instrument	Aim	Impact Summary on HFC TIS
Industrial Relations Act (HMG, 1971)	Reduce the power of the unions in the energy sector.	Subsequent strikes and power cuts left the country with a sense of its "overwhelming reliance on energy and … [its] vulnerability" (Wilson, 2012, 48). HFC advocates made much of HFCs' potentially positive contribution to energy security in the future.
European Communities Act (HMG, 1972)	Ensure harmonization between legislation passed in Brussels and the UK.	This Act boosted funding for HFC academic RD&D projects in the UK at a time when the post-1973 energy policy did not prioritise HFCs. The Act meant that the UK HFC TIS now had two levels of state governance which could drive technological change.
Energy Conservation (CPRS, 1974b) / *Energy 1974, And After* (CPRS, 1974a)	Set priorities for energy policy: coal, conservation and nuclear energy (termed 'CoCoNuke').	HFC RD&D was sidelined from 1974 to 1995 thanks to these reports. The CoCoNuke approach did favour wind and wave power, but HFC researchers were 'locked out' until Period 2.
Industry Act (HMG, 1975a)	Encourage hi-tech industrial activity with longer-term state financing.	The HFC transport sector benefitted from improved financing up to around 1981. However, the decline in the UK car industry in the 1980s meant alternative drivetrain RD&D largely stopped.
Scottish / Welsh Development Agency Acts (HMG, 1975b, HMG, 1975c)	Encourage regional industrial activity with longer-term state financing.	These Acts enabled PPP efforts in Period 2 with a third level of governance and funding in these nations. Regional PPP activity has included public leverage, JVs and strategic partnering.
Industries Development (N Ireland) Order (HMG, 1976)	Encourage regional industrial activity with longer-term state financing.	The Northern Ireland Development Agency (renamed Invest Northern Ireland in 2002), has been less active with HFCs (in Period 2) than its national partner agencies in Scotland and Wales.
Energy Act (HMG, 1983)	Let private generators trade electricity and access distribution networks.	The Act had the potential to lead to earlier support for, and development of HFC CHP units, but failed to do so in the context of the policy 'lock out' via the CoCoNuke approach.
Gas Act / Electricity Act (HMG, 1986) (HMG, 1989)	Deregulate the markets for gas and electricity supply.	Smaller companies entered the market. This shift helped HFC activity in stationary power in Period 2 because of partnering and competition between larger companies trialing CHP units.

Table 10: Period 1 (1954-1994) - National Legislative Acts Affecting HFC Innovation and Diffusion in the UK

Legislative Act / Policy Instrument	Aim	Impact Summary on HFC TIS
Non-Fossil Fuel Energy Obligation (NFFO) (DTI, 1990)	Subsidize the nuclear sector.	This instrument forced electricity distributors to buy low carbon energy which, in an unintended way, boosted RD&D activity in the renewable sector (creating interest in hydrogen storage).
Environmental Protection Act (HMG, 1990)	Produce a national air quality strategy.	The Act encouraged a wide range of public and private actors to consider ways of complying with regulations via innovation.

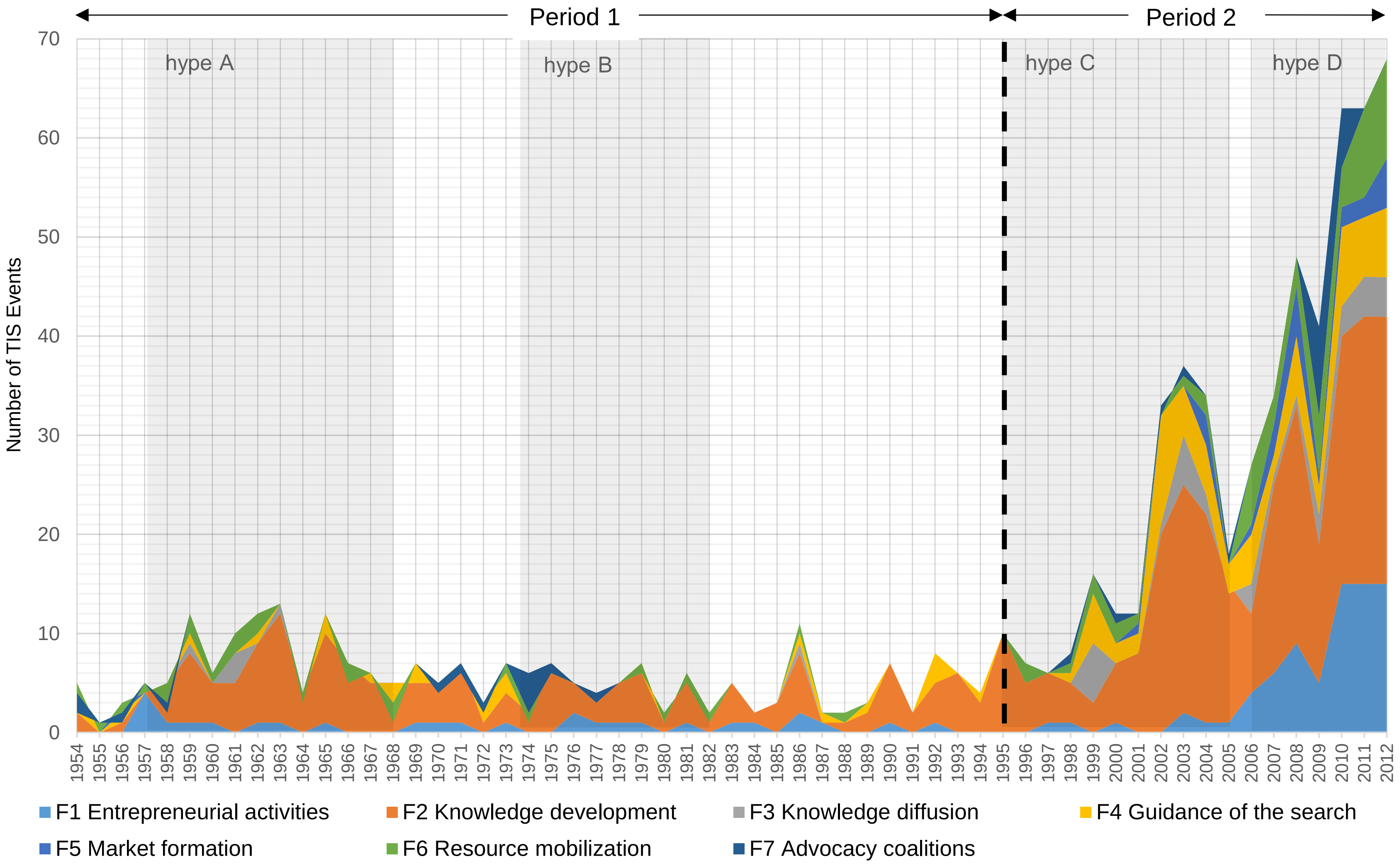

Figure 10: Annual Totals of Functional Activity in the UK HFC TIS, 1954-2012

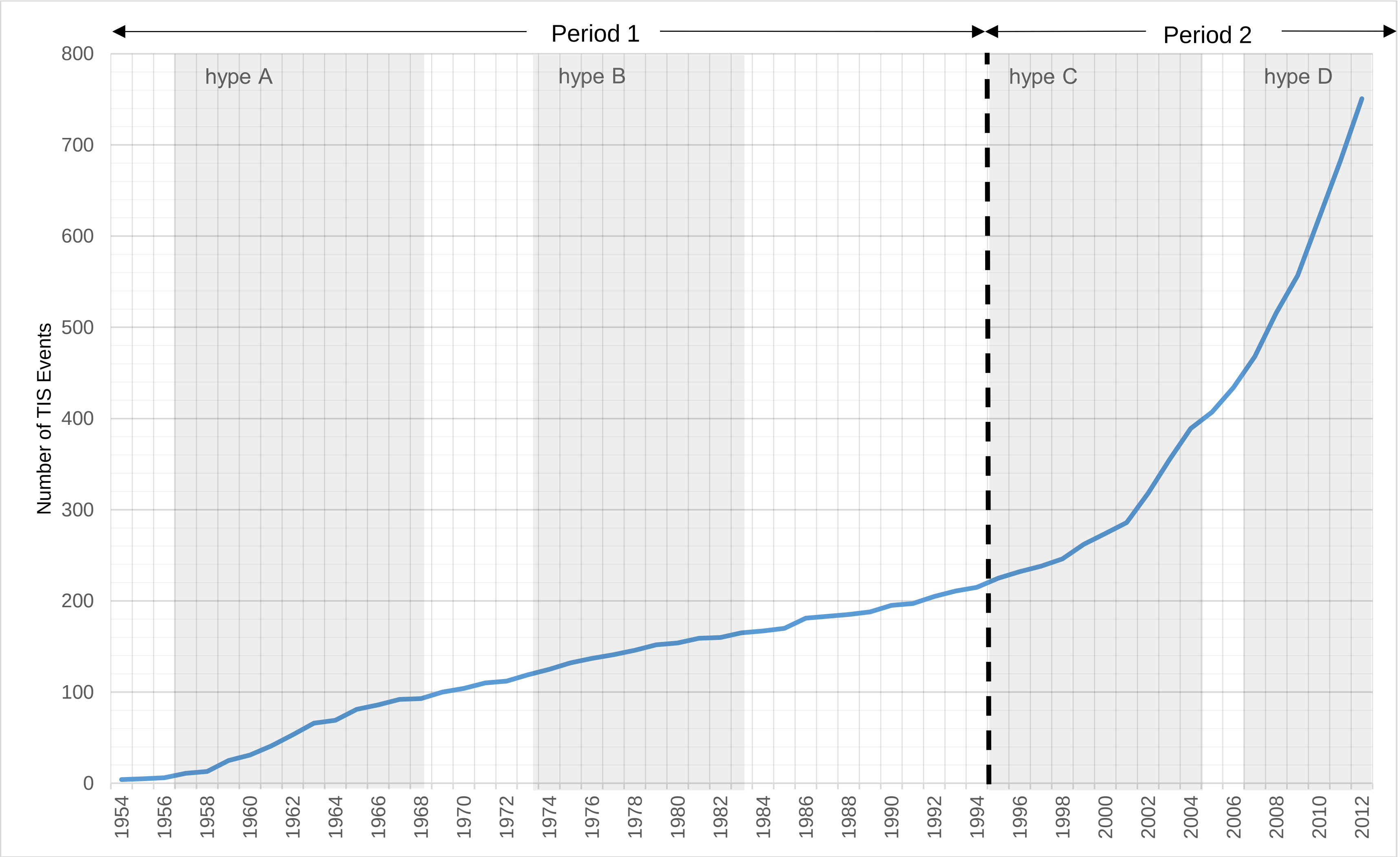

Figure 11: Cumulative Total of All Functional Activity in the UK HFC TIS, 1954-2012

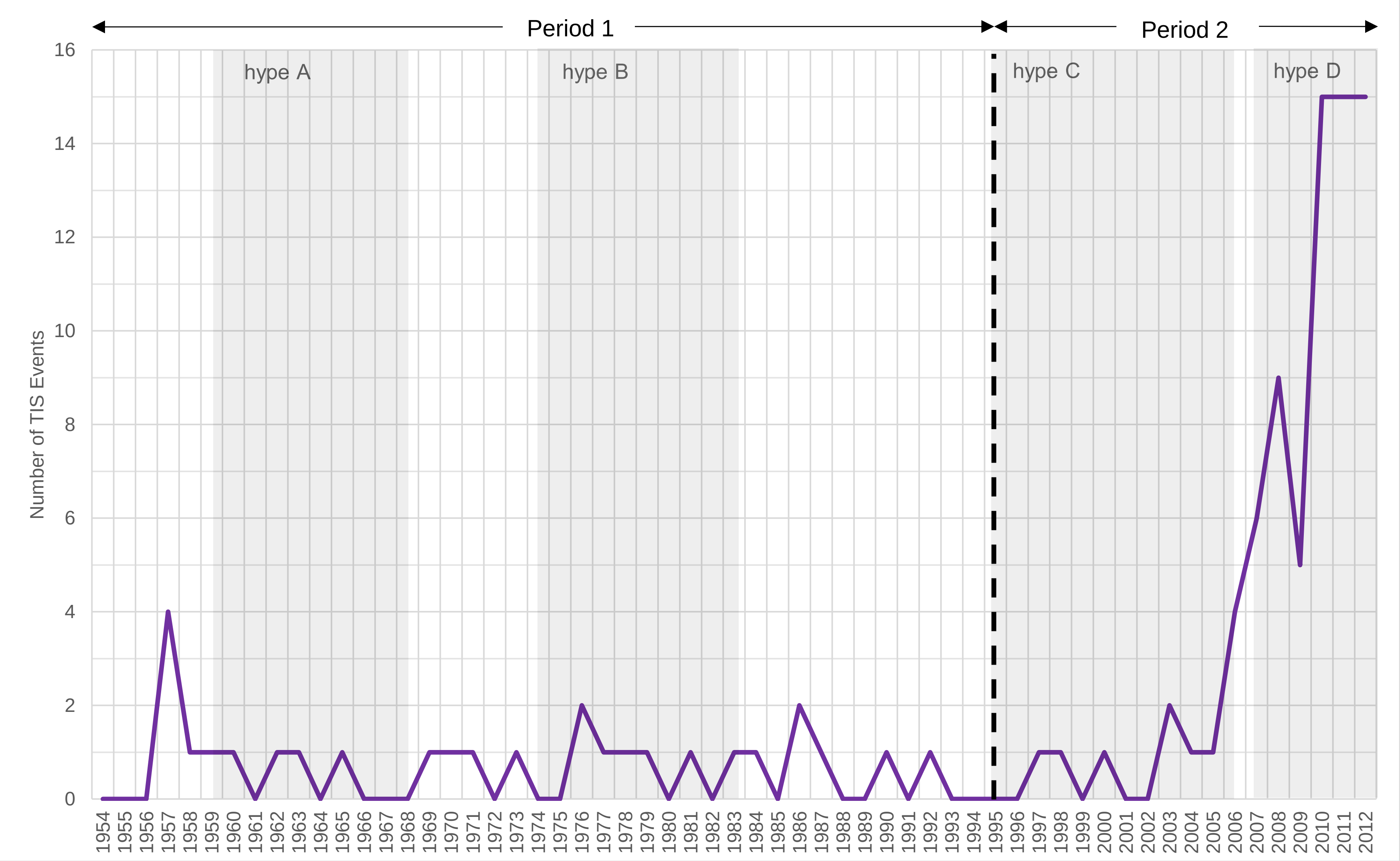

Figure 12: Entrepreneurial Activity (F1) in the UK HFC TIS, 1954-2012

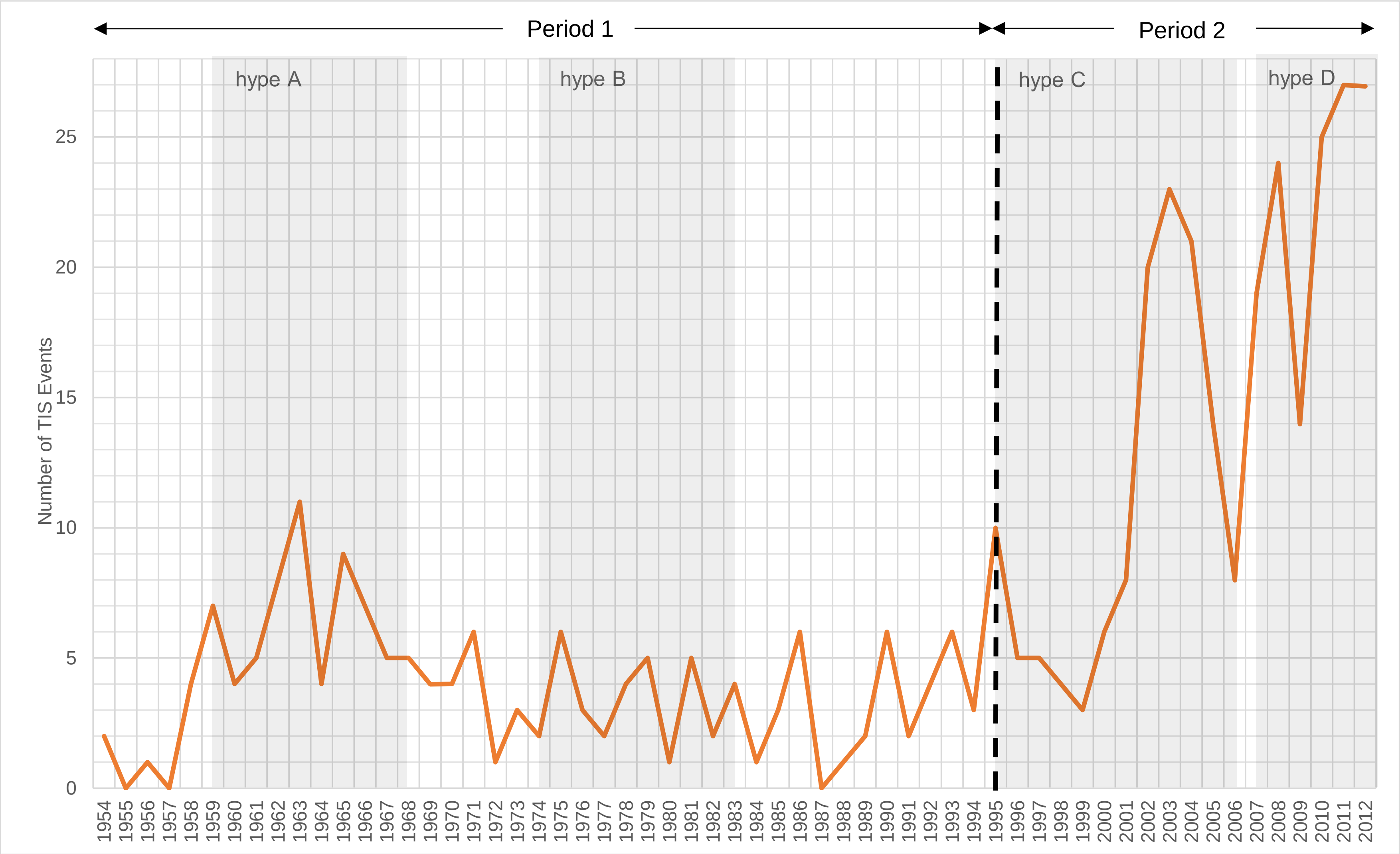

Figure 13: Knowledge Development (F2) in the UK HFC TIS, 1954-2012

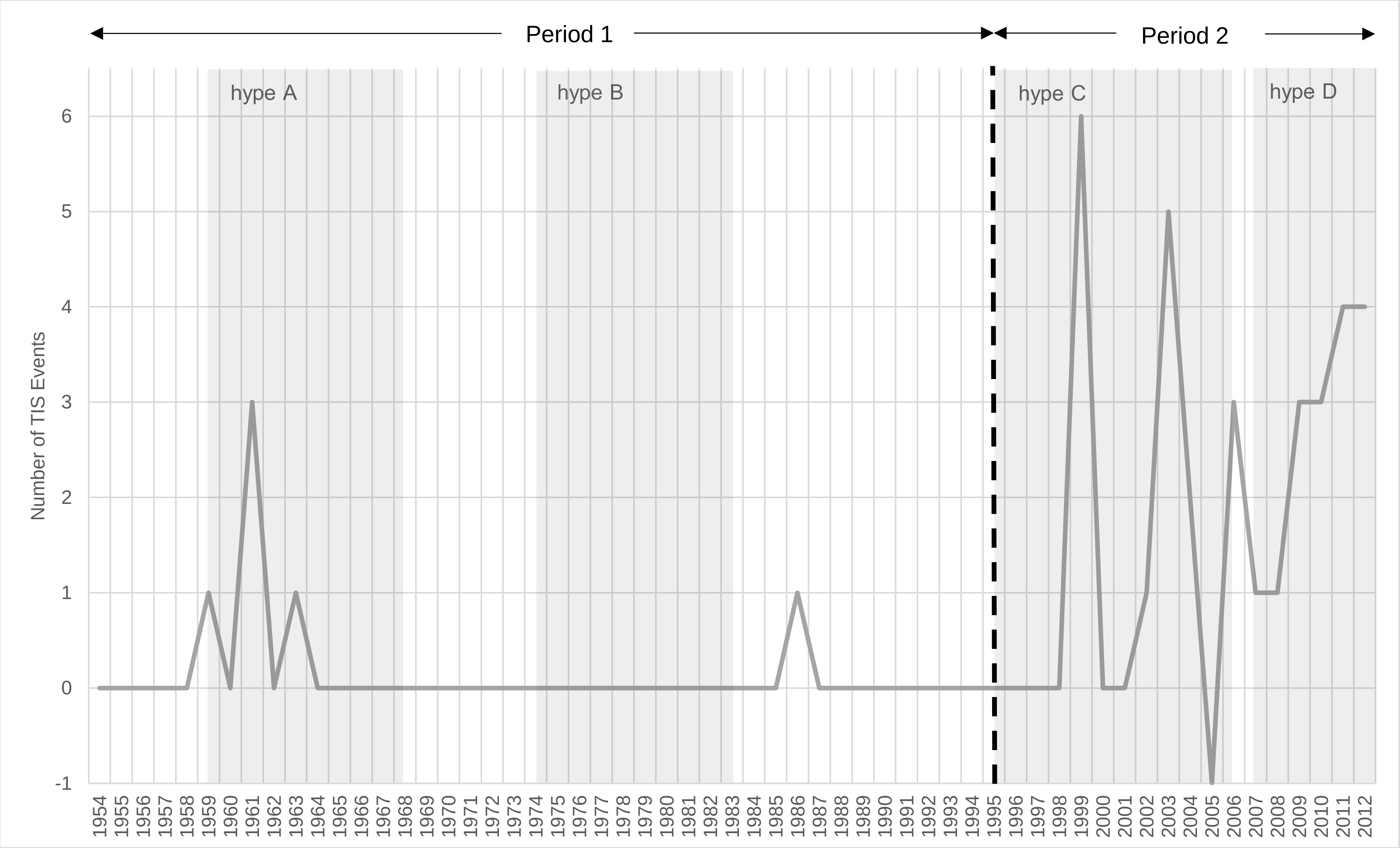

Figure 14: Knowledge Diffusion (F3) in the UK HFC TIS, 1954-2012

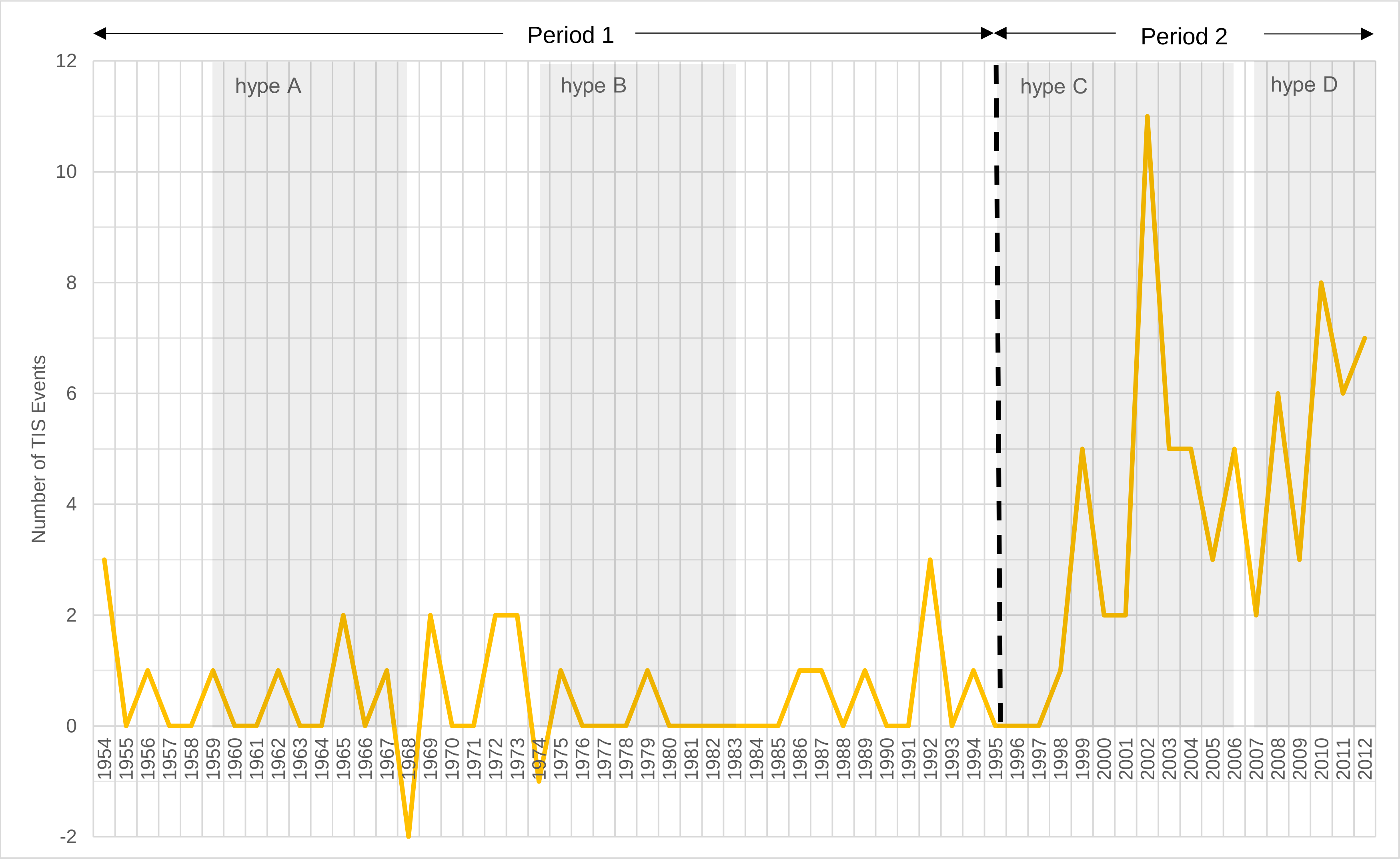

Figure 15: Guidance of the Search (F4) in the UK HFC TIS, 1954-2012

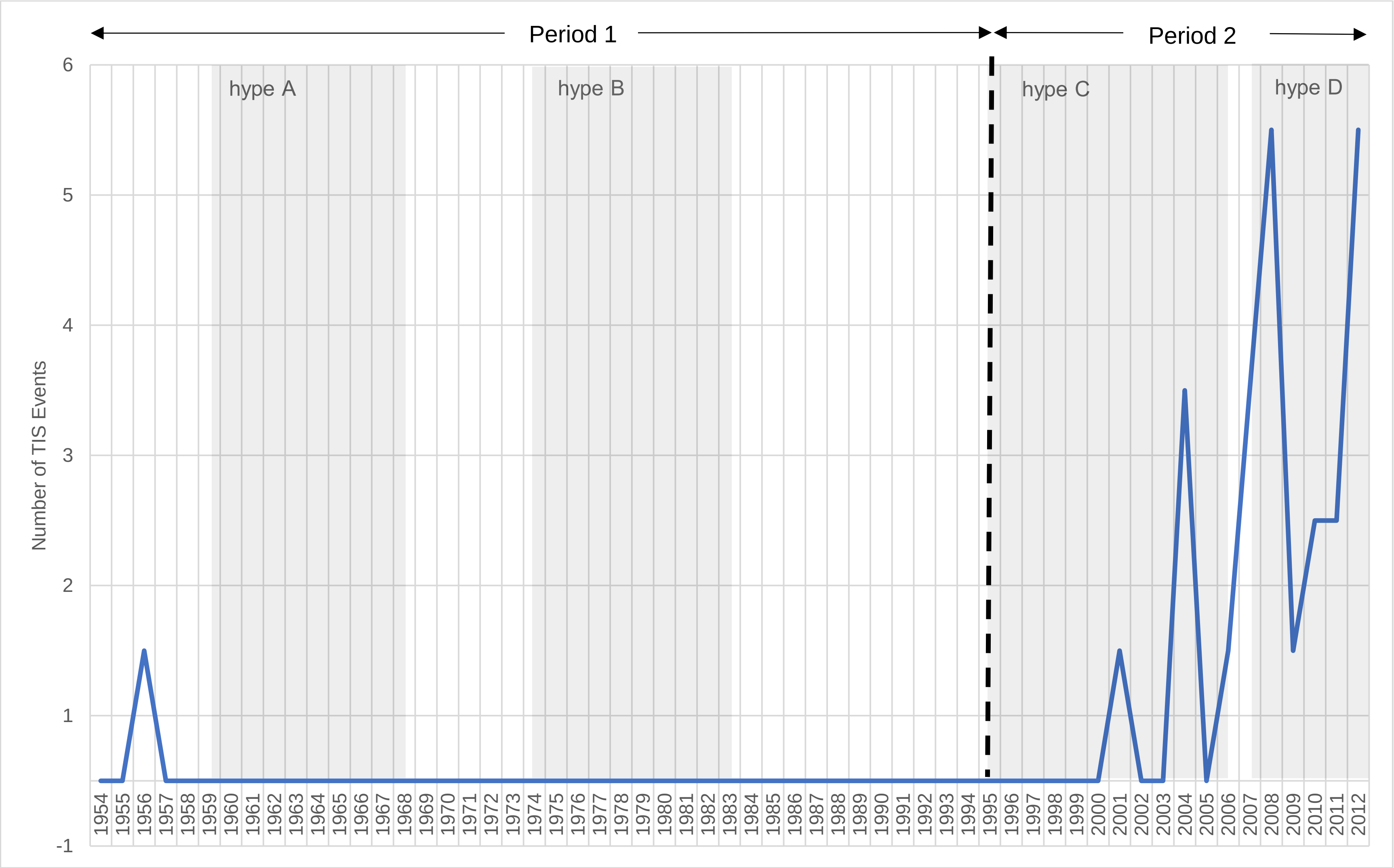

Figure 16: Market Formation (F5) in the UK HFC TIS, 1954-2012

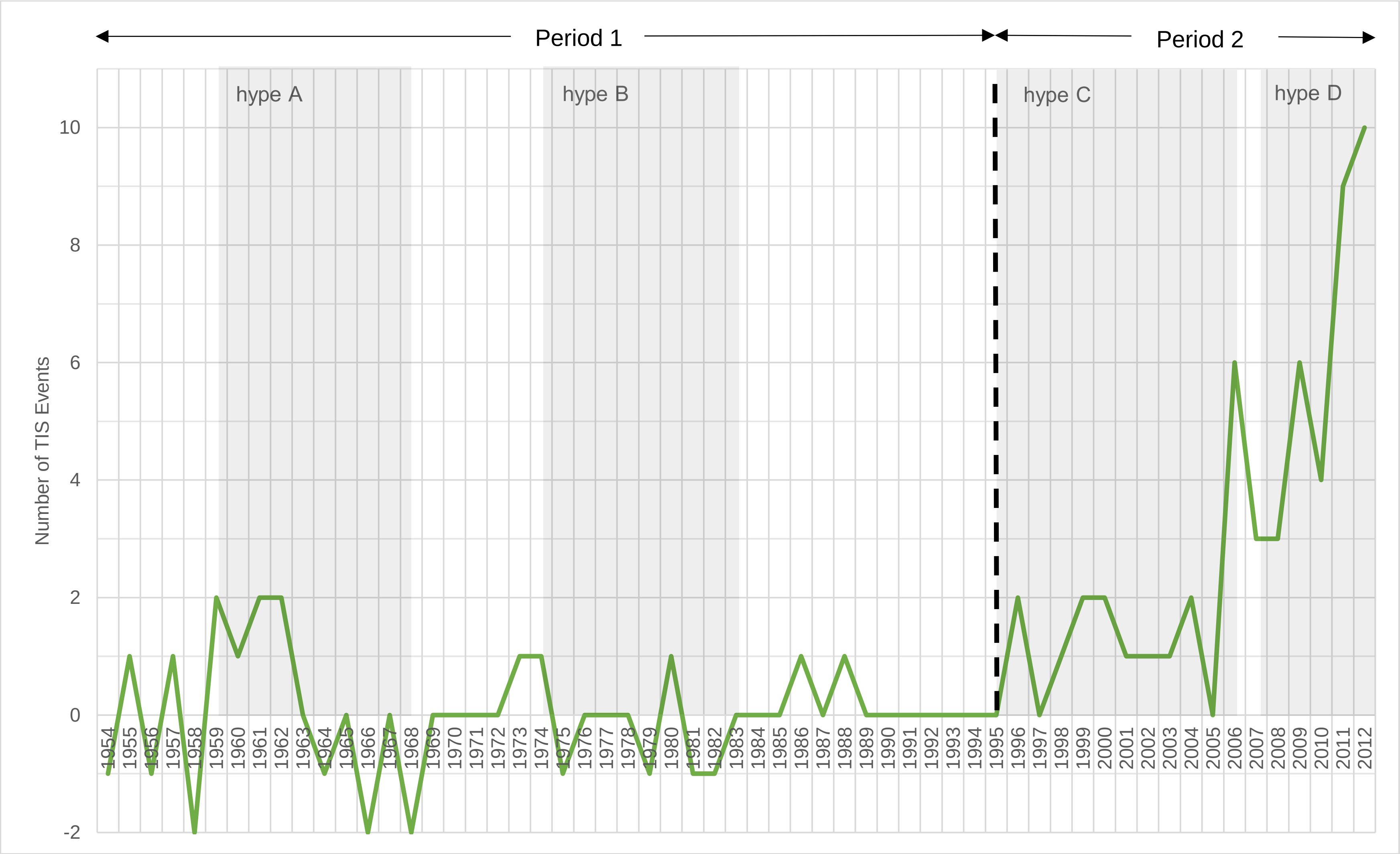

Figure 17: Resource Mobilisation (F6) in the UK HFC TIS, 1954-2012

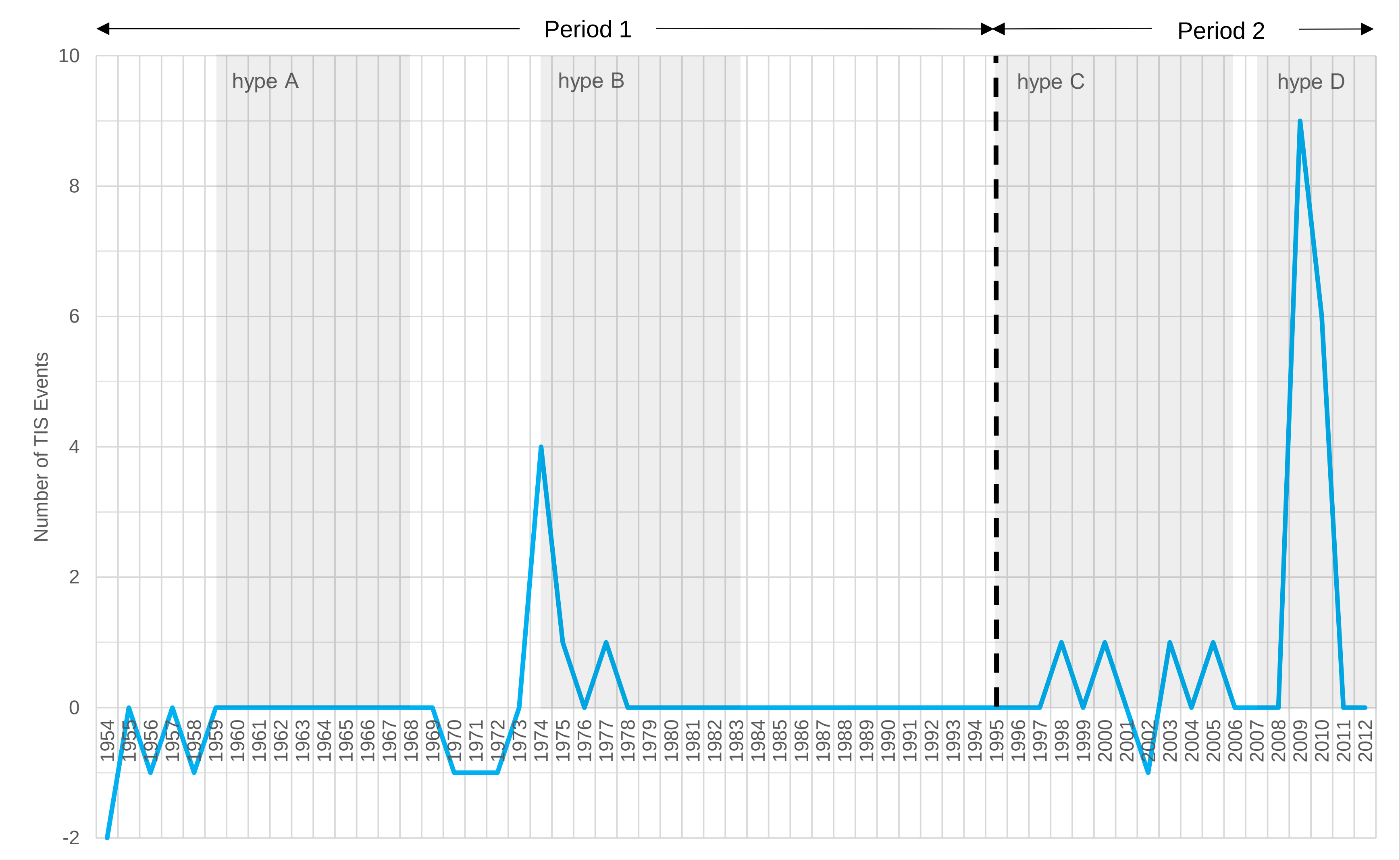

Figure 18: Advocacy Coalitions (F7) in the UK HFC TIS, 1954-2012

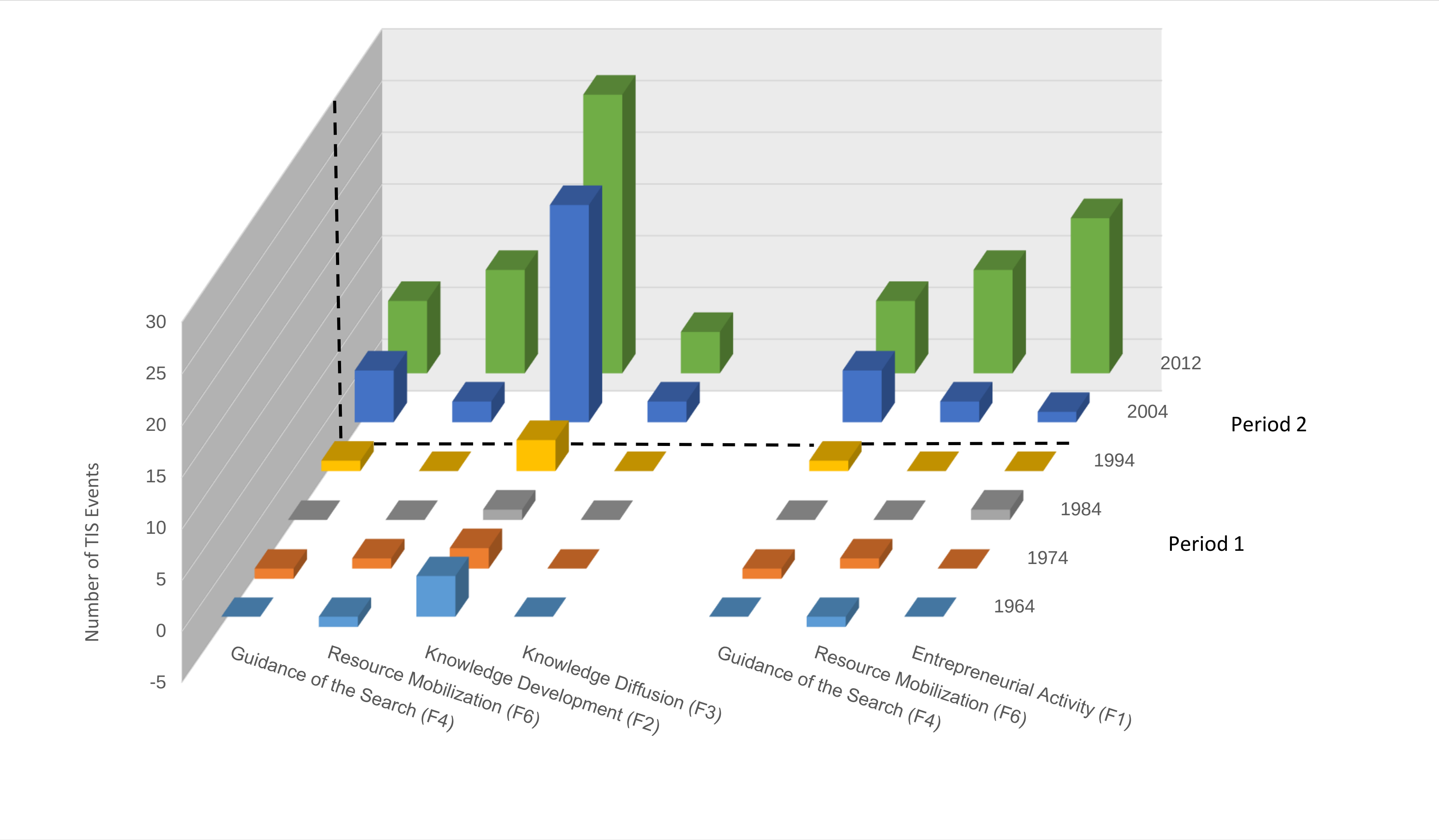

Figure 19: UK - Science and Technology Push (STP) Motor

their patent portfolios), ii) contracting-out (in defence) and iii) joint ventures (JVs). An example of this was Energy Conversion Ltd, a JV PPP described in Section 4.2.3. Market activity during hype A included submarine electrolyser production for the Navy, the licensing of Bacon's patents to US aircraft engine manufacturer, Pratt and Whitney, and the construction of an electrolysis-based sewage treatment works on Guernsey.[38] Knowledge development TIS events dominated throughout Period 1. This dominance suggests that the *Science and Technology Push (STP) motor* – a TSIS feedback loop was not functioning at this time (there is scant evidence for any of the other motors in Period 1) (cf. Suurs and Hekkert, 2012). The increased TIS event activity occurring during hype A did not therefore produce particularly resilient innovation and diffusion in the UK. The Navy's electrolyser contract was the exception and it survived in a well-protected niche while the other two sectors were subject to a distinct slowing/constraint of activity between 1974 and 1998.[39]

The single biggest change to the governance of the UK HFC TIS in Period 1 was made by the Heath government in 1973. It took the UK into the European Economic Community (EEC) via the *European Communities Act* (see Table 11 for European legislation affecting the HFC selection environment). Between 1975 and 1983, for example, the NRDC and the Commission of the European Communities jointly funded two four-year Hydrogen Energy R&D programmes at City University in London. Similarly, cooperation between corporate multinational actors, individual nations and the European Economic Community (EEC) in transport and stationary power began in Period 1 via PPPs which continued into Period 2. Increasing numbers of environmental policy instruments and Directives also began emerging. However, in 1979, the UK state's involvement in energy RD&D began a 25-year decline (Appendix E). Neoliberal policy instruments involving market liberalization and privatization shifted Whitehall's approach to innovation away from 'market pull' towards 'technology push' in order to avoid picking 'winning' technologies and so avoid costly individual engineering projects like Concorde (Nemet, 2009, cf. Hacking, 2013). In this context, well-resourced European-level energy PPPs began to emerge in the 1990s as increasing numbers of environmental policies and Directives appeared. For example, Brussels pursued more robust governance of vehicle emissions via emission limit values (ELVs) for stationary as well as mobile

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[38] In 1962, Pratt and Witney licensed Bacon's patents to NASA for its manned space programmes.

[39] During hype B on Figure 10 more activity occurred in the German HFC TIS than in the UK.

Table 11: Period 1 (1973-1994) - Supranational Policy Initiatives Affecting HFC Innovation and Diffusion in the EEC/EU

Legislative Act / Policy Instrument	Aim	Impact Summary on HFC TIS
1st Environmental Action Programme (1973-1976)	The research agenda covered nuisance from pollutants, the causes of pollution, and approaches to setting criteria for environmental objectives.	National HFC researchers could henceforth legitimize their work on clean technologies in terms of further impending EEC environmental regulation. This was because the Treaty of Rome (1958) required the transposition of EEC instruments onto national statute books and for them to be subsequently enforced.
European Regional Development Fund (1975)	To overcome regional disparities in the European Economic Community (and later the EC).	The ERDF would later become an important source of funding for regenerating regions involving HFC RD&D as well as individual projects.
2nd Environmental Action Programme (1977-81)	To complete the internal market.	Suggestion that improvements in air quality could be achieved without strong state policy intervention. Onus placed on academia and industry to innovate via Europe-wide HFC RD&D funding programmes.
3rd Environmental Action Programme (1982-1987)	To harmonise environmental emissions standards to achieve a fair internal market.	HFCs' emissions benefits emphasized alongside economic benefits, e.g. employment gains from environmental policies, waste avoidance, efficient resource use and integrated environmental technologies.
The Brundtland Report (1987)	To produce more environmental policy integration within and between nations.	This UN-level report encouraged countries to coordinate sustainable thinking into social, economic and environmental policymaking.

Table 11: Period 1 (1973-1994) - Supranational Policy Instruments Affecting HFC Innovation and Diffusion in the EEC/EU

Legislative Act / Policy Instrument	Aim	Impact Summary on HFC TIS
4th Environmental Action Programme (1987-1992)	To reduce energy or material inputs and to close cycles to minimize waste.	Involved environmental impact of strategic economic sectors inc. energy and paved the way for governance via incentive-based instruments, e.g. taxes, subsidies or tradable emission permits seen in Period 3.
UN Framework Convention on Climate Change (UNCED (1992)	To produce international agreement on stabilizing greenhouse gas concentrations in the atmosphere at a level that will prevent dangerous human interference with the climate system.	This broad driver of governmental change produced reassessments in the 1990s of the potential of clean technologies such as HFCs to help nations meet their international commitment to the UNFCCC.
5th Environmental Action Programme (1992-1999)	To orient policies towards ecological structural change via sustainable development (cf. Brundtland et al., 1987).	A sectoral approach favouring public transport, energy efficiency and waste prevention was pursued driving HFC RD&D. Market-oriented instruments and consensus building were encouraged.

pollution sources (Ehret, 2004, Hey, 2005). ELVs were relevant to accelerating RD&D in HFC mobility. However, in the UK transport sector, there was steady industrial decline in the 1970s and 80s (Whisler, 1999). As described below, knowledge development TIS events in the transport sector dried up (see Appendices J to N).[40] By the 1990s, the EC sought new institutional means of environmental governance and different policy options to reduce emissions were assessed on cost-effectiveness, sound science and transparency for all emission sources. Bigger and more-well-resourced PPPs, that operated at two and then three levels of governance would emerge in Period 2 and exhibit as much agency as private actors.

4.2.1 Defence and Aerospace

As neofunctional approaches to innovation and diffusion suggest, external system shocks are powerful shapers of technological pathways (Hekkert et al., 2007a, Suurs and Hekkert, 2012). This was the case in the defence and aerospace sector.[41] In 1956, Egypt nationalized the Suez Canal. This move deprived Britain of 80% of its crude oil from the Middle East (Bamberg, 2000). After Suez, the early UK HFC TIS – beginning during hype A - was driven in two significant ways. Firstly, the security of future energy supplies became a top priority for Whitehall. Bacon, who had previously been funded by a public-private body, the Electrical Research Association, was encouraged by the national innovation agency, the National Research Development Corporation (NRDC), to create a bigger, forty-cell prototype of the Bacon Cell first demonstrated in London in 1954 (Bacon, 1969). Secondly, after Suez, the UK Navy opted for closer integration with the US Navy's nuclear submarine technology. The 1958 US-UK Mutual Defence Agreement (see Table 10) involved technology transfers that included submarine electrolysers to assist with cabin life support systems.[42] These transfers coincided with the first HFC contracting out PPP activity in defence which was between the Admiralty/Royal Navy and electrolyser supplier CJB Developments Ltd (described below in Text Box 5).

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[40] Note that Appendices L and M are the same data, but Appendix M displays it at a higher resolution in order to see more of the trends on the right-hand side of the data displayed in Appendix L.

[41] TIS event data for the Defence and Aerospace sector is tabulated in Appendix F and displayed in Appendices G and H.

[42] Oxygen production by electrolysis gives safe and comfortable atmospheric control inside a submerged nuclear submarine which, at the time, could be maintained for up to two months.

Text Box 5: Project-Level Narrative – UK Navy Nuclear Submarine Contracting-Out PPP

The UK's first HFC contracting-out public-private partnership (PPP) began in 1958. It was between the Admiralty, Vickers Ltd in Barrow-in-Furness and CJB Developments Ltd (CJBD) in Portsmouth, a chemical engineering research subsidiary of the shipbuilder CJB Ltd. CJBD's high pressure electrolyser was based on elements of US and UK AFC research. The technical challenges to be overcome included user safety, the need to operate the electrolyser at a range of angles and to pass all component parts through relatively small hatches. The first commercial unit went into the UK's second nuclear-powered submarine, *HMS Valiant*, laid down in 1962 (see Appendix I for a full list of UK nuclear submarines ordered and delivered with electrolysers up to 2012 using the expertise of CJBD and its successors). The political context in which this HFC innovation took place was the rush to produce *HMS Valiant* (and its successors) in which the technologies could be described as 'all-British'. This PPP drew on skilled engineers at several existing submarine ports while CJBD was able to attract electrochemists to work within the environs of the UK's submarine fleet HQ in Portsmouth.

In the 1990s, another opportunity for HFC diffusion in defence was lost. The Royal Navy wanted to extend the range of its diesel-electric submarines beneath the polar ice cap. It had first contacted Vickers Shipbuilding and Engineering Ltd. (VSEL) based in Barrow-in-Furness in Cumbria in the early 1980s and the project-level details are given below in Text Box 6.

Text Box 6: Project-Level Narrative - Royal Navy Diesel-Electric Submarine JV PPP

In 1985, VSEL's engineers unveiled designs for a stealthy fuel-cell-powered air-independent propulsion (AIP) drive for its new Type 2495 diesel-electric submarine (Mart and Margeridis, 1995). The technical challenges included: i) difficulties with fuel storage, ii) cell sensitivity to impurities, iii) the need to develop supporting systems, iv) the fact that HFCs were not widely used in the market, and v) the high capital costs of RD&D. VSEL opted for an AIP system that included: i) methanol reformers to supply hydrogen, ii) cryogenic storage of liquid oxygen (stored under very high pressure), and iii) hydrogen peroxide held at the same pressure as seawater. No external energy input was required. The system was silent, but the progressive poisoning of the fuel cell stack by carbon dioxide proved problematic in testing. VSEL approached its existing PPP partners, CJBD and the Ministry of Defence (MoD), and a new collaborator, the Canadian PEMFC manufacturer, Ballard Power Systems, to design and access resources to solve technical problems (including future manufacturing). When the source material was investigated in detail, it revealed the nature of the thinking by individuals on the project team about contested technological pathways and the barriers and enablers likely to be encountered when working to solve these issues. Beyond the TSIS approach, the *organisational* dimension of being involved in a PPP adds to networked agency while the *spatial* dimension of where this innovation takes place – in this case highly-skilled workforces embedded in the UK's North-West region and on Canada's west coast – suggests accessing unevenly distributed resources was a key strategic task of project managers.

When the Cold War ended in 1990, the MoD made major cuts to the Navy. A 20kW demonstration PEMFC propulsion unit was produced by VSEL, but research into HFC AIP propulsion and its support systems stopped in 1994. The marketing agreement with Ballard ended and Ballard began work in 1995/6 with German state-owned submarine manufacturer, Howaldtswerke-Deutsche Werft in Kiel on AIP drives for Type 212, 214 and Dolphin Class diesel-electric submarines (described in Section 5.4.1 in Chapter 5). VSEL's patents were published and have since been widely cited but the company's plans to diversify (and so diffuse) its HFC knowledge and skills were again halted by global political events.

The only resilient HFC defence activity in the UK – CJBD's submarine atmosphere control technology – continued into Period 2 (thanks to its renewing contracting-out PPP).

Powerful external events shaping sectoral activity in the evolving HFC TIS were also evident in the transport sector in Period 1, as described in the next section.

4.2.2 Transport

When details of the Bacon Cell were first published in 1954, a number of multinational petro-chemical and coal companies suggested that hydrogen feedstocks should be based on reformed hydrocarbons.[43] In 1959, Shell's researchers at Ellesmere Port in the North West began a dedicated HFC research programme. This technology assessment (TA), undertaken in the context of the Suez Crisis and NASA's support for fuel cell technology, was to evaluate whether or not HFCs could be "a competitive prime mover for road transportation" (McNicol et al, 1999, 16).[44] Project-level activity for Shell's development of a fuel cell vehicle is given below in Text Box 7.

Text Box 7: Project-Level Narrative - Shell Oil and Lucas Industries' Private JV

Shell's team sought operating conditions close to ambient pressures and temperatures because of the need for user safety. Existing gas electrodes gave a poor performance when operating on ambient air so Shell's researchers made innovations with the diffusion of oxygen into the electrolyte and with diffusing nitrogen away from the catalyst pores.[1] A new platinum/ruthenium catalyst was discovered in 1962 making it possible to build direct methanol fuel cell (DMFC) stacks. The advantage of using methanol as a fuel instead of hydrogen is that it is a liquid at ambient temperatures. The DMFC oxidizes liquid methanol fuel into carbon dioxide and water. This removed the need for a pressurised external hydrogen fuel supply and it allowed the construction of small systems ranging in size from a few watts up to several kilowatts (Cameron et al., 1987). Shell's composites functioned well on air and this put its researchers in a position to make fuel-cell electrodes with a large surface area at low cost. A number of stacks, including a 5kW unit, were built. Pure hydrogen came from a methanol–water mixture which was purified via a palladium–silver diffuser. Initially, sulfuric acid was tested in the electrolyte (as compared to Bacon's alkaline approach) but the team eventually settled on hydrazine hydrate which is highly toxic. A self-contained vehicle unit started in fifteen minutes. It responded immediately to load changes and a cold start below 8ºC was demonstrated.

In the early 1960s, Shell began a private JV with vehicle components' manufacturer Lucas Industries based in Birmingham in the West Midlands. Very specific resources - highly skilled electrochemists and vehicle engineers - were

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[43] The argument was that AFCs needed broader legitimacy. See Figure 1 for possible HFC feedstocks.

[44] TIS event data for this sector is tabulated in Appendix J and displayed in Appendices K, L, M and N.

drawn from very specific places: the North-West and West Midlands regions respectively. Throughout, socio-technical aspects of the DMFC pathway were contested between individual team members and by other (non-HFC) transport actors. For example, from 1967, some of Shell's researchers considered DMFC engineering to be relatively straightforward and the "most likely contender" for a future FCEV dominant design. In the competitive arena for EV RD&D, however, Shell's DMFC was regarded as the "wild card in the pack" because of its use of hazardous hydrazine hydrate (McNicol, 1999, 7). The Shell researchers also thought methanol could easily be added into existing vehicle fueling infrastructure. Other non-HFC transport actors disagreed. Ultimately, these partners struggled and failed to gain legitimacy for their particular FCEV pathway. When oil prices dropped in 1981, Shell's research stopped and the team was reassigned elsewhere. The DMFC FCEV did not satisfy Shell's management in terms of performance and commercialization prospects.

Electric vehicle (EV) advances in the global transport sector were a key potential enabler of successful FCEV development. EV research in the UK was active in the late 1960s and through the 1970s. Most multinational original equipment manufacturers (OEMs) based in or with operations the UK were developing EVs with various drive systems and battery types. However, after the global oil price shock in 1979, the price then dropped throughout the 1980s and into the 1990s. Without dominant designs emerging during the early years of the Thatcher administration, FCEV and EV vehicle programmes lost state support and largely faded in the UK (cf. Hekkert and den Hoed, 2004). Competitive advantages in terms of knowledge, both tacit and coded, were lost. UK innovation in evaluating an FCEV, based on work by Bacon, Shell and others, had been created in hype A in the context of fears for oil scarcity after the Suez Crisis and was temporarily abandoned by the perceived global availability oil and gas, particularly for the UK via the North Sea, at least in the short term, post-1979.

External events, institutions and actors similarly shaped technological pathways in the stationary power sector in the HFC TIS which is discussed in the next section.

4.2.3 Stationary Power

In terms of stationary power in Period 1, it was thanks largely to drivers stemming from Suez that HFC activity emerged more strongly during hype A. This was then largely extinguished after the 1973 Oil Crisis when research into HFCs generally was downgraded by energy policymakers in Whitehall even though energy security became a serious issue. Unexpectedly, given how global oil crises have tended to prompt innovation in renewables and storage, a number of strands of UK stationary power knowledge development faltered after 1973, as is described below.

In 1954, Bacon first demonstrated a six-cell battery at an exhibition in London. This Electrical Research Association (ERA)-funded stationary device generated about 150W. Bacon received no interest from British industry in developing it, but convinced that the technical hurdles were not insurmountable, was “determined to go on at all costs." (Bacon, 1969, 579). In 1957, Bacon’s new NRDC-backed engineering research team at Marshall of Cambridge Ltd. produced a 40-cell unit. Each cell had two 25cm diameter electrodes. In testing this unit, the link between a low vapour pressure in the electrolyte and improved performance was discovered by chance. The successful demonstration of this 6kW fuel cell in an airport hangar at Cambridge in 1959, included enough stationary power for some welding. It was revealed that the AFC unit was 70% fuel efficient. Bacon later stated that sintering the electrodes was the key technical challenge.[45] But, again, struggling to find any backers, Bacon joined the first HFC Joint Venture PPP, Energy Conversion Ltd., whose activities at the project level are outlined below in Text Box 8.

Text Box 8: Project-Level Narrative - Energy Conversion Ltd.’s JV PPP

Energy Conversion Ltd. (ECL) was a joint venture PPP created by the NRDC in 1961. It was based at BP’s headquarters at Sunbury-on-Thames near London. ECL’s aim was the commercial development of fuel cells. It consisted of BP, British Ropes, GKN and the NRDC. Bacon joined in 1962 as principal consultant. R&D spending was around £500,000 a year. ECL’s assets were the molten carbonate fuel cell (MCFC) and alkaline fuel cell (AFC) patents assigned to the NRDC.

In 1967, ECL unveiled a natural-gas-powered 5kW 'Total-Energy' fuel cell system at the International Building Exhibition in London. This micro- combined heat and

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[45] Sintering techniques largely drove strong US interest in his patents (Eisler, 2009).

power (CHP) unit for individual homes, blocks of flats and schools raised UK expectations for stationary power HFCs. Advantages included the lower cost of piping natural gas - a quarter of that of transmitting electricity. Waste heat could be used locally for heating air and water depending on the type of central heating system used. Energy efficiency of 70-80% was aimed for. The technical problem of inverting the current to conventional AC and transforming it was not considered insurmountable. The system was later installed in 300 sites in the US via ECL’s patent licensing and research partners. Despite this, there was little interest from UK businesses. By 1969, the technology worked. But, as *New Scientist* reported: “[N]agging matters of cost, efficiency, reliability and control of a complex reaction kept it out of the market place. NRDC found itself holding the baby. Far from being the 'joint venture' so bravely begun, the [NRDC] had put in 60 per cent of the cash..." (Fishlock, 1971, 167). The aims of ECL’s partners had also been poorly aligned: BP saw the new HFC 'engine' as another outlet for oil; GKN admired the electrochemical prowess; British Ropes simply wanted to diversify. To resolve its funding dilemma, the NRDC stopped ECL’s work on AFCs and MCFCs in 1970 and transferred all research to a new public leverage PPP, Fuel Cells Ltd, based alongside state-supported nuclear fission and fusion researchers at Harwell near Oxford amongst others.

In 1970, HFC researchers at Harwell were working with the Gas Council and the Ministry of Defence on a high-temperature stationary MCFC energy plant running at around 900ºC on natural gas. The socio-technical focus for the new Fuel Cells Ltd PPP was: i) reducing the unit cost of methane-air fuel cells by three to four times in order to compete with the cost of the wholesale distribution of electricity, and ii) improving the performance and endurance of large MCFC stationary power plants (typically 100-250kW). Thus, in the run up to the 1973 Oil Crisis, several HFC technologies either worked or showed promise. Some of Whitehall’s energy policy advisors at the Energy Technology Support Unit (ETSU) at Harwell had initially favoured funding HFC RD&D. Yet, when the country’s first formal energy policy appeared in 1974, this early advocacy evaporated. Priorities were set for coal, conservation and nuclear, or ‘CoCoNuke’, (plus limited wave and wind power funding) (see Table 10 and Appendix E).[46] State support for RD&D into HFCs was sidelined. There was only steady, low-level, knowledge development for the rest of the period up to 1995 in the three sectors. HFCs as a technology effectively 'locked out' of the UK's energy policy, post 1973. This is typical of a relatively weak *Science and Technology Push* (STP) *motor* where limited knowledge development (F2) by a few actors in universities and industry is the only coded function, i.e. there is no opportunity for cumulative causation between functional activities (see Figure 19) (cf. Suurs and Hekkert, 2012).

The strands affected included Shell's research team's unsuccessful TAs of small, 500W DMFCs for stationary leisure applications, e.g. caravanning and boating. Similarly, the Parliamentary Combined Heat-and-Power Group, set up in 1975 (which also covered district heating, or DH), could have made a commitment to developing urban CHP-DH. This might have involved AFCs and/or MCFCs had it not been undermined by a report from Lord Marshall at Harwell in 1979.[47] Harwell's employees, dominated by nuclear researchers up to the 1980s, provided the country with 'establishment' views on energy. The broader problem, according to Babus'Haq and Probert (1996, 50), was that: "Free-market forces [mean] ... the responsibility for long-term energy planning has been abrogated ... slavish adherence to the philosophy of free-market forces does not necessarily lead to the adoption of the wisest energy policy for the nation."

Ultimately, plans for commercial HFC CHP schemes which could have accelerated HFC stationary power innovation and diffusion did not appear in the UK in Period 1. Another barrier to HFC innovation in stationary power was the 1983 *Energy Act* (seeTable 10) which only helped industrial and small-scale CHP investors. The Central Electricity Generating Board (CEGB) and the Local Electricity Boards (LEBs), who had the most resources, were reluctant to build CHP plants despite favourable forecast returns.

4.2.4 Summary

By the mid-1990s, the UK energy system was poorly diversified due to the domination of oil, gas and nuclear electricity but with few renewables (Stirling, 1994). HFC prospects

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[46] Bacon and other researchers welcomed the UKAEA's nuclear building programme as a future source of low-carbon hydrogen, but in the short term, civilian nuclear power was perceived as a significant drain on human and financial resources for innovative HFC actors (Wilson, 2012).

[47] CHP-DH was said to be uneconomic when set against the cost of electricity and heat (CH&PG, 1979).

remained relatively poor thanks to a number of largely socio-economic and political barriers. Fears in Whitehall about energy security were allayed thanks to North Sea oil and gas coming on stream in the 1970s and, in the 1980s, there was a stated intention to build more nuclear reactors (Pearson and Watson, 2012). UK public sector funding for energy RD&D declined even more rapidly after the deregulation of the gas and electricity markets via the *Energy Act* (1983), the *Gas Act* (1986) and the *Electricity Act* (1989) (as shown in Appendix E). Towards the end of Period 1, commitments were made in Whitehall to reduce the amount of fossil fuels burned in future, but these pledges were only framed in terms of energy efficiency and money saving not in terms of environmental governance and/or moves towards a green industrial policy (cf. Rodrik, 2013). Climate change did not impact upon the UK's governance of environmental regulation until the mid-1990s. Sectorally, in the next period – Commercial Orientation – I describe how change in the UK HFC TIS began to accelerate from the late 1990s apparently thanks to more sustained positive feedback taking place between functions.

4.3 Period 2: 1995 to 2012 – Commercial Orientation

For Period 2, I again identify below the leading structural elements before looking at HFC TIS activity in three sectors: defence, transport and stationary power. As before, the focus is on how, when and where HFC TIS events occur. 1995 to 2012 was a period when the UK state's regulation of energy, industry and the environment became further coordinated and hence more sustainable. The leading policy drivers of HFC innovation and diffusion at all levels of governance were the security of energy supplies, climate change, energy efficiency and the potential economic benefits.[48] 1995 was chosen as a relatively arbitrary starting point for Period 2 because the TIS event data suggest the beginnings of a juncture at this point based on the empirical picture in both countries (i.e. it is "emergent" not completely arbitrarily imposed). Many more HFC TIS events occur in both the UK and Germany after this date in line with a global rise in HFC TIS events, i.e. in the US, China, South Korea, Japan, Canada and elsewhere (Huang and Yang, 2013). For the purposes of this study, Period 2 ends arbitrarily at the end of December 2012 when my data gathering for the Supergen DoSH study ended.

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[48] The rank order of these drivers depended upon the individuals that I talked to.

4.3.1 Supranational Institutions

At the global level, HFC TIS knowledge events were rising in the 1990s. This shift was led largely by the US, China, Japan, South Korea, Canada and Germany (Huang and Yang, 2013). The Kyoto Protocol in 1997, shown in Table 12, led to a recognition at the national and regional levels in some signatory countries that longer-term, more coordinated, and more sustainable, planning efforts were going to be needed to effect a low-carbon energy transition (Helm, 2002, Bulkeley and Kern, 2006). At the European Level, the European Parliament and Council, shown at the supranational level in Figure 20, drove much of the UK's national legislative changes with directives and other instruments relevant to energy, the environment, industry and HFC RD&D and infrastructure. Directives typically encouraged neoliberal approaches to progressive decarbonisation in Member States. Market stimulation was tackled chiefly via target setting, e.g. EU Regulation 443/2009 on cutting CO_2 from motor vehicles by 2050, and tax incentives. Overall, as EC directives became more integrated in terms of their contribution towards sustainable policymaking, they contributed more positively to the institutional landscape that public and private HFC actors in the UK face via transposed national legislation.

4.3.2 National Institutions

At the UK level, a range of actors in the Labour governments of Tony Blair (1997-2007) and Gordon Brown (2007-2010) produced more coordinated and long-term plans for meeting this supranational commitment (state actors are shown in yellow in Figure 20's mapping of the national level bodies influencing the UK HFC TIS and their impact is described in Table 13). However, after two decades of neoliberal reform in the UK, the ability of Whitehall to effectively achieve joined-up governance in energy the environment and industry was greatly reduced (Bulkeley and Kern, 2006). The Labour and Coalition governments avoided controlling markets and the ownership of businesses. Instead, they tried to correct market failures through a mixture of incentives, taxation, creating new bureaucratic structures (see Table 13) and knowledge-based approaches which, for example, involved high-tech clustering (DTI, 1998b, DTI, 1998a). The UK's specific national policy instruments and/or 'schemes' which have been relevant to HFC innovation and diffusion – and which transpose the EU Directives - are shown in Table 14. These measures included taxes, grants, subsidies and expenditure programmes, regulations, incentives, policy targets, the creation of regional development agencies (RDAs) in

Table 12: Period 2 (1995-2012) - Supranational Policy Instruments Affecting HFC Innovation and Diffusion

Legislative Act / Policy Instrument	Aim	Impact Summary on HFC TIS
Kyoto Protocol *(UNFCCC,* 1997)	Commit signatories to reduce greenhouse gas emissions	A broad driver of governmental change from the late 1990s and 2000s. The potential of clean technologies, including HFCs, to help nations meet international commitments was reassessed.
Directive on Electricity Production from Renewable Energy Sources (2001/77/EC)	Set indicative targets for renewable energy production in member states.	A rise in renewable energy use has helped make a case for sustainable hydrogen production and storage.
Energy Performance of Buildings Directive (2002/91/EC)	Help member states to comply with Kyoto in terms of hoped-for future cuts in domestic energy consumption.	Drove HFC innovation in decentralised stationary power units for residential and commercial premises via measures to reduce energy consumption and CO_2 emissions from boilers.
Electricity and Gas Market Directives (2003/54/EC	A liberalised, market stimulation approach aimed at removing barriers to cross-border trade and the disclosure of the origin of electricity and supplied to consumers.	Boosted potential consumer demand for a cleaner mix of electricity and gas supplies (with hydrogen as a storage option).
Energy Taxation Directive (2003/96/EC)	Progressively reduce tax on low carbon energy sources.	Hydrogen, with its potential for zero emission energy storage, were favoured by this legislation.
Directive on the Ecodesign of Energy-Using Products (2005/32/EC)	Improve products' energy efficiency over their entire life cycle.	HFC actors were favoured by this legislation because of the ever-increasing round-trip efficiency figures for a range of HFC product designs in Period 2.
Energy End-Use Efficiency & Energy Services Directive (2006/32/EC)	Set an indicative target for member states to improve energy efficiency by 1% on average every year up to the end of 2016.	(as above)

Table 12: Period 2 (1995-2012) - Supranational Policy Instruments Affecting HFC Innovation and Diffusion

Legislative Act / Policy Instrument	Aim	Impact Summary on HFC TIS
EU Waste Framework Directive (2008/98/EC)	For member states to deal with waste via the 'waste hierarchy' (actions ranked according to environmental impact).	This legislation includes reference to a range of waste technologies, including gasification and pyrolysis, which produce energy and hydrogen that can be stored and used with HFCs and electrolysers in a decentralised way.
Clean Air For Europe (CAFE) Directive (2008/50/EC)	Establish a long-term, integrated strategy to tackle air pollution. Protect against air pollution's effects on human health and the environment.	This legislation has the potential to accelerate existing moves being made by HFC actors in the transport and stationary power sectors to make innovations, diffuse knowledge and bring their products to market.
Renewable Energy Directive (EU-RED) (2009/28/EC)	Require 20% percent of energy consumed within the EU to be from low-carbon, renewable sources by 2020 via a National Renewable Energy Action Plan (all member states to submit one by 2010). Set a target of 10% renewable energy in transport by 2020 (the UK must achieve 15% of its energy consumption from renewable sources by 2020).	National renewable energy capacity rose across Europe in Period 2 helped make the case for sustainable hydrogen production and storage.
EU Regulation 443/2009	Establishes emissions performance of 120g CO_2/km as average emissions for the new car fleet.	Target can only be achieved by 2050 with more radical vehicle technologies, e.g. BEV, FCEV.
Fuel Quality Directive (FQD) (2009/30/EC)	Establish a low-carbon fuel standard (LCFS) involving reducing the transportation lifecycle greenhouse gas intensity by 6% by 2020.	Accelerate existing moves being made by HFC actors in the transport sector: innovate, diffuse knowledge and bring products to market.
Clean Vehicles Directive (2009/33/EC)	Introduce environmentally-friendly vehicles to the market. Ensure lifetime energy and environmental impacts linked to the operation of vehicles are taken into account.	Has the potential to accelerate existing moves by HFC actors in the transport sector: innovate, diffuse knowledge and bring products to market.
Energy Efficiency Directive (2012/27/EU)	Establish a binding set of measures covering the entire energy chain in Member States. Compliance is designed to help the EU meet its 20% energy efficiency target by 2020.	(as above)

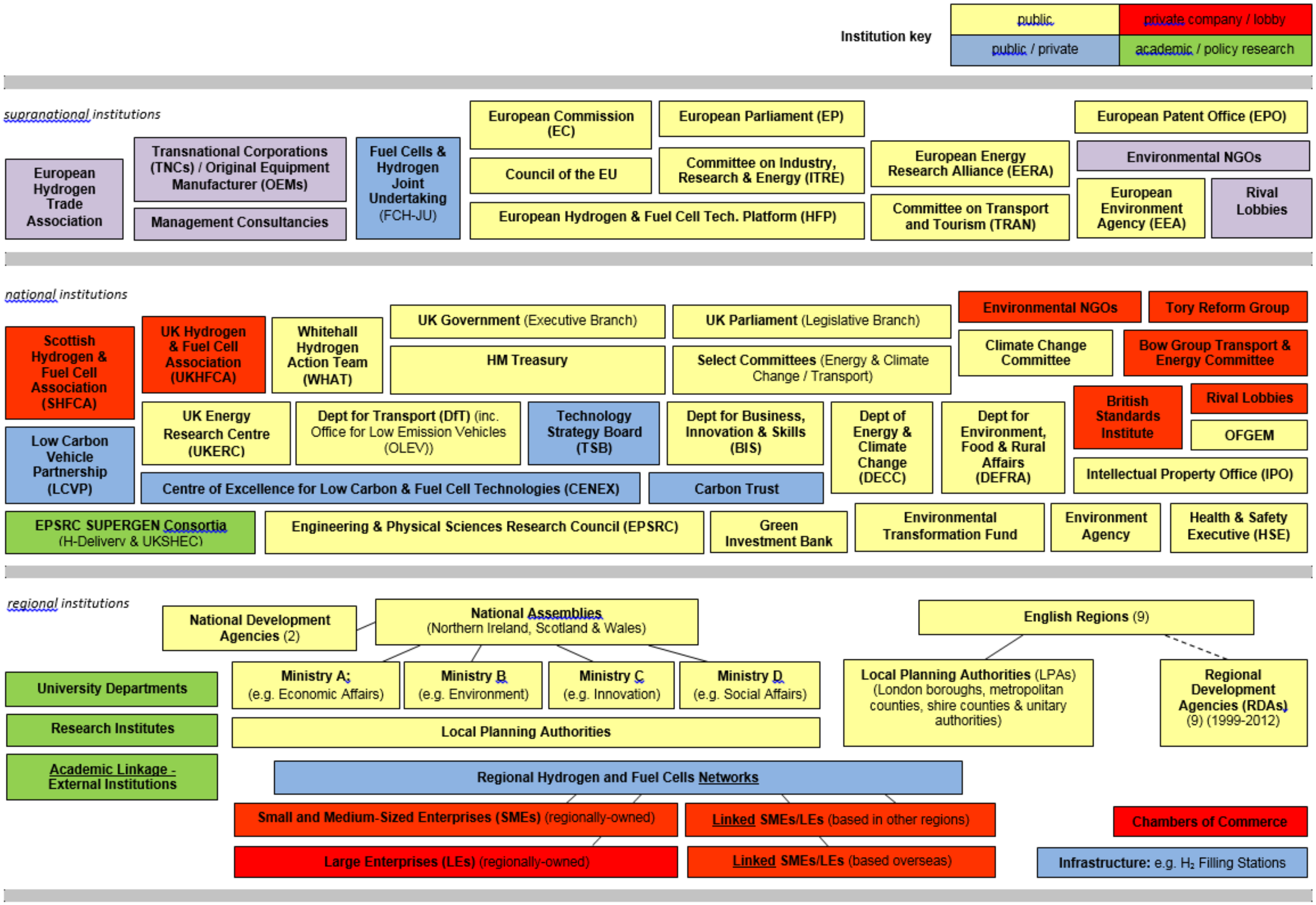

Figure 20: UK - Multi-level Mapping of Actors Linked to HFC Actors in 2012

Table 13: Period 2 (1995-2012) – UK State Agencies Affecting HFC Innovation and Diffusion

Body	Aim	Impact Summary on HFC TIS
Technology Strategy Board (TSB) (2004-)	Fund, support and connect innovative UK businesses. Accelerate sustainable growth.	Runs a Knowledge Transfer Network on HFCs. Funds certain demonstrations and competitions.
Energy Technologies Institute (ETI) (2007-)	Act as a conduit between academia, industry and the government to accelerate the development of low carbon technologies.	A PPP between global energy and engineering companies and the UK Government funded research into hydrogen fuels for CHP and CCGT applications. Tendered for hydrogen storage and flexible turbine systems research within its CCS programme.
Environmental Transformation Fund (ETF) (2008-2012)	Offer financial support for tackling climate change within the UK and developing countries.	ETF had the potential **t**o reduce carbon emissions **in** the long term through the use of technologies including HFCs (ETF had an HFC Demonstration Programme).
Department of Energy and Climate Change (DECC) (2008-)	Ensure the UK has secure, clean, affordable energy supplies and promote international action to mitigate climate change.	In 2012, DECC began work with the Department for Transport (DfT) and the Department for Business Innovation and Skills (BIS) in a strategic partnering PPP with industry known as the UK H_2Mobility project.
Committee on Climate Change (CCC) (2008-)	Recommend five-year carbon budgets and make technology assessments towards 2050	The CCC is Independent of government Consisting of external energy and climate experts, the CCC’s recommendations have included evaluations of the potential contribution of HFCs to low carbon innovation.
The Low Carbon Innovation Group (LCIG) (2009-)	Make technology-specific innovation needs assessments (TINAs).	A coordinating initiative between the Technology Strategy Board (TSB), the Carbon Trust and the ETI. Renamed ‘Low Carbon Innovation Coordination Group’ (LCICG) in 2011, this body had not yet produced a TINA for HFCs by the end of 2012.
The Infrastructure Planning Commission (IPC) (2009-)	Oversee nationally significant infrastructure projects (NSIPs) including new power stations.	The IPC has the potential to accelerate the delivery of major HFC infrastructure such as pipelines, power plants and large storage facilities.

Table 13: Period 2 (1995-2012) – UK State Agencies Affecting HFC Innovation and Diffusion

Body	Aim	Impact Summary on HFC TIS
Office of Low Emission Vehicles (OLEV) (2009-)	Support the early market for ultra-low emission vehicles (ULEV).	DfT-BIS cross-departmental unit focusing on i) energy storage, ii) electric machines, iii) light-weight vehicles, and iv) disruptive technologies. Electric vehicles are prioritized.
Whitehall Hydrogen Action Team (WHAT) (2009-)	Support coordinated HFC policy efforts and ensure delivery.	This HFC policy group is staffed by individuals from DECC and OLEV who helped to establish the UKH2Mobility policy review in 2012.

Table 14: Period 2 (1995-2012) - National Legislative Measures Affecting HFC Innovation and Diffusion in the UK

Legislative Act / Policy Instrument	Aim	Impact Summary on HFC TIS
Environment Act (HMG, 1995)	Produce national air quality & waste treatment strategies.	Further refined the governance of air pollution from a wide range of sources which has been a leading driver of HFC innovation in transport and stationary power.
Regional Development Agencies Act (HMG, 1998b)	Further economic development and regeneration; Promote business efficiency and competitiveness; Promote employment; Enhance the development and application of skills relevant to employment, and contribute to sustainable development.	The Act created nine RDAs in England to add to those already in Scotland, Wales and Northern Ireland. These pro-active non-departmental public bodies supported HFC RD&D efforts through the alignment of corporate and academic HFC actors via PPPs (public leverage, joint ventures and strategic partnering). Match funds and other organisational support came from Whitehall and Europe.
Scotland Act (HMG, 1998c) / *Government of Wales Act* (HMG, 1998a)	To give certain devolved powers to these nations.	The Scottish Parliament received devolved powers in energy giving it greater latitude than Wales in its plans for regeneration via renewable energy. The Welsh Assembly uses its duty under section 121 of the Government of Wales Act to promote sustainable development. Plans for a hydrogen economy in Wales were linked to the nation's commitment to 10%+ renewables by 2010 rising to 20% by 2020.
Waste Minimisation Act (HMG, 1998d)	Require local authorities to produce strategies for waste minimisation.	The effective governance of waste from a wide range of sources is a driver of HFC innovation. For example, markets have been expanding for the production and storage of renewable energy from waste (as well as hydrogen-from-waste).
National Cluster Policy (1998)	Encourage high-tech innovative actors to locate nearby and so benefit from knowledge spillovers.	The DTI pursued clustering in other sectors after examining the UK's spatially clustered biotechnology sector. Integrating HFC actors into high-tech clusters within the nations and regions has been a dominant policy approach to growth.

Table 14: Period 2 (1995-2012) - National Legislative Measures Affecting HFC Innovation and Diffusion in the UK

Legislative Act / Policy Instrument	Aim	Impact Summary on HFC TIS
Pollution Prevention and Control Act (HMG, 1999)	Require local authorities to regulate smaller industry in terms of emissions and energy efficiency.	The effective governance of pollution and improved energy efficiency, asked for with this Act, are leading drivers of HFC innovation.
The Warm Homes & Energy Conservation Act (HMG, 2000)	Establish a target of ending fuel poverty 'as far as reasonably practicable' for all households within 15 years.	Lowering the unit cost of energy for the end user drives innovation and entrepreneurship in the HFC TIS.
Renewables Exemption from the Climate Change Levy (2001)	Exempt electricity from renewable sources from the Climate Change Levy.	Boosting market activity with renewables leads to innovation with HFCs: HFC renewable energy can be stored in hydrogen (as a vector).
Green Fuel Challenge (2001)	Achieve cleaner, greener road transport with alternative fuels.	HFC mobility began facing a strong challenge from biofuels after the major reductions in duty rates that came about with this instrument.
Sustainable Energy Technology Route Map for Hydrogen (2002)	Align the varied interests of the many UK HFC actors.	This route map, produced as part of the DTI's Foresight Vehicle Technology Roadmap, is said to have been effective in introducing HFC mobility actors into the UK HFC TIS.
Renewables Obligation (RO) (2002)	Subsidise RD&D into renewable energy.	Supporting the development of renewable sources of electricity struggling with carbon lock (so spurring hydrogen storage innovation), but, as with the NFFO, the RO's efficacy has been challenged.
CHP Exemption from the Climate Change Levy (2001)	Exempt indirect supplies of low carbon electricity for combined heat and power (CHP) schemes from the Climate Change Levy from 2003.	Creating a stronger market for CHP schemes encourages innovation via HFCs which offer unique, market-leading attributes.

Table 14: Period 2 (1995-2012) - National Legislative Measures Affecting HFC Innovation and Diffusion in the UK

Legislative Act / Policy Instrument	Aim	Impact Summary on HFC TIS
Energy White Paper (DTI, 2003)	Focus on the environment, energy reliability, affordable energy, and competitive markets; a national 60% reduction in CO_2 production was required by 2050	Business opportunities were outlined for "cleaner, smarter energy" (DTI, 2003, 6) with HFCs' future use in zero-carbon buildings cited.
Energy Efficiency Implementation Plan (2004)	Improve the energy efficiency of residential accommodation in England.	This DEFRA roadmap encouraged greater energy efficiency via a range of renewable energy technologies. Greater demand for domestic energy efficiency accelerated innovation with HFCs in CHP units, in particular.
Climate Change and Sustainable Energy Act (2006)	Cut carbon emissions. Reduce fuel poverty via a micro-generation strategy.	Greater demand for domestic micro-generation has accelerated innovation with HFCs in CHP.
The Climate Change Act (2008)	Meet Kyoto and domestic CO_2 emissions targets; UK target of 80% reduction in six greenhouse gases by 2050 compared to the 1990 baseline.	HFC innovations in transport and stationary power involve zero emissions. If uptake of such applications is scaled up, then this has the potential to greatly improve air quality and human health.
The Planning Act (2008)	Speed up the process of approving new energy infrastructure projects inc. nuclear and waste facilities.	Potential to accelerate large-scale HFC infrastructure projects: e.g. pipelines, hydrogen fuelling stations, and stationary power plants.
Low Carbon Transition Plan (DECC, 2009)	Cut carbon emissions by 34% by 2020 (against 1990 benchmark).	Provided a broad governance framework for HFC actors. Key messages: i) radical rather than incremental technological change, ii) focus on reinvigorated transport sector, and iii) need decentralised stationary power schemes for communities.
Renewable Transport Fuel Obligation (RFA, 2009)	To require 3.25% of all fuel sold in UK to come from renewable source by 2010, and 5% by 2014.	Potential to help growth of hydrogen supplies in transport (the sustainability of some hydrogen feedstocks is contested). However, more readily available substitute fuels, like biofuels whose sustainability is also contested, were becoming more established.

Table 14: Period 2 (1995-2012) - National Legislative Measures Affecting HFC Innovation and Diffusion in the UK

Legislative Act / Policy Instrument	Aim	Impact Summary on HFC TIS
Energy Act (2010)	Encourage carbon capture storage (CCS); propose new schemes for reducing fuel poverty; further regulate the gas and electricity markets via the Office of Gas and Electricity Markets.	CCS plants should produce hydrogen on a large-scale. Secondly, decentralised domestic energy schemes involving renewables, fuel cells and hydrogen storage can increase energy efficiency and security, and reduce CO_2 and fuel bills. It is debatable whether investment in HFC RD&D is more likely with more deregulation in the UK energy market.
The Waste (England & Wales) Regulations (2011)	To prevent, reduce and manage waste.	This regulatory framework, transposed in line with EC legislation, has the potential to accelerate the construction of new energy-from-waste schemes (which can be linked both to decentralised hydrogen production and storage).
Ultra-low Emission Vehicle (ULEV) Grants (2011)	Support the early market for ultra-low emission vehicles (ULEVs) via a 25% grant towards the cost of new plug-in cars (to a maximum of £5,000).	This long-term framework of state support for the ULEV market gives greater investment certainty for HFC mobility actors developing FCEVs and FCVs (alongside approval under the UKH_2Mobility programme evaluation).
UKH_2Mobility programme evaluation (BIS, 2012)	Evaluate hydrogen as a fuel for ULEVs in the UK. Develop an action plan to match an anticipated roll-out to consumers in 2014/15 by German and Japanese OEMs.	UK HFC actors made their case for ULEV support via this review. State investments via PPPs were suggested to commercialise HFC mobility technologies. This includes RD&D and production facilities and refuelling infrastructure.
Energy Efficiency Strategy (DECC, 2012)	Increase energy efficiency and security and increase productivity through decarbonising the production of energy for heating.	This strategic framework was thought likely to encourage HFC stationary power actors to innovate and develop markets further for micro-CHP products, in particular.
The Renewable Transport Fuel Obligation (2012)	Encourage potential market growth from biofuels.	Biofuels came to the market ahead of planned HFC vehicle launches. HFC actors may benefit in the long-term if this support continues. However, there is a risk for HFC actors that biofuels become locked in to the market making the future market entry of hydrogen more difficult.

Table 14: Period 2 (1995-2012) - National Legislative Measures Affecting HFC Innovation and Diffusion in the UK

Legislative Act / Policy Instrument	Aim	Impact Summary on HFC TIS
Energy Bill (DECC, 2012a).	Close coal-fired power stations over two decades; continue financial incentives for reducing energy consumption; construct new nuclear power stations. Targets: produce 30% of electricity from renewables by 2020; cut GHG emissions by 50% on 1990 levels by 2025 and by 80% on 1990 levels by 2050.	These cuts in targets were thought likely to cause investors to drop out of funding clean technologies. A key recommendation was for buildings be virtually zero carbon by 2050. HFC technologies were said to be "a credible solution for many energy applications" (DECC, 2012, 51) with benefits in terms of intermittent supply from localised storage. The possible privatisation of the Government Pipelines and Storage System would be highly significant in terms of future large-scale hydrogen storage.

England, planning controls, the underwriting of liabilities (e.g. that of the Nuclear Decommissioning Authority), and the funding of academic research. Certain RDAs, in particular, were active enablers of HFC activity in Period 2 via regional PPPs, e.g. One North East (Hughes, 2007). However, the resilience of HFC PPPs involving the RDAs was weakened from 2010 with the Coalition government's decision to scrap the English RDAs and replace them with less-well-resourced Local Enterprise Partnerships (LEPs) (cf. Walker et al., 2004, Fiksel, 2006).

4.3.3 Regional Institutions

At the regional level, the UK's nations and regions wanted economic prosperity from its targeted HFC policies (see Table 15 for select policies for the English regions). Neither the Scotland Act (1998) nor the Government of Wales Act (1998) (Table 15) established fully devolved governments for each country. However, efforts to overcome the deindustrialization in both nations since the 1960s were typically energy-orientated. After North Sea oil output peaked in the 1980s, Scotland's energy sector began making tentative steps away from oil and gas into renewable energy. From 1998, this shift was occurring thanks to policy support at all three levels of governance. Several enabling instruments in Scotland are shown in Table 16. Wales has witnessed a long-term decline in coal production. The new National Assembly in Wales committed the country to using over 10% of renewables by 2010 rising to 20% by 2020 (Table 17). In terms of regional economic priorities, knowledge, RD&D and innovation capacity were highlighted in the National Assembly for Wales' new economic policy. The Welsh Development Agency (WDA) became involved in innovation incubators - 'Techniums' – based on a policy of bringing together academia and industry. High-tech growth sectors and clusters were targeted especially in the transport and clean energy sectors in Wales (Hodson and Marvin, 2005b). In this policy context, Wales was one of the first regions, along with the North-East, to adopt HFC-specific proposals.

In sum, from 1998, the institutional context of the UK HFC TIS was at three levels from the supranational to the regional. These evolving institutions contributed to and responded to the millennial bubble of HFC activity - hype C. This period of activity peaked in the UK in 2003 (mirrored by *guidance of the search* in Figure 15). UK academics had informed policymakers in 2002 that: "If deep cuts (around 50% or more) in carbon emissions are to be achieved in the long term, then the development of the hydrogen option ... will become critical." (ICEPT, 2002, 81-2). The national and regional

Table 15: Period 2 (1995-2012) – Policy Instruments Affecting HFC Innovation and Diffusion in Selected English Regions

Legislative Act / Policy Instrument	Aim	Impact Summary on HFC TIS
Strategy for Success (2001)	Adapt the existing industrial infrastructure, skills and economic processes to create new jobs and economic prosperity.	The RDA One North East used this regional economic policy to help align the different agendas of HFC stakeholders at the local, sub-regional, regional, national and supranational levels of activity in terms of the resource implications.
Tees Valley Action Plan (2001)	Create new jobs and economic prosperity in a specific district.	The RDA One North East used this regional industrial policy to help align the different agendas of HFC stakeholders at the local, sub-regional, regional, national and supranational levels of activity in terms of the resource implications.
Tees Valley Hydrogen Project (TVHP) (2001)	Encourage economic growth and raise educational attainment and skill levels.	A number of HFC demonstration projects in the Tees Valley in the early 2000s involved integration with buildings and monuments that symbolized the region's historical activity in petrochemicals, steel and coal.
Energy Innovation Zone (2001)	Break down socio-economic barriers and build upon local strengths to counteract continuing population and employment decline in the Outer Hebrides.	Public leverage of funding for activity including HFC demonstration work.
The London Hydrogen Partnership (LHP) (2002)	Strategically align public and private actors, legitimise HFCs, facilitate knowledge transfer and de-risk investment with the overall aim of establishing a regional hydrogen economy.	In 2002, the Greater London Authority (GLA) launched the LHP. The long-term aspiration was to contribute to carbon reduction targets and boost the regional economy.

Table 16: Period 2 (1995-2012) - National and Regional Policy Instruments Affecting HFC Innovation and Diffusion in Scotland

Legislative Act / Policy Instrument	Aim	Impact Summary on HFC TIS
Outer Hebrides Structure Plan (2003) / *Outer Hebrides Local Plan* (2008)	Set priorities for economic development and associated land use.	Coordination of public leverage of funding for activity including HFC demonstration work.
Building (Scotland) Amendment Regulations (HMG, 2006, HMG, 2011)	Require regular air conditioning systems inspections. Give advice to occupants on reducing energy consumption.	These regulations have had the potential to encourage HFC RD&D and HFC market development in stationary power.
Scottish Renewables Action Plan (SG, 2009b)	Set out how to meet the Scottish Government's Renewable Energy targets (over 24-36 months).	This plan encouraged HFC RD&D and market development via increased demand for technical solutions to the demand for the localized storage and release of renewable energy.
Climate Change (Scotland) Act (SG, 2009a)	Reduce greenhouse gas emissions and transition to a low carbon economy based on increasing sustainable economic growth. Set target of an 80% cut in GhG emissions in Scotland by 2050.	The Act encouraged HFC RD&D and market development via increased demand for technical solutions to the demand for the localized storage and release of renewable energy.
National Renewables Infrastructure Plan (N-RIP) (2010) (SE/HIE, 2010)	Develop a spatial framework of first phase sites for renewable infrastructure projects.	The plan set in train investment decisions for renewable projects which, once they become facts on the ground, would add to demand for innovation with the localized storage and release of renewable energy.
Non-Domestic Rates (Renewable Energy Generation Relief) (Scotland) Regulations (HMG, 2010)	To permit local authorities to reduce the sums payable in rates for properties in Scotland used for the generation of renewable heat or power (or both).	Although HFC technologies were not identified alongside eligible renewables, this move adds to demand for innovation for the localized storage and release of renewable energy.
Routemap for Renewable Energy in Scotland (SG, 2011)	Deliver 100% energy generated by renewables in future via infrastructure delivered through its own planning system.	The route map accelerated the delivery of renewable projects which, as they become facts on the ground, should add to demand for innovation and delivery over time of localized storage and release technologies to complement renewable energy.

Table 17: Period 2 (1995-2012) - National and Regional Policy Instruments Affecting HFC Innovation and Diffusion in Wales

Legislative Act / Policy Instrument	Aim	Impact Summary on HFC TIS
Automotive Strategy (2000)	Continue to develop growth in the Welsh automotive sector.	The significant cluster of vehicle components manufacturers in South Wales wants to be part of future HFC mobility supply chains.
Accelerate Wales (2001)	Use networking as the primary means of knowledge exchange for 35 'lead companies' and a further 300 members.	The success of the Accelerate Wales network would also begin to assist knowledge exchange regarding the potential of future HFC mobility supply chains.
Rural Development Plan (NAfW, 2001)	Offer a recovery plan for the rural economy. Draw on and develop export possibilities from existing renewable resources via 'global showcase'.	Kickstarted targeted HFC policymaking in the UK with references to a potential future hydrogen economy based on the production of hydrogen thermally from woody biomass or from the fermentation of carbohydrate-containing organic matter (Maddy et al, 2003).
A Winning Wales (NAfW, 2002)	Improve international competitiveness. Reduce Wales' regional differentials in growth with the UK. Improve enterprise and innovation. Boost skills and learning	This economic policy, and its successor *Wales, A Vibrant Economy* (2006), looked at numerous ways for the Welsh Assembly to pro-actively support businesses through better coordination and the targeting of sectors.
H2 Wales (GU, 2003)	Develop Welsh industry in technologies related to hydrogen production, storage, distribution and use.	This route map and Glamorgan University research clarified the Welsh Assembly's policy approaches to HFC opportunities. It attempted to align actors, e.g. diversification into crops for hydrogen; construction of networks to work together strategically; develop 'an expert knowledge base to inform industry and to support decision-making in for sustainable energy policy.
A Vision of the Hydrogen Economy in Wales (NAfW, 2004)	Offer a rationale, a timeline and a set of technical, political, economic, social and environmental requirements to achieve a 'successful' hydrogen economy in Wales.	This Glamorgan University report, based on a meeting of HFC stakeholders including policymakers, helped to further develop HFC-specific policy options for the Welsh Assembly Government.

Table 17: Period 2 (1995-2012) - National and Regional Policy Instruments Affecting HFC Innovation and Diffusion in Wales

Legislative Act / Policy Instrument	Aim	Impact Summary on HFC TIS
Hydrogen Valley Initiative (NAfW, 2004)	Achieve a zero emission energy based economy supported by sustainable business community through the exploitation of leading edge technologies and stimulation of emerging niche markets.	This geographically-focused initiative was a Welsh Development Agency (WDA) project designed to stimulate activity in areas of traditional heavy industry (steel, coal, car manufacturing) many of which had been under threat. Attracting high-tech HFC businesses, especially in the automotive sector, had not been realized by 2012 (although Riversimple would relocate in 2014 to Llandrindod Wells).
Low Carbon Economic Area (2010)	i. Exploit existing hydrogen & alternative fuels expertise. ii. Increase green jobs in the automotive & stationary power sectors. iii. Gain a competitive advantage to attract HFC RD&D investment. iv. Accelerate growth in low carbon industries, skills & supply chains.	This geographically-focused initiative was designed to link the HFC activities of manufacturers and universities in South Wales, Bristol and Swindon into a state-backed cluster. While many of the aims had not been realised by 2012, policy learning between HFC stakeholders was advanced.

policymaking that helped steer the HFC TIS at this time (shown in Tables 14, 15, and 16) was occurring in the context of rising global expectations for HFCs. For example, in 2003, President Bush committed $1.2 billion to the Hydrogen Fuel Initiative, an HFC mobility RD&D PPP.

Figure 10 and Figure 11 show that hype C ended in the UK in 2005/6. Another upswing - hype D - swiftly started in 2007 and likely built on gains made during hype C. Figure 12 and Figure 13 show that, in 2011 and 2012, entrepreneurial activity in purple and knowledge development activity in orange peaked at 15 events and 27 events respectively. Resource mobilization peaked at 10 events in 2012 (Figure 17) as did market formation with 5 events (Figure 16). Guidance of the search hit a peak in 2012 of seven that was lower than a previous peak in 2002 of 11 events (Figure 15). Similarly, knowledge diffusion peaked at four events in 2012, two lower than a previous peak in 1999 and one lower than one in 2003 (Figure 14). However, the remaining function – advocacy coalitions - dipped sharply from a peak of nine events in 2009 to zero in 2012 (Figure 18). This suggests that – in line with the analytical method outlined in Section 3.3.1.5 - not only was the TSIS approach's *STP motor* in evidence (Figure 19), but so too was the *entrepreneurial motor* (Figure 21), the *system building motor* (Figure 22), and the *market motor* (Figure 23). The only concern in terms of these potential positive feedback loops was the lack of advocacy coalition TIS events by 2012. Given that HFC lobbying actors are known to be active in the UK, this particular result might reflect a concern with the coding. However, this result may also reflect the fact that HFC lobbying efforts are relatively small compared to that of the other, much larger energy-based lobby groups.

4.3.4 Organisational Context: Private JVs and PPPs

Better-resourced and more policy-experienced UK HFC actors than in Period 1 embarked upon a further range of PPPs and private JVs from 1998. This activity coincided with hype C (1998-2004). Post-2004, much of the private cash flowing through HFC firms was eliminated (Interviewee UKFIN1 – 2011). Nevertheless, HFC activity from 2006 – hype D - was still much more numerous and more functionally diverse than anything in Period 1 and, approaching 2012, path creation was occurring (see TIS narrative below). As one Scottish academic HFC researcher stated of path creation:

> "I think policy … [creates] certainty ... Government has to think ahead as to what the

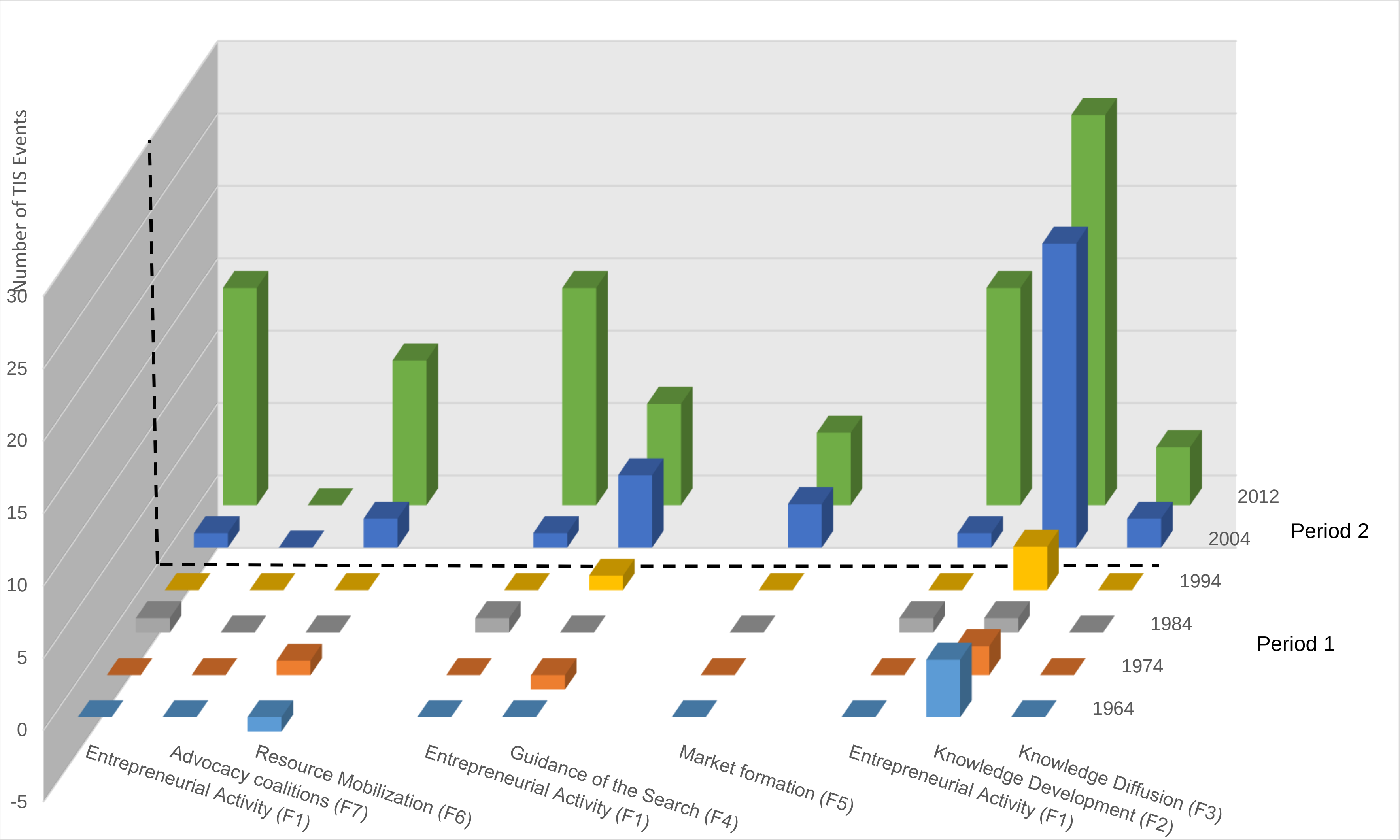

Figure 21: UK - Evidence for the Entrepreneurial Motor, 1964-2012

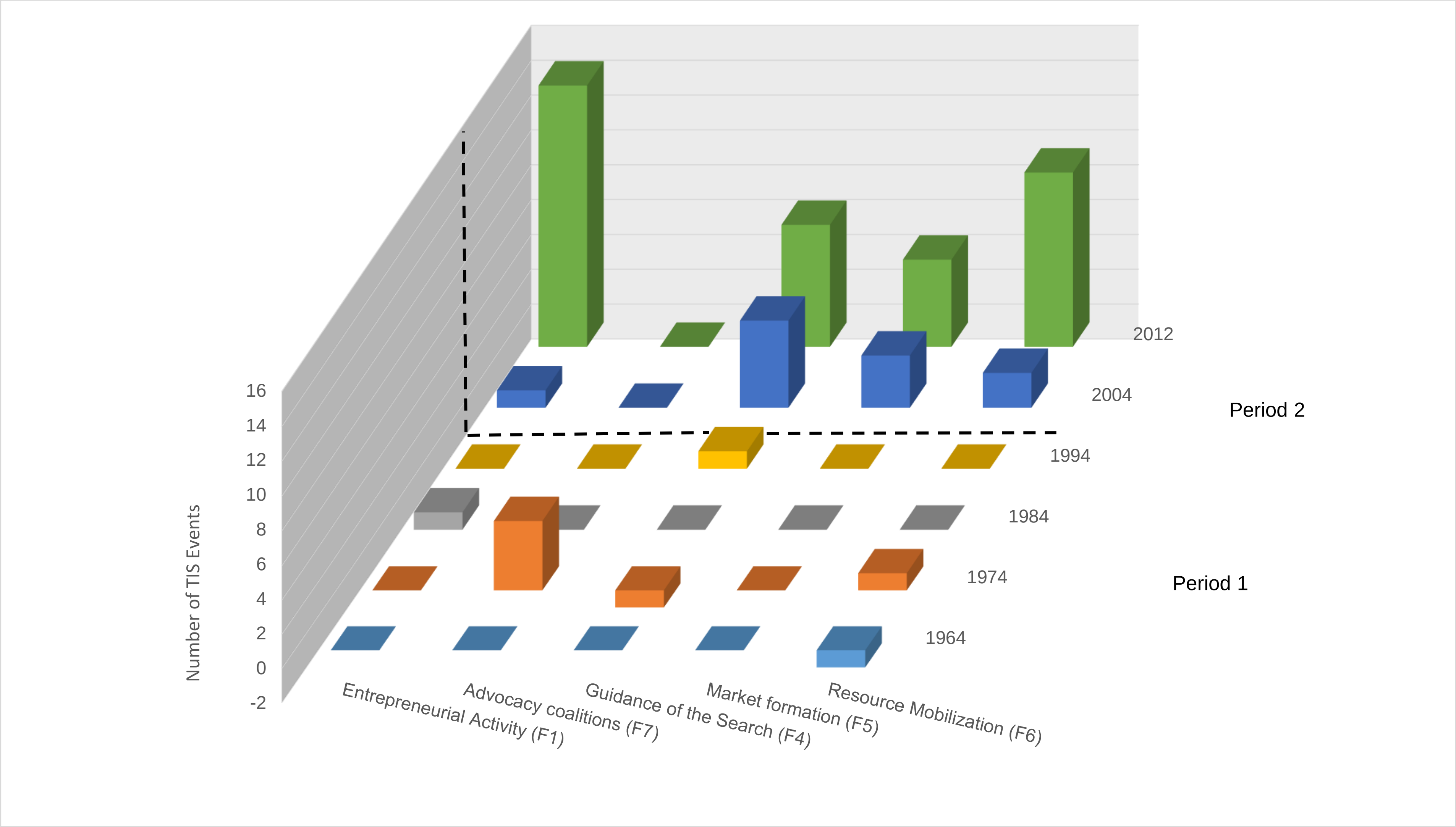

Figure 22: UK - Evidence for the System Building Motor, 1964-2012

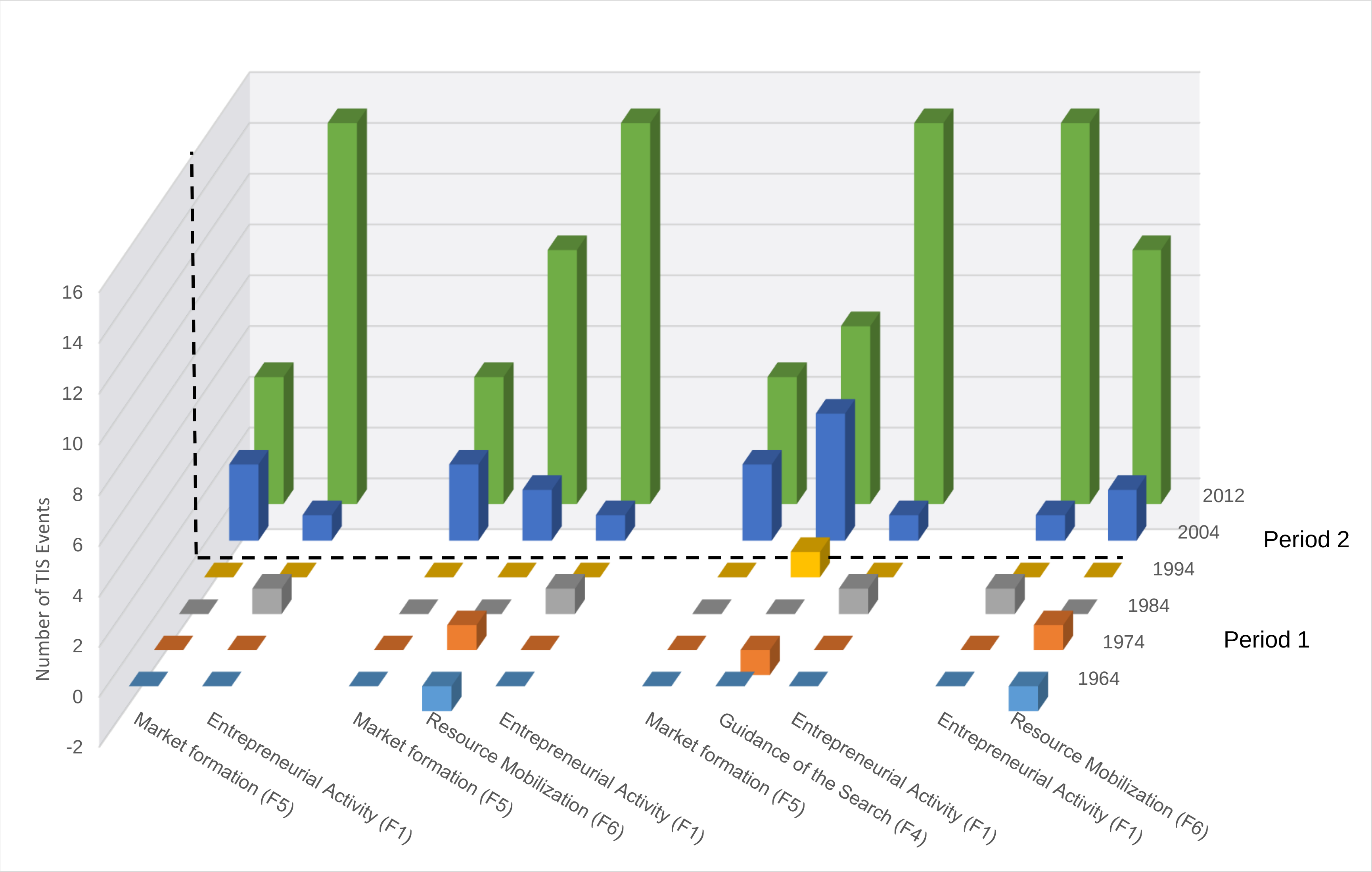

Figure 23: UK - Evidence for the Market Motor, 1964-2012

> possible scenarios are so it ... doesn't ... [pick] the wrong technology… It's quite difficult to displace something ... when it's been installed." (Interviewee SCO2 – 2011)

In Period 2, links between academic HFC researchers and industry expanded with state support. British-based multinational engineering firms like Rolls-Royce and Johnson Matthey were joined by AMEC plc and Ricardo UK Ltd. Then, from 2003, new private HFC actors, including AFC Energy Plc, Intelligent Energy Plc and ITM Power Plc, were listed on London's Alternative Investment Market (AIM). These companies have worked closely with state agencies in PPPs to avoid the 'Valley of Death' where RD&D and marketing funds dry up. As the interviewee at the Technology Strategy Board (TSB) told me:

> "Risk increases just before you get to market, there's a real 'Valley of Death' ... We try and support businesses get through that, help them with interventions, funding competitions ... to help them get over the barriers and to de-risk the next stage of investment. ... We can help bring the partnerships together [and] support that programme." (Interviewee UKFIN4, TSB – 2011)

Post-2005, there was a rapid rise in strategic partnering PPPs which likely helped maintain private investor interest. Post-2005, there was also policy learning from the negative feedback in hype C. This learning has involved proactively dampening down claims made in public in hype cycle D (see Section 2.3.3) and broadening and strengthening actor coordination via road maps (McDowall, 2012).

To further investigate how HFC innovation and diffusion may have been affected by patterns of actor ownership, extra coding of the TIS events dataset was undertaken. This coding identified:

- the type of funding for each event, i.e. 'public only', 'private only', 'public and private (no partnership)' and 'public-private partnerships (PPPs)',

- the degree to which 'private only' activity involved JVs, and

- the PPP type - based on the typology in Table 4 in Chapter 2.

Figure 24 and Figure 25 show that private-only and PPP funded TIS events ran neck-and-neck in Period 1, but private funded TIS events increased more quickly in Period 2 from 2000.[49] It seems unlikely that state support for PPPs was not influencing this private spending in terms of indirectly de-risking HFC activity. Figure 26 and Figure 27 reveal that, of the different types of PPPs highlighted in the typology in Table 4 in Chapter 2, the rise of strategic partnering PPPs post-1998 added the greatest number of TIS events to Period 2.[50]

These strategic partnering PPPs were supported by a new range of state agencies, like the TSB (shown in blue at the national level in Figure 20 and with its impact outlined in Table 14). This PPP activity appeared to underpin a bounce back from the potentially negative impact of the 2008-9 credit crunch (as shown in Figure 10). Nevertheless, as one of the two interviewees from the Carbon Trust said, VC investment is place specific:

> "[T]he appetite of venture capitalists … in London which is … maybe the world's largest financial centre … is very low compared to … Silicon Valley … Access to bolder venture capital funding would be a key step in overcoming this barrier. It's a matter of sort of investment culture so you can't solve it in one day." (Interviewee UKFIN1, Carbon Trust – 2011)

Similar spatially-specific factors also appeared to be producing uneven rates of regional growth in TIS events, as I describe in the next section.

4.3.5 Spatial Context

In this section, I offer evidential support for a spatial dimension to the UK's HFC TIS events. Thirty-two higher education bodies and research institutes and 111 corporate HFC actors in operation in December 2012 are listed in Appendices Q and R respectively. Appendix S reveals that, from this data, the region with the greatest concentration of estimated employees *working with* HFCs (set against numbers for all other employment) were: the South-East, the North-East, East Midlands, West Midlands, Scotland and the East, in that order. The uneven geographical distributions of both of these sets of HFC actors are shown in Figure 28. The greatest concentrations of HFC actors were in leading urban areas, e.g. London, Tyneside, Loughborough, Birmingham and Scotland's

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[49] Data coded according to the funding status of TIS events is tabulated in Appendix O.
[50] The data, coded according to the PPP typology, is tabulated in Appendix P.

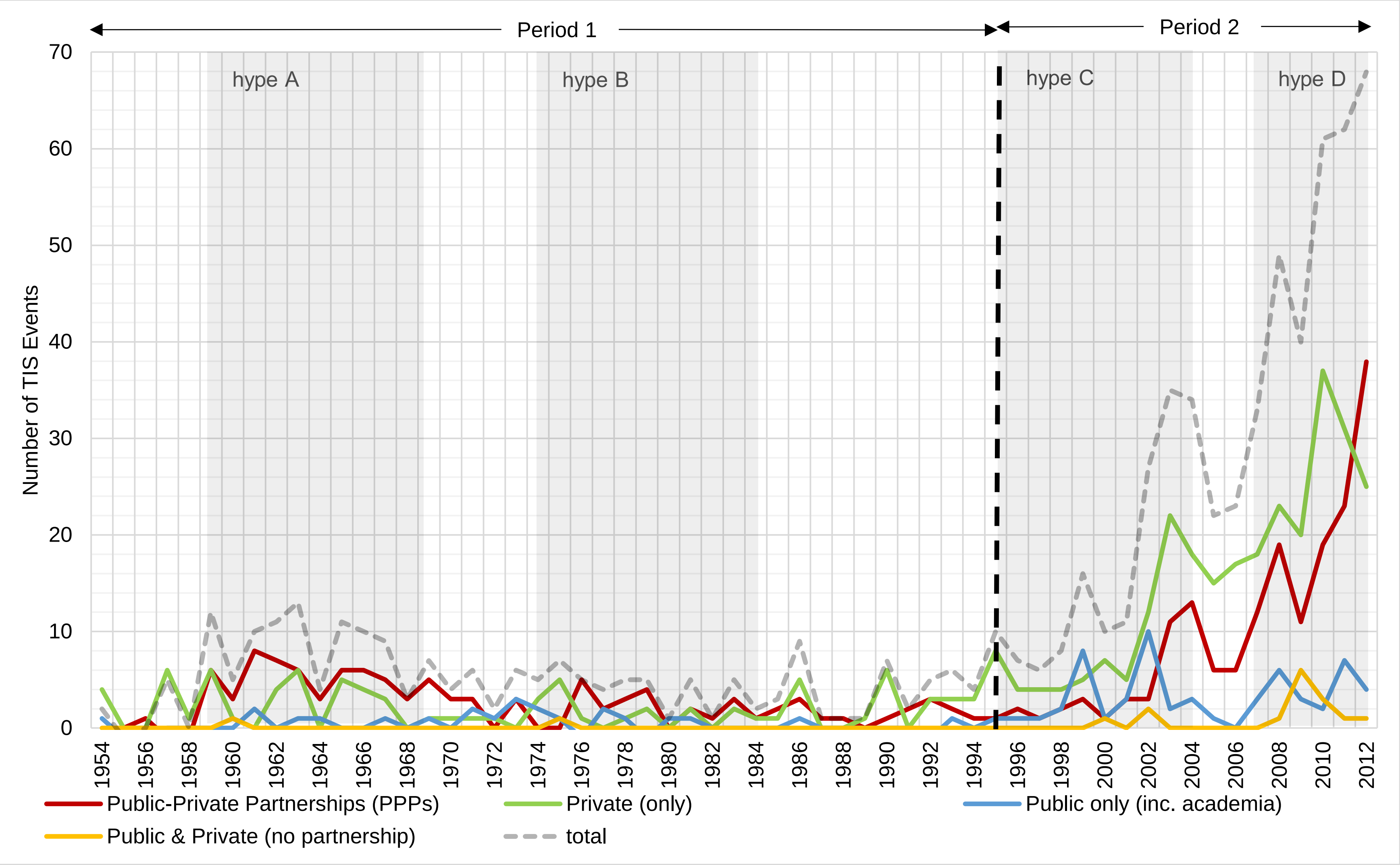

Figure 24: UK – Annual Totals of All TIS Events by Actor Funding Type, 1954-2012

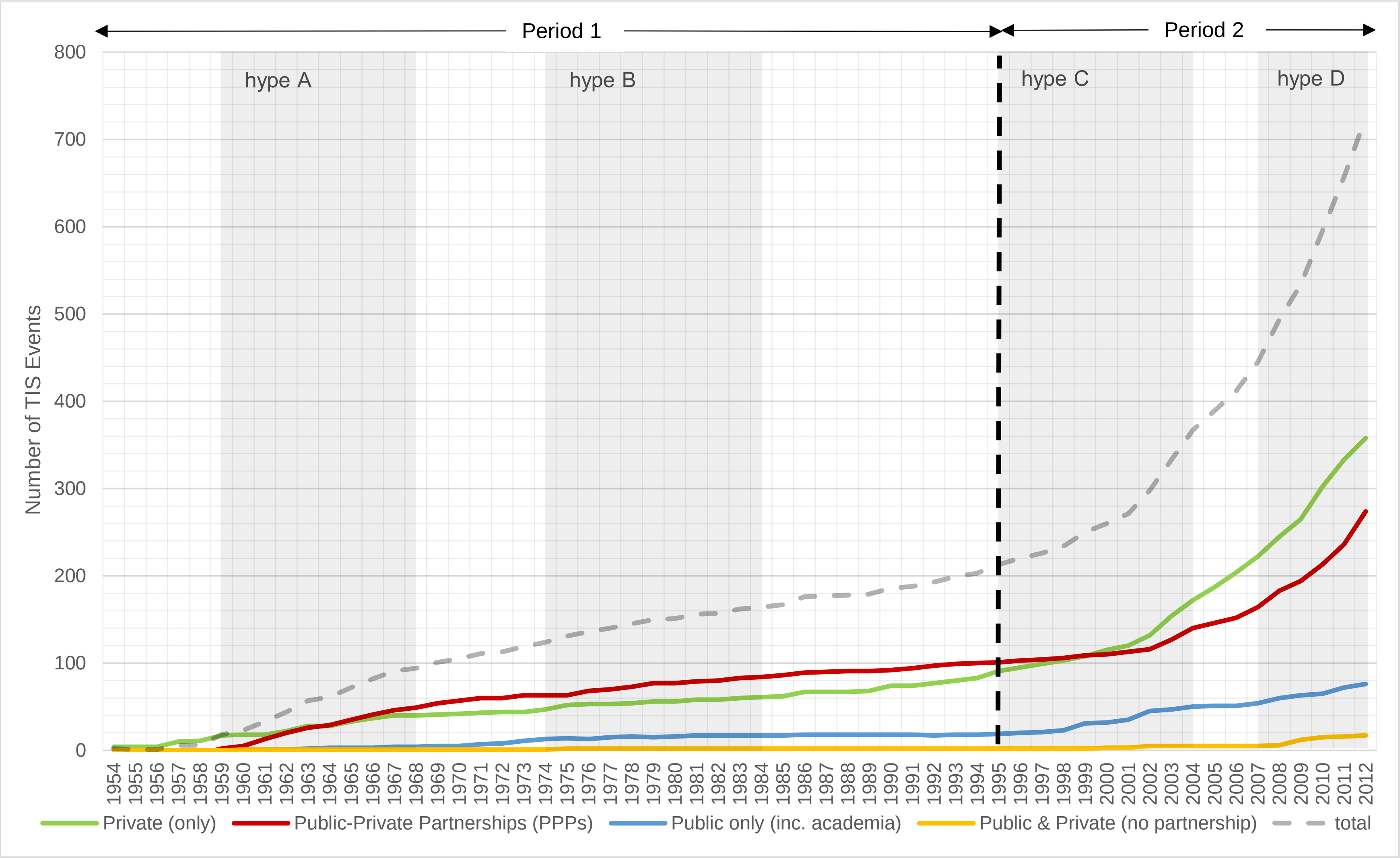

Figure 25: UK - Cumulative Totals of All TIS Events by Actor Funding Type, 1954-2012

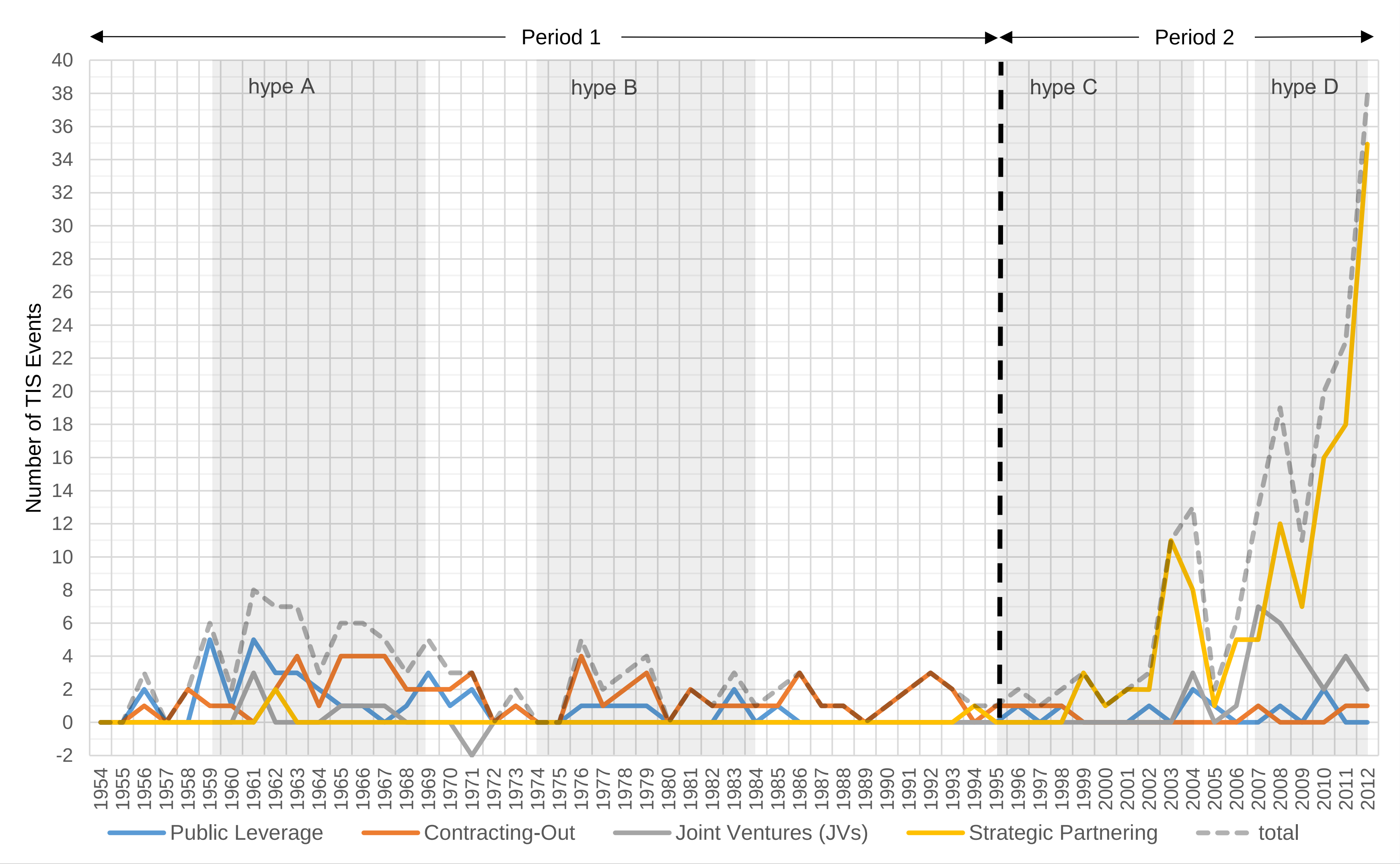

Figure 26: UK – Annual Totals of Public-Private Partnerships (PPPs) by Type, 1954-2012

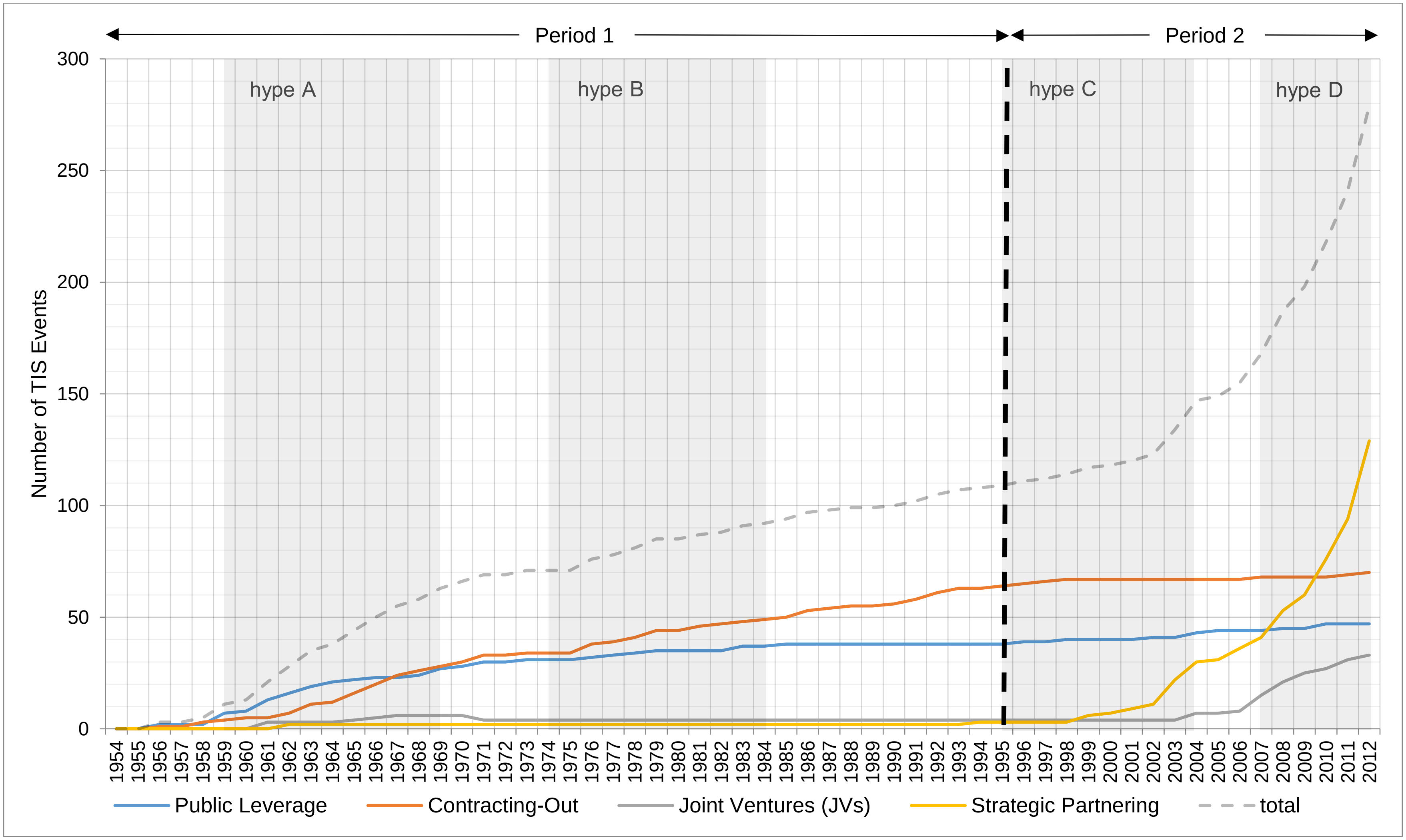

Figure 27: UK – Cumulative Totals of Public-Private Partnerships (PPPs) by Type, 1954-2012

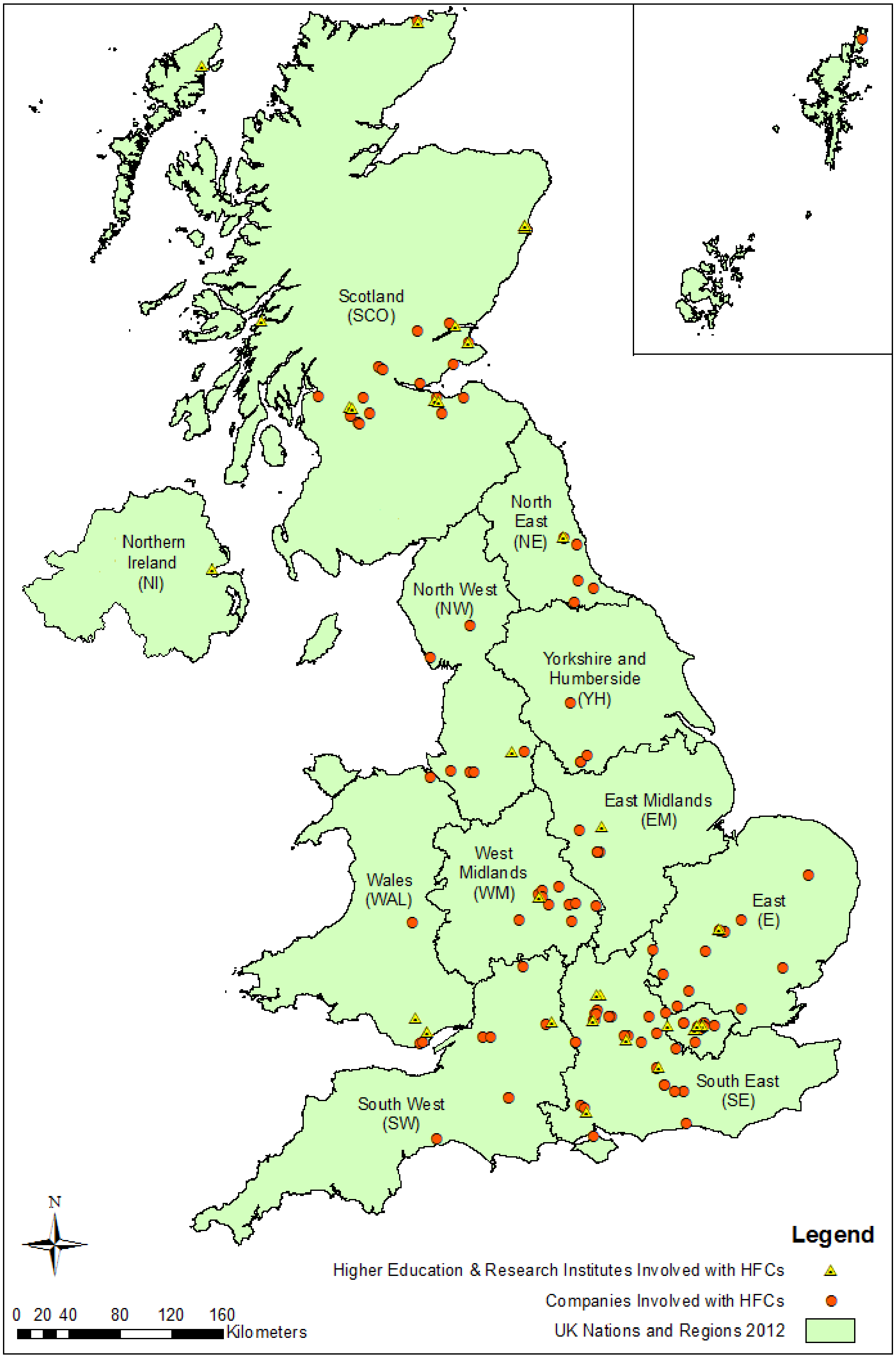

Figure 28: UK - Geographical Distribution of HFC Actors in 2012

Central Belt. To further explore the quantitative nature of this likely clustering activity in terms of possible correlations between HFC firms and research sites, I used the Multi-Distance Spatial Cluster Analysis tool (based on Ripley's K function) in ArcGIS software. This analysis revealed that each group, on its own, was clustered in a statistically significant way over a range of distances (Appendix T). When I analysed this data in Stata14's statistical software package for the interpoint distance distribution, Appendix U shows how both of these distribution patterns of research bodies and companies were correlated with each other in a statistically significant way. Correlations, however, do not imply causation and need to be interrogated further. I was then able to triangulate this 2012 snapshot of where UK HFC actors were located with a longitudinal regional record of knowledge development activity (F2) (Figure 29). Figure 29 suggests path dependence is at work because regions in which activity was first established in Period 1, i.e. the South East, also saw the greatest increase in activity in Period 2.[51] This regional breakdown was then applied to entrepreneurial activity (F1) post-1998 to see if similar regional differentials existed (Figure 30). Figure 30 shows that entrepreneurial activity had the greatest rises in Period 2 in the South-East, West Midlands and Yorkshire and Humberside in TIS events by 2012. Again, the South East saw the first entrepreneurial activity in 1999 and its event tallies rose at the steepest rate thereafter. This regional breakdown was finally applied to all the TIS events coded for PPPs (Figure 31). Figure 31 reveals that, by 2012, the greatest amount of PPP activity occurred in Scotland, Greater London, the West Midlands, the South East, Wales, the North West and the North East in that order.[52]

I then checked to see if there were correlations between the TIS events I had coded for strategic partnering PPPs and those coded for knowledge development (F2) and entrepreneurial activity (F1) because of the relevance to gauging the effectiveness of HFC-specific policymaking with PPPs. The results, shown in Appendix Y, suggest a weak to moderate positive relationship between strategic partnering PPPs and knowledge development and entrepreneurial activity (the strongest correlation at 0.45 was between F1 and F2).

In terms of regional differences, I also compiled some market data on HFC firm size, employee numbers and ownership patterns as indicators of the dynamism, maturity and

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[51] TIS event data by region is tabulated in Appendix V.

[52] Ignoring the South West region which had lots of TIS events where the EPSRC and TSB are located.

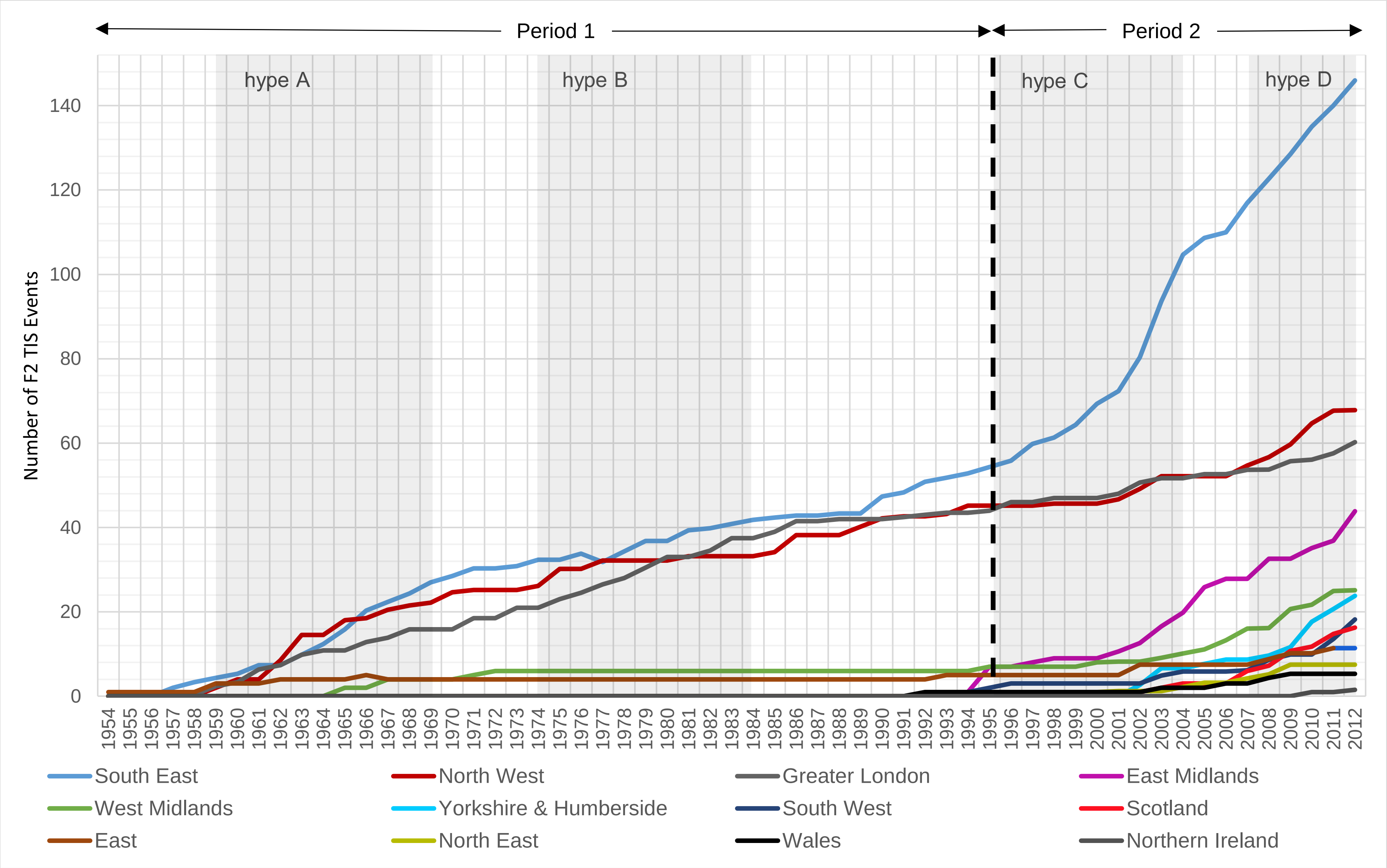

Figure 29: UK – Cumulative Totals for Regional Diffusion of HFC Knowledge Development Activity (F2), 1954-2012

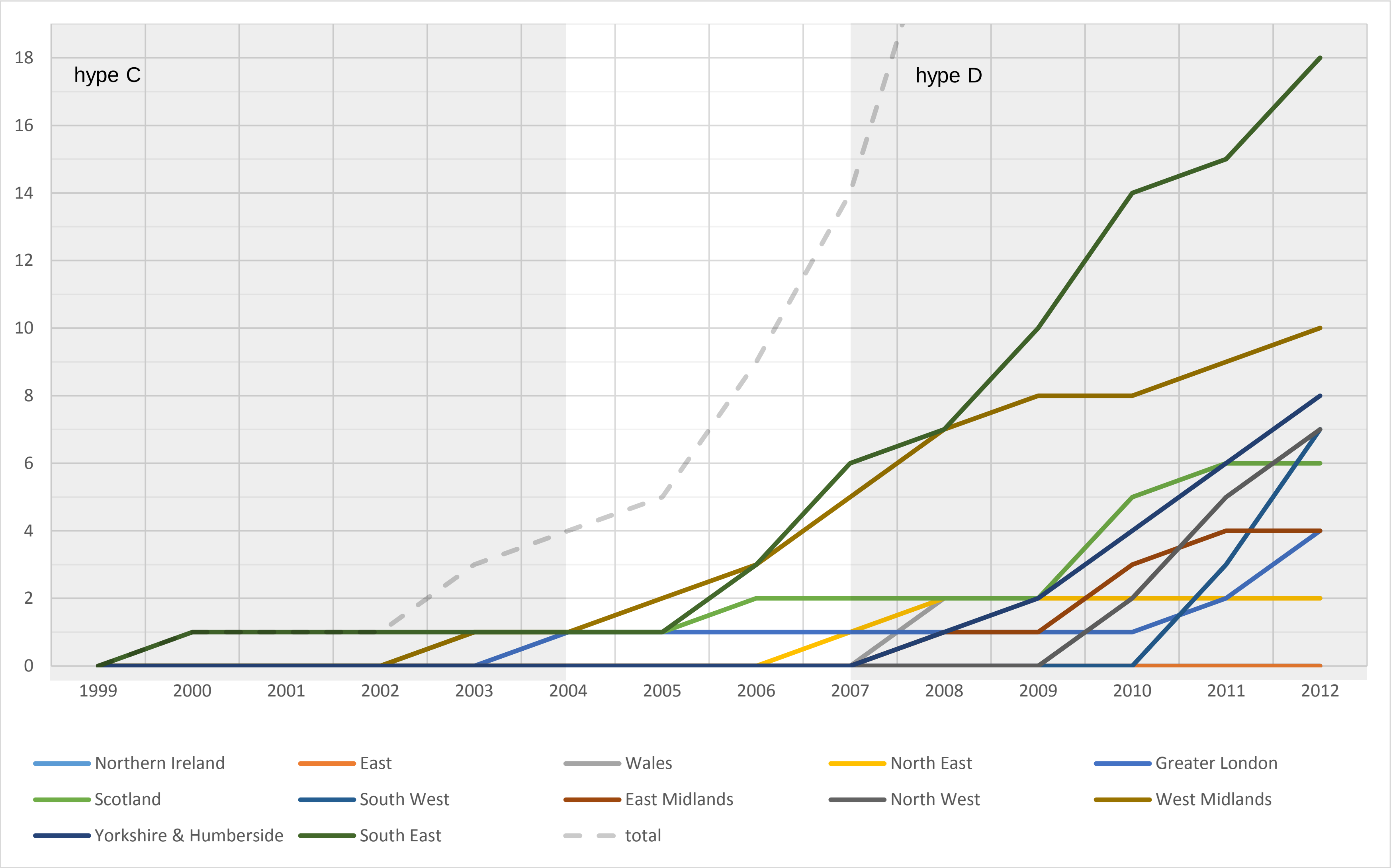

Figure 30: UK – Cumulative Totals for Regional Diffusion of HFC Entrepreneurial Activity (F1), 1999-2012

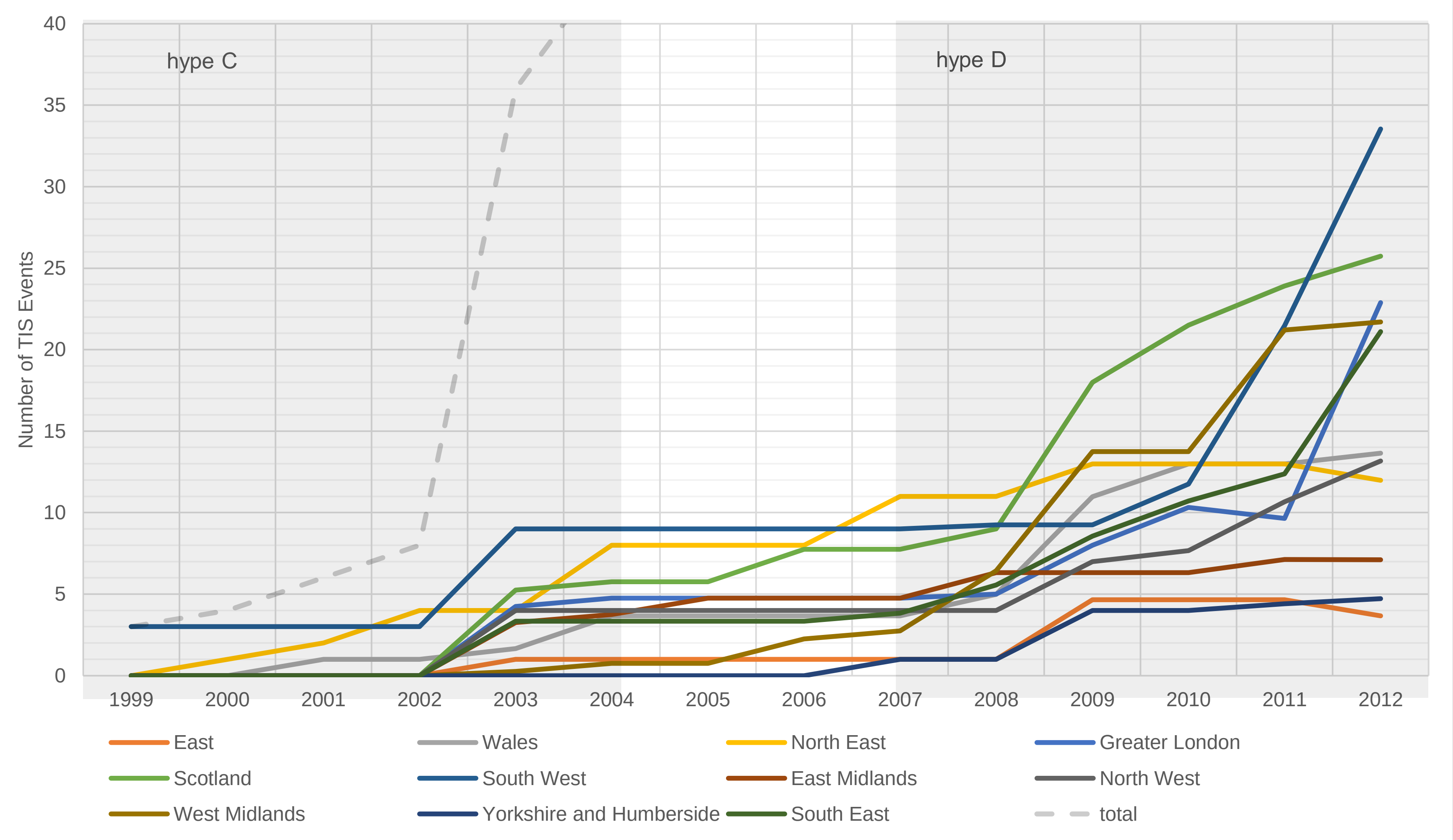

Figure 31: UK – Cumulative Totals for Regional Diffusion of PPP Activity, 1999-2012[53]

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[53] The total has been ignored on the right-hand side of this graph for clarity's sake.

resilience of the evolving UK HFC TIS. In terms of estimated firm size, Appendix Z indicate that, out the 68 corporate actors in the six most clustered regions (by employee location quotient or LQ) in 2012, the ratio of small companies (1 to 250 employees) to larger ones (251+ employees) was 47:21 or 2.2:1. This ratio, of smaller HFC companies outnumbering larger ones, suggests the UK HFC TIS in 2012 was in a more mature phase in its structural evolution. TIS events in Period 1, by contrast, were predominantly associated with large firms. My total estimated figure for employment in smaller firms in 2012 in these six regions was around 779 individuals compared to 1,168 by larger ones. The ratio of UK-owned to foreign-owned HFC firms, an indicator of both the context of the UK's *laissez-faire* approach to capital (cf. Hall and Soskice, 2001) and the relative maturity of the HFC TIS, was 75:35, or roughly 2:1 (Appendix Z). This asymmetry in firm size and ownership has implications for HFC-specific policymaking. A nation or region committed to HFC growth must decide on the relative costs and benefits of its efforts to encourage the growth of small, domestic firms and attract larger overseas firms to invest, a point which will be returned to in Chapter 7.

Overall, the TIS event data suggests that the rise in TIS activity in Period 2 was stronger, more functionally diverse and potentially more resilient than that of hype A in Period 1. In fact, with an increase in all functional activity in Period 2, positive feedback appears to have been occurring. This appears to have led to system-wide potential for more commercial 'take off' by 2012 (cf. Suurs and Hekkert, 2012). My market data and extended coding of the TIS events adds to this picture by offering further insights into *where* and *how* innovation and diffusion occurred (i.e. in JVs/PPPs and unevenly in space). These extended indicators hint at micro-level socio-technical processes at work, such as path creation and path dependence, which work out at the regional and sub-regional levels (levels of analysis that are not presented in the TSIS approach).

In order to contextualize the co-evolution of HFCs in the UK, I use the next three sections to describe how, in a narrative fashion, actors, individuals, networks, institutions and technologies interacted in the three sectors from 1995 to 2012.

4.3.6 Defence and Aerospace

In Period 2, the contracting-out PPP involving the Navy, Wellman Defence Ltd. (formerly CJB Developments) and BAE Systems Maritime (formerly VSEL) continued to fit further low-pressure PEMFC-powered electrolysers for atmosphere control and drinking water to submarines (see Appendix I). Oxygen was produced by the PEMFC unit at near ambient pressure (0.7 bar) and the by-product (hydrogen) at 7-bar pressure. By 2001, some of the cell stacks had reached over 30,000 hours of operational service with 100% reliability. However, two separate but identical incidents of cell stack failure occurred within the fleet that year. The low pressure electrolyser's polypropylene filter element, which allows resin beads from the demineralizer column to enter the cell stack via the process water inlet pipe, failed. Subsequently, the resin beads blocked individual cells causing a reduction in flow of demineralized water across the cell membranes leading to overheating and ultimately cell failure. The only remaining technical challenge for these electrolyser units remains fault-free endurance.

In Text Box 9 below, competing views within a private submarine joint venture PPP are outlined.

Text Box 9: Project-Level Narrative - BMT Defence & Rolls Royce Private JV PPP

VSEL had failed to commercialize an HFC air-independent propulsion (AIP) system in 1994. Germany's Type 212 HFC-powered AIP submarine then appeared in 2002. Up to that point, UK submarine designers had turned their attention away from AIP. After 2002, however, VSEL's HFC work on diesel-electric propulsion was reappraised. In 2004, Bath-based BMT Defence Services Ltd unveiled a design for a high mobility submarine known as the Ship Submersible Gas Turbine (SSGT). Developed jointly with gas turbine specialists Rolls Royce, the SSGT would be relatively cheap yet its performance – at least on paper - approaches that of a nuclear submarine. Once in-theatre, the SSGT shuts down its gas turbines, dives and can operate fully covertly for up to 25 days using its AIP. Fuel cells and advanced Zebra batteries provide power and permit submerged operations up to 10 knots and short tactical sprints at 30 knots respectively. Kerosene powers the gas turbines and the fuel cells (via reformers). Liquid oxygen is stored to enable the fuel cells to operate when the boat is submerged. SSGT may also run its fuel cells at the surface taking air using a conventional snort mast. In this way, an SSGT vessel represents a potentially new technological pathway, one that means it can stay out of sight whilst in transit and still preserve its stored liquid oxygen. But this pathway will not be pursued unless the social, economic and institutional context is favourable.

Other military HFC products began development in the UK in Period 2. One of these PPPs is described at the project level in Text Box 10 below

Text Box 10: Project-Level Narrative - British Army Contracting-Out PPP

In 2004, the MoD entered a bilateral knowledge exchange agreement with the US military. This covered RD&D in power sources, power management, fuel cells and batteries. The MoD then formed a PPP, including Black and Decker, Ineos Chlor, Intelligent Energy, and QinetiQ, to develop and manufacture a handheld PEMFC for recharging conventional batteries as part of its future infantry soldier technology (FIST) programme. This PPP's design overcame the typical loss of cell performance from dehydration. This improvement was achieved via better water management with a porous, hydrophobic layer over the cathode current collector. A platinum catalyst was recommended along with a rechargeable and replaceable metal hydride cartridge. The design of this mobile PEMFC meant that one or more multi-element fuel cells could be linked together in any configuration to create a larger power source. The design also means this mobile PEMFC can be manufactured to different power specifications using the same production process. Secondary sources indicate that this particular HFC technological pathway was heavily contested between these PPP partners.

The interviewee I talked to from the venture capital (VC) fund, Conduit Ventures, described how and why such military HFC applications have the potential for rapid uptake:

> “The products ... in terms of weight and supply chain simplification, in terms of less fuel consumption (so less fueling logistics) ... are pretty compelling, and so cost is less of an issue ... It doesn’t take much of a military purchasing programme to fill the capacity of a company’s ability to produce ... The uptake dynamic ... could go very quickly ... once you have buy-in and validation.” (Interviewee UKFIN3, Conduit Ventures – 2011)

In Period 2, similar large- and small-scale HFC innovations were occurring in very specific niches in the UK defence sector. This suggested to one of the interviewees from the TSB that state-sponsored HFC RD&D via contracting-out PPPs - followed by state-led procurement – could be a successful route to stimulate the early growth of HFC applications in the UK defence market:

> "That's one barrier. We're really bad at [state procurement] in the UK, using Government buying power to drive innovation ... [With] a lot of these technologies, it would be a Government that's going to take it up first, or [a] local authority or something, rather than other businesses, and then businesses are second and ... then you create the market." (Interviewee UKFIN4, TSB – 2011)

In this context, state RD&D support followed by procurement may be a useful way forward in all HFC sectors not just defence. This point will be returned to in the policy section of Chapter 7.

4.3.7 Transport

In Period 2, there was sustained involvement in the UK HFC TIS by a number of multinational automotive and energy majors. However, fuel cell electric vehicle (FCEV) RD&D programmes restarted in Period 2 with different actors from Period 1 and none of the multinational transport OEMs dominated this activity (as shown in Appendix L).

From 1989, US and European PPPs known as Auto/Oil Programmes had been undertaken. These were designed to help improve air quality by providing further knowledge (and advising regulators) about the relationships between vehicle fuels, engine technology, vehicle emissions and urban air quality (Legge, 1997). In the post-Kyoto era, new private HFC JVs and PPPs built on Auto/Oil Programme collaboration. This was a time when everything: "changed dramatically, with practically every major oil company … actively involved in fuel cells for transportation applications. This has been via alliances or agreements with car manufacturers at the leading edge of fuel cell technology" (McNicol, 1999, 10).

In the UK, at the national level in 1996, the Department of Transport introduced PowerShift grants. These were designed to promote the take-up of cleaner vehicle technologies. Although, these did not involve formal co-operation with local government, there would be synergies in Period 2, for example, in London where alternative fueled vehicles (AFVs) on the PowerShift register did not have to pay the Congestion Charge.[54] This would begin leading to a relatively higher demand for AFVs in the London area, for example.

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[54] The UK government ended its PowerShift grants in 2005.

When a new period of global hydrogen hype began in the late 1990s, oil multinationals like the Royal Dutch Shell and BP were able to swiftly re-engage with a range of industry actors promoting the prospects for refueling hydrogen vehicles (just as Shell had done during the hype of the 1950s and 1960s when it collaborated with Lucas). For obvious reasons, the technological routes for producing hydrogen feedstocks were from oil, gas and coal (see Figure 1), a situation unchanged from the 1950s.[55] At the Millennium, Shell's CEO Mark Moody-Stuart, made a strong signal to the marketplace by reaffirming that: "We believe the way forward [with hydrogen mobility] is through onboard conversion of gasoline to hydrogen." (Moody-Stuart, 2000). However, no home-grown technological partners were available in the UK because, after decades of decline, the car industry there was only just starting to grow again (cf. Whisler, 1999). In 2000, there were no equivalents to Daimler, BMW, GM or Toyota, for example, each with deep pockets and significant state support. As part of a demonstration, Shell instead went into a joint venture with Canadian HFC manufacturer Ballard and produced a hydrogen filling station in Iceland in 2003 (Park, 2011). In the UK, HFC innovative activity began to pick up amongst a range of smaller vehicle engineering operators from 2001 onwards (see Appendices J to M).

A relatively smaller HFC vehicle engineering firm was ZeTek Power Plc. It went into a private JV with London Taxi International in the late 1990s. The context of this failed branching point for AFC mobility is described in Text Box 11.

Text Box 11: Project-Level Narrative - ZeTek & London Taxi International Private JV

In 1996, ZeTek Power Plc formed from the remains of leading Belgian AFC company, Elenco, which had gone into receivership. In 1998, ZeTek Power opened a new division, Zevco Ltd – a 'zero emissions vehicles company'. Zevco's engineers considered AFC the automotive technology to have been overlooked with the surge in interest in PEMFCs in the 1990s. Having made some significant updates to AFC stack technology, a hybrid EV with a pure hydrogen-powered AFC and a lead-acid battery offering 5kW of power from the cell was used to power fleet vehicles run by the City of Westminster, Marks & Spencer and Post Office. A similar HFC-powered black taxi produced with Coventry-based London Taxi International was also demonstrated. ZeTek Power's system configuration was considered reliable and the performance was thought to be very promising. A

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[55] Bacon was approached by BP just after he applied for his first patents in 1954. He went on to work in a PPP, Energy Conversion Ltd., with BP in the 1960s.

similar HFC-powered black taxi produced with Coventry-based London Taxi International was also demonstrated. ZeTek Power's system configuration was considered reliable and the performance was thought to be very promising. A number of technological promises were made within a relatively short time frame by ZeTek's British managing director, Nick Abson. However, the advanced plans of ZeTek's management for commercial manufacture of its AFC cells via automation in factories in Germany and in the US were reportedly halted by the 9/11 tragedy. The shutdown of the US banking system, and the loss of so many banking staff, came at the moment that ZeTek Power needed financial completion on funding from venture capitalists, it was suggested, putting the company out of business. The situation left many HFC actors, including investors, critical of Abson's management of technological expectations, i.e. accusing him of overpromising on what its HFC technologies could deliver (Fagan, 2001, Interviewee UKLOB1, UKHFCA - 2011).

Crucially for the policy discussion in Chapter 7, HFC-specific policy learning subsequently centred in large part on resilience, i.e. how best to avoid Zetek's demise. In terms of HFC technology pathways, a branching point in HFC mobility was therefore reached in 2001 with the AFC approach stalling. Instead, the PEMFC designs of DaimlerChrysler, Ballard and Ford advanced as the dominant design (with BMW's hydrogen ICE approach running a close second) (see section 4.6.2 for details of German HFC mobility developments).

The Pure Energy Centre in Scotland was involved in one of several PPPs which are described in Text Box 12.

Text Box 12: Project-Level Narrative - Outer Hebrides Council's Strategic Partnering PPP

In Scotland, the council in the Outer Hebrides, Na h-Eileanan Siar, was advised by the Promoting Unst Renewable Energy (or Pure) Energy Centre in 2010 about a phased demonstration project designed to overcome the high costs of imported fuel. Pure Energy was set up on Unst at the far northern tip of the Shetland Isles in 2006. Pure Energy runs the world's first community-owned renewable energy project which uses wind power and hydrogen storage. This Hebridean project covered an exploration of the whole value chain of hydrogen technologies by looking at hydrogen production from biogas, hydrogen storage, a hydrogen filling station and hydrogen use in both stationary and transport applications. In transport, there was a hydrogen road trial in 2010 with a fueling station supported by the US-owned multinational Air Products. A Hebridean Hydrogen Growth (‘H_2growth’) project was then planned to market the outcomes of H_2 SEED, a prior project covering the whole value chain of hydrogen technologies including H_2 production from biogas, H_2 storage, H_2 filling station and H_2 use in both stationary and transport applications. In terms of drivers of change, a council member said in 2011 that the potential of HFC applications was closely linked to the place-specific needs of community members:

> “They’re very close to the consequences … of climate change and the consequences of continued fossil fuel use. If I take economic to mean financial, the costs of energy are, have always been, higher here, so the prospect of lower cost energy is one that’s very attractive. And again they can start, they’re starting to see that hydrogen offers more … possibilities.” (Interviewee SCO7, Na h-Eileanan Siar - 2011).

The council approached the European Commission in early 2012 to fund a hydrogen highway across the islands entitled HIGH2WAY, however, Na h-Eileanan Siar did not win funding. Primary and secondary sources reveal the internal policy debates in the council about whether HFC technologies can help to achieve the desired social and economic outcomes which are highly place-specific.

In England, Greater London hosted the European CUTE and HYFLEET CUTE HFC bus demonstrator programmes between 2003 and 2006. This activity was organised by a PPP involving DaimlerChrysler, BP, the Greater London Authority (GLA) and the European Commission (EC). Since then, there has been a hydrogen-powered demonstration bus service, the R71, in operation thanks to PPP collaboration between the GLA, Transport for London (TfL), London Bus Services Ltd, Wrightbus, Ballard, ISE Corp and Air Products Ltd.

UK-based HFC companies, ITM Power and Intelligent Energy, have run vehicle trials in London for black cabs and scooters respectively. They suggest that London will remain a significant showcase for HFC demonstrations where the public in greater numbers are beginning to experience HFC buses, taxis and scooters, for example. However, HFC and other innovative vehicle manufacturing innovative activity in the

UK largely takes place outside of Greater London and the South-East regions as the interviewee at the Technology Strategy Board (TSB) indicated:

> "We've got Honda, we've got Nissan ... and ... the Nissan investment in the LEAF and [this] has shown that we can demonstrate ... the UK's the place to make these things ... We're still a large part of the [global] automotive supply chain. We make a huge number of engines ... Why not make all the fuel cells? We should be focusing on the high value end ... We've got a lot of expertise, design, consultancy, with integrating these technologies. [Get] the research happening here." (Interviewee UKFIN4, TSB – 2011)

One of the Carbon Trust interviewees suggested that, in 2011/2, the greatest technical challenges were reducing the cost of installing refueling infrastructure and keeping the vehicle unit costs down:

> "The feedback that we're getting from major global OEMs is that the technology that they're putting in these cars ... is still too expensive … That's fine … That's the way it happened … when Toyota marketed the Prius … [But] without [unit cost reductions] their products ... will remain a niche. So [we want to] de-risk the technology to a point where it can be picked up by industrial end users, … build on ... the strengths of the UK research base, and … deliver quite significant carbon savings." (Interviewee UKFIN1, Carbon Trust – 2011)

One factor that cannot be ignored was raised by the interviewee from Friends of the Earth. This individual suggested the fossil fuel industry may well support HFCs, but this support might also help to relax the environmental governance of polluting vehicles/fuels in the present:

> "[The OEMs have] already got a strong voice within Government ... If they're saying we need to move forward in this direction then the Government will support it. [But] the fossil fuel industry has possibly had a vested interest in [hyping it] ... [They might think] 'We can carry on doing what we're doing because ... this magic technology is coming down the pipe'." (Interviewee LOB2, FoE – 2011)

This view suggests that a realistic view needs to be taken when establishing the strategic motivations for the actions of some HFC transport actors.

A major step forward in the HFC transport sector came as a result of the McKinsey/Powertrain Alliance report (McKinsey and Alliance, 2010). This unique exercise permitted commercial HFC mobility actors in Europe to exchange precise, technical knowledge about the state of HFC research through a ‘clean room’ approach where HFC documents were shared anonymously via McKinsey staff. The report concluded that a portfolio of different vehicle types would likely co-exist in a decarbonised transport sector and that FCVs are ready for commercial deployment (Dodds and Ekins, 2014). This exercise built trust, aligning convinced and skeptical vehicle industry actors around an agreed technological pathway going from mass production of electric vehicles and on to hydrogen vehicles thus de-risking investments in both sub-sectors (cf. McDowall, 2012).

Up to this point, the HFC transport sector included a number of different expectations for the range of technologies (cf. McDowall and Eames, 2006a). Amongst a range of factors, these collective corporate expectations depend on the size of the company, the length of its financial horizons and its approach to environmental governance. As the Friends of the Earth interviewee suggested, some HFC transport sectors actors operating in both countries would be openly supporting *future* HFC mobility in order to undermine the EU’s environmental governance of polluting vehicles in the *present* (Interviewee LOB2, FoE – 2011). Such a cynical position has been taken by some carmakers, for example:

> “Detroit's eco-car efforts have been largely a matter of public relations. As they cynically … [promise] hydrogen-powered cars, automakers have been using their muscle to keep federal fuel-efficiency standards exactly where they were when enacted in 1975. Freed of stringent regulation, the Big Three have reaped billions selling high-profit, gas-guzzling SUVs.” (Baum, 2002, no page number)

In the case of the German automotive giant, Daimler, however, there were genuinely high expectations in 2011 for their HFC vehicles (Interviewee G-MNC4, 2011). With hundreds of millions of Euros spent via public and private R&D over decades, there was a continuing expectation, just as had been the case with DAUG in the 1960s and 1970s, that such investments could be recouped from sales and licensing of Daimler’s HFC patents to other car makers. No similar such UK-owned vehicle manufacturer existed in the UK in the 2000s. HFC actors in the UK transport sector would likely have to settle for being ‘fast followers’, having relatively little influence over the direction of particular HFC technological pathways and investing in the HFC technologies of other nations when the cost, timing and availability are right (Williamson, 2010).

In summary, by 2012, UK HFC transport actors were clearly accepting of the EC's direction of travel in terms of environmental governance. Some happily and some grudgingly accepted the rationale of the McKinsey report that HFCs needed developing alongside EVs to meet climate targets. These actors would also work with others on evolving standards, for example. However, the lack of central government commitment to a clear set of well-funded HFC policies was cited by most interviewees as the leading barrier to change.

4.3.8 Stationary Power

The leading stationary power demonstration projects run in Period 2 include a number involving the Pure Energy Centre. In 2011, the Pure Centre was involved with the setting up of the Hydrogen Office in the docks at Methil in Fife on the east coast of Scotland. As in Unst, this demonstration project stores wind energy as hydrogen, but Fife Council also hoped the Hydrogen Office would be able to provide cheap, renewable energy for entrepreneurial companies wishing to locate there and whose activity might help regenerate the area.

The interviewee from the TSB expressed concern that the market focus of stationary power applications needs to be global not national:

> "There's not enough of a market … You've got five big companies … you're going to put some hydrogen systems in ... you've done it ... Right, next. It's not a market ... You've got to have these applications working in all sorts of different parts of the country ... There's benefit in clustering around [the] supply chain, but the UK is not a big place. We're a cluster, as a whole country! ... Pure Energy ... can collaborate with anybody in Europe. [They] can get on a plane." (Interviewee UKFIN4, TSB – 2011)

Overall, innovation and diffusion in the stationary power sector started later than the other two sectors given the lack of competitive advantage and path creation in Period 1. Nevertheless, the potential for rapid uptake in this sector *appeared* relatively higher than other sectors in the UK by 2012. The market demand ought to be very strong given successful demonstrations of back up UPS power systems in commercial settings (e.g. UPS Systems plc, Ceres Power, and Ceramic Fuel Cells Ltd) and the testing of micro-CHP units for domestic use (e.g. Intelligent Energy and Ceramic Fuel Cells Ltd). The benefits in terms of job creation were recognised (Interviewee

UKLOB1, UK Hydrogen Fuel Cell Association - 2011), for example. So was the cumulative contribution of such niche applications towards significant carbon reduction, as the interviewee from the Technology Strategy Board said:

> “People talk about the hydrogen economy … but I don’t think that’s helpful … It needs to be about individual applications … You would never start from scratch and build an economy … if we talk about those applications and the niche … we [must] develop this coherent platform for capability and providing hydrogen logistics, storage, generation, then you might end up in fifty years’ time with a hydrogen economy.” (Interviewee UKFIN4 – TSB, 2011)

The fact that uptake of stationary fuel cells in the UK in 2012 was not as high proportionally as in Germany is explored further in Chapter 6.

4.3.9 Policy Context/Summary - UK HFC TIS in 2012

Overall, the interviewee from the EPSRC summed up their view of the UK HFC TIS in 2011:

> “UK researchers … [are] as capable as the rest of the planet. [But] somebody somewhere has to take the policy decisions as to where as a nation we’re going to go ... You need to have a look at the impact on Government revenue ... Once you can make that case and you can show that actually it will pay to go down this route, then you’ll find that people in Government will start to relax a little bit.” (Interviewee UKFIN5, EPSRC – 2011)

A Scottish academic HFC researcher agreed and suggested that state procurement would be the best way to reduce unit costs:

> “We need leadership from local authorities and Government encouraging people to adopt the technology ... These large customer bases, people with fleets and significant amounts of money to invest ... [should] use …group purchasing power to bring down the costs of these things and… get the stuff going ... The technology is there, it works, we know it works ... But we need numbers. It comes back to leadership, and ultimately that leadership has to be political.” (Interviewee UKSCO5, University of St. Andrews – 2011)

In this context, the Interviewee on the Energy and Climate Change (ECC) Committee said:

> "I don't think we've got a clear policy on hydrogen at all ... There isn't that much interest … in hydrogen issues in DECC and I think that just reflects the sort of personal interests of some of the senior civil servants [notably DECC's former Chief Scientist, the late Sir David Mackay] ... The Treasury ... are taking a closer and closer interest in the sort of incentives that DECC can offer ... there's a slightly more interventionist approach at the EU level … You could have a slightly more strategic approach." (Interviewee UKPOL2, ECC – 2011)

However, one of the interviewees at the Carbon Trust was starkest in their forecast:

> "The UK will definitely lose in the global race to develop fuel cell technologies … We're actually very good at [it] … You won't see the impact … under the current Government. It will be felt a lot later and we'll lose out, like the UK lost out on lithium ion technologies, like the UK lost out on onshore wind technologies, where it had a lead and it lost it because the right investment wasn't provided to the right people at the right time." (Interviewee UKFIN1, Carbon Trust – 2011)

This view tallies with data showing that the UK featured relatively low on the list (10th) of countries submitting HFC papers and patents given all its advantages in the sector (cf. Huang and Yang, 2013). The UK's energy, environmental and industrial policies became progressively more numerous and coordinated in Period 2 (as shown by comparing the content of Table 10 for Period 1 with the content of Tables 14 to 17 for Period 2) (cf. Baker and Eckerberg, 2008). This policy shift has meant on one level that the institutional selection environment for HFC RD&D, with its moves towards sustainable development, was more favourable in Period 2 than in Period 1. The technical challenges first identified in the 1950s and 1960s, were considered to have been largely solved by 2012 although, as ever, further cost reductions in components were needed to help ease the market entries of all applications. State RD&D support and procurement were sought in all three sectors and, in transport, PPPs have been prominent in refueling infrastructure provision. Defence applications appeared to be at a commercial or pre-commercial stage, while transport and stationary power – as much as HFC products are likely to be manufactured in the UK – were at a pre-commercial stage. There was distinct policy learning with PPPs in Period 2 because of i) finance/hype lessons from ZeTek's demise which I described in Text Box 12, and

ii) the global blowout in HFC hype which impacted the UK HFC TIS from around 2004-5. Subsequently, thanks to the activity of several UK-based PPPs, applications in all three sectors moved closer to market preparedness by 2012. Ultimately, the UK HFC defence and aerospace sector appeared in 2012 to be closest to manufacturing mass-produced commercial products with the transport and stationary power sectors likely to do so later in the 2010. Despite all this, in Chapter 6, I examine why relatively similar circumstances have shaped the different outcomes seen between the UK and Germany.

To conclude this case study examination of the evolution of the UK HFC TIS, I present my warranted assertions in the next section. These assertions draw on a triangulation of data in three datasets covering the UK: the coded data from the TSIS indicators, the coded data from my own extended indicators and the interview material.

4.4 Findings / Assertions – Evolution of the UK HFC TIS

In this final section, I give my findings, or warranted assertions, about the UK case study in the context of Activity 2 (cf. Smith, 1997). I divide my assertions firstly into what was revealed about the UK HFC TIS via the TSIS indicators of Hekkert et al. (2007a) and secondly by my extended indicators. The TSIS approach helped me to give a longitudinal picture of structural, functional and technological co-evolutionary change in the UK HFC TIS. From this perspective, institutional governance of the TIS was largely shaped by regime-level legislative responses – whether supranational, national and/or regional - to external, landscape-level events (cf. Geels, 2010). From 1954, UK public and private actors in two distinct periods of activity organized themselves into increasingly powerful and sophisticated private JVs and PPPs (cf. Soecipto et al., 2015). Such projects in Period 1 were generally not resilient while some in Period 2 appeared more so. These actors were largely motivated to reduce the inherent financial risks of HFC RD&D. UK HFC research was shown to be world-class in both periods. What was less evident from the TSIS approach was: i) the ways that the emerging HFC technological pathways in each of three sectors of interest were contested in both periods (i.e. subject to power relations) (cf. Avelino and Rotmans, 2009), and ii) the relative importance of the spatial context of TIS events in terms of causality (Coenen et al., 2012, Binz et al., 2014).

4.4.1 TSIS Indicators

In terms of what the TSIS indicators revealed, an emergent division in the rate and number of TIS events around 1995 suggests the beginnings of a system-wide transition towards more sustained positive feedback (Hekkert et al., 2007a, Suurs and Hekkert, 2012). Rises and falls in functional activity were revealed by the motors of sustainable change approach to be dominated by knowledge development in both periods. The resulting hype cycles (C and D) – linked directly and/or indirectly to global oil, environmental, and political crises as well as financial speculation - exhibited greater resilience in Period 2 as compared to Period 1 (cf. Walker et al., 2004, Fiksel, 2006). In Period 1, the TSIS results reveal that resilience of UK HFC TIS activity was relatively poor. UK scientists and engineers, led by Bacon, started making significant progress in overcoming a number of technical barriers associated with HFCs. In spite of specific barriers to innovation and diffusion, chiefly in guidance of the search, resource mobilization and advocacy coalition areas, these actors entered into corporate JVs and early PPPs (involving public leverage, contracting-out and JVs). In an institutional environment dominated by the significant amounts of state funding for nuclear RD&D and prestige engineering projects like Concorde, HFC actors did manage some very limited HFC market activity. But plans to diversify (and further diffuse) HFC technologies were typically halted by institutional resource cuts following on from major external events.

Early HFC prospects worsened from 1974, for example, with the UK's first formal energy policy based on CoCoNuke. This policy 'lock out' between 1974 and 1997, helped to delegitimize HFCs and made acquiring resources, especially public funds, difficult for actors (Unruh, 2000). In Period 2, by contrast, the resilience of UK HFC RD&D actors was shown by the TSIS approach to be greater as actors continued to try to reduce financial uncertainties, boost the recombination of knowledge and organize the coordination of RD&D and planned manufacturing between each other and with the pro-active support of the state. Positive feedback appeared to be occurring, particularly from 2002 onwards (Figures 21 to 23), as both public and private activity increased (cf. Hekkert et al., 2007a, Suurs and Hekkert, 2012). By 2012, the UK's HFC TIS functions appeared particularly well varied with tallies in every category except advocacy coalitions (F7).

Sectoral analysis showed that, in Period 1, transport activity had an initial lead with the development of Shell's and Bacon's HFC vehicles. However, the HFC transport actors in Period 1 did not build on their historic comparative advantages in Period 2. Transport sector activity ended after the end of hype cycle A (i.e. post-1983) for economic, technical and political reasons: unit costs were too high, there was no dominant design, there was policy lock out and the motor vehicle industry had become significantly weakened compared to two decades earlier. HFC transport innovative activity around the historic core of Birmingham ended in the early 1980s (but would restart in Period 2 via PPPs linked to local firms and universities). Nevertheless, the rise in knowledge development post-2002 was stronger in the transport sector than in defence and aerospace (and stationary power) and there were many new entrants. A new period of hype – D - was building from 2007 onwards giving further longitudinal evidence of the uneven timing of socio-technical processes (chiefly cumulative causation) in the UK HFC TIS.

4.4.2 Extended Indicators

The extended indicators enriched the picture of HFC innovation and diffusion by going beyond the TSIS's neofunctional approach to increase the emphasis in analysis on 1) organizational forms, specifically PPPs because of their ability to increase the agency of networked actors (Hodge and Greve, 2005, Roehrich et al., 2014), and on 2) notions of space and place with the TSIS heuristic because of the use of consolidated *spatio-temporal* data (cf. Louis, 1982, Onwuegbuzie and Teddlie, 2003) to improve understandings of causation (Coenen and Díaz López, 2010, Coenen and Truffer, 2012).

Firstly, in terms of the institutional ownership of events, these extended indicators revealed that the UK has deployed a number of HFC PPPs ranging from public leverage to strategic partnering. Early UK public leverage PPP efforts with Energy Conversion Ltd failed in large part due to the civil service's lack of coordination and poor commercial orientation. There was no agreed roadmap, no political champion and so private partner confidence eventually fell away. Resilience in this period was achieved via the contracting-out PPP success in defence with CJBD and the Royal Navy. The policy lock out between 1974 and 1998 revealed relatively weak networked agency and few prospects for innovation and diffusion (cf. Unruh, 2000). However, in Period 2, the UK witnessed an evolution in the PPP typology, shown in Table 4 in Chapter 2, from public leverage and contracting-out towards strategic partnering. Hypes A, C and D coincided with the periods of greatest increases in the UK HFC TIS event narrative's tallies (i.e. this was when networked agency was strongest). Sectorally, CJBD and Vickers, working in defence, were part of the UK's 1st PPPs with submarine electrolysers, but CJBD's diffusion of HFC technology with a contract in the 1960s for water treatment and Vickers' JV PPP development of AIP propulsion in the 1980s/90s both ended because of changed external political and economic circumstances. Arguably, greater resilience for these activities might have been witnessed if successive UK governments had pursued a long-term industrial policy (cf. Rodrik, 2007). Certainly, the degree of state procurement linked to defence contracting-out PPPs in Period 2 suggests a clear recognition by the Ministry of Defence of the need to protect these HFC niches through the ‘Valley of Death’ and into the marketplace. In other areas of state involvement, the extended indicator data on organizational funding in the transport sector revealed that, in Period 2, the emergence of the UK HFC Mobility PPP in 2012 came only once the UK car industry had been supported and revitalized in the 1990s. Similarly, in the stationary power sector in Period 2, PPPs were used to help identify dominant HFC CHP designs (cf. Hekkert and den Hoed, 2004). Overall, in a largely liberalised marketplace in the UK, there was nevertheless strong evidence of state-led path creation with HFCs (cf. Morgan, 2013).

Secondly, my other extended indicator covering geographical location permitted data consolidation to occur within my neopragmatic methodological framework (cf. Louis, 1982, Onwuegbuzie and Teddlie, 2003). I merged the time-dependent and spatial data to create an expanded dataset which reveals a very uneven *spatio-temporal* picture of innovation and diffusion by region between 1954 and 2012. This aspect of the evolution of the HFC TIS was linked in part to uneven structures of spatial governance – i.e. relative levels of devolution - and a ‘varieties of capitalism’ assessment of the UK as a liberal market economy (cf. Hall and Soskice, 2001).

In Period 1, HFC actors were operating chiefly in the South East, the East, Greater London and the North West regions. The particular sites were where there was long-standing access to academic/industrial research centres and/or a workforce with specific engineering and research skills. New entrant regions emerged after 2002, but these grew more slowly than the leading established region, the South East. Outside of steady growth in the South East, HFC innovation rates slowed in some other leading regions (e.g. the North West and Greater London). Elsewhere, regional activity grew steadily for the first time (e.g. in the East and West Midlands, Yorkshire and Humberside, and Scotland). Regional growth differentials in entrepreneurial activity (F1) and knowledge development (F2) were shown to at least weakly correlate with the regional use of strategic partnering PPPs. This relative pattern of diffusion suggests that the large HFC actors active in Period 1 were likely building on their historic competitive advantage (but finding the precise socio-technical processes for this from aggregate data is not possible). The longitudinal evidence of regional shifts in knowledge development, where early innovation leads to later diffusion, is at least suggestive of a degree of path dependency based on historic competition for access to resources (cf. Grabher, 1993). To more fully warrant such an assertion would require further investigations at the micro level which is beyond the scope of this thesis: Activities 2 and 4 specifically refer to the use of Innovation Studies approaches, specifically evaluating the use of the TSIS heuristic with HFCs.

Ultimately, the spatial indicators suggest that the cumulative causation that is in evidence is occurring unevenly in time *and* space. However, while the first new batch of regional movers in Period 2 (i.e. Wales and the North East from 2001) have valuable hydrogen infrastructure (chiefly pipelines) and the presence of automotive manufacturers and suppliers, they appeared to underperform in relative terms up to 2012 as ‘hoped for’ HFC clusters (cf. Mans et al., 2008). Instead, the West and East Midlands regions fared better thanks to global and local academic-industry links. Such linkage was shown to be both geographical *and* relational – i.e. ‘global-local’ or ‘glocal’ - and underpins the institutional embeddedness of clustering activity within these regions (cf. Braczyk et al., 1998, Heidenreich, 2004, Heidenreich, 2012a). The ‘extended indicators’ help to achieve a better understanding of the nature of innovation because they reveal that individuals and actors networked in teams and located in space are having an impact upon temporal conceptions of causation. This analysis is redolent of the realist approach known as methodological situationism which suggests that social systems are created in local areas and actor behaviour is shaped by a response to immediate situations (Duncan, 1989, Day and Murdoch, 1993, Massey, 1993, Massey and Jess, 1995, Murdoch and Marsden, 1995). Proponents claim that, contrary to neofunctionalism, for example, locality is not the result of general structural processes, but rather the outcome of networked associations in actor-space, a point I return to in Chapter 7. This point underpins the critique of neofunctionalist innovation models made by Coenen et al. (2012) and to which I return to in the methodological discussion in Chapter 7.

4.5 Conclusion

To conclude this chapter, I note that I have completed one half of Activity 2. This involved describing *how*, *when* and *where* innovation and diffusion activity occurred in the UK HFC TIS between the 1954 and 2012. I offered warranted assertions about the emergent trends in the UK HFC TIS based upon the triangulation of all data sources. Constructing this national HFC TIS events narrative has also allowed me to reveal how, methodologically, the TSIS indicators and my extended indicators have performed in terms of offering insights into the nature of socio-technical change with HFCs in the UK. My warranted assertions about the UK HFC TIS now feed into a comparative analysis of both case studies in Chapter 6 where I compare what the TSIS functional analysis and my extended indicators have revealed about HFC socio-technical processes in both countries. Based on the warranted assertions given here and at the end of Chapter 5, I can now highlight which socio-technical processes appeared most important to the evolution of these two HFC TISs in the comparative analysis in Chapter 6. This chapter's warranted assertions also feed into Chapter 7's methodological and policy discussions.

Before that analysis is undertaken, I turn to the evolution of Germany's HFC TIS in the next chapter in order to complete Activity 2.

Chapter 5: Evolution of the German Hydrogen Fuel Cell (HFC) TIS

5.0 Introduction

In this chapter, I present results for the German HFC TIS in order to achieve Activity 2 which involves: “characterising HFC innovative activity in the UK and Germany between the 1950s and 2012 via two case studies that draw on qualitative and quantitative data and are informed by innovation theory” and describing “events and processes in terms of *how*, *when* and *where*” (Text Box 4 in Chapter 1). I do this after using a neopragmatic research design informed by the TSIS approach and employing my four methodological modifications from Chapter 3.

In Chapter 1, I stated that attempts in the last two decades to mitigate and/or adapt to climate change have involved decarbonising the energy use of individual nations. In this context, hydrogen fuel cells (HFCs) are a disruptive technology with the potential to help policy makers decarbonize national, regional and local energy systems (Hardman et al., 2013). Some researchers have suggested that HFC innovation and diffusion can happen anywhere, but others disagree. The reasons why HFC innovative activity ‘takes off’ in one country (or one region or locality) but not in another, are not fully understood (cf. Tanner, 2014, Tanner, 2016). This and other knowledge gaps should matter to policymakers who have limited budgets and cannot afford to target funds at the wrong time and in the wrong places. To remedy this situation, I highlighted the specific knowledge gaps in the literature about the nature of HFC innovation and diffusion in Chapter 2. I then identified four areas of methodological concern associated with the Technologically-specific Innovation Systems (TSIS) heuristic (cf. Hekkert et al., 2007a). In Chapter 3, I proposed a neopragmatic research design that is informed by the TSIS approach. I then advanced four methodological modifications to the TSIS heuristic to help overcome the concerns that I found. These modifications include two additional indicators for use with the Technological Innovation Systems (TIS) approach: coding for organizational funding and geographical location. I also interview a broader number of actors linked to known HFC networks and offer project-level text boxes at technological branching points in the national HFC TIS event narratives. The latter illustrates the nature of more finely-grained analysis that the TSIS heuristic, with its neofunctional approach, lacks (Coenen and Díaz López, 2010, Coenen et al., 2012). Chapter 3’s assessment of methodology and methods therefore adds confidence to my analysis of the socio-technical processes at work with HFCs.

In this chapter, the methodological modifications I have made to the TSIS approach give me greater levels of confidence in my warranted assertions I make by the end. These assertions feed into analysis and discussion in Chapters 6 and 7.[56] In the sections below, I produce a sectoral narrative timeline of HFC innovation and diffusion events in the German HFC TIS between 1959 and 2012. Enablers and barriers to HFC innovation are identified along with other insights into the dynamic co-evolution of HFC technologies in the German HFC TIS. 1959 was chosen as a starting date for the German HFC TIS narrative because researchers at the engineering company Siemens and the battery manufacturer Varta began working together that year in a private joint venture (JV) to develop 1st generation alkaline fuel cells (AFCs). Their innovations subsequently became influential in all sectors. December 2012 was selected as the end date for the timeline because that was when primary source data gathering for the EPSRC DoSH study ended in both countries. Insights from Germany, along with those from the UK HFC TIS event narrative from Chapter 5, are then fed into Chapter 6's comparative country and regional analysis and Chapter 7's methodological and policy discussions.

In terms of the structure of this chapter, I give a brief overview of the distinction between the methodologies employed with the TSIS approach and my extended indicators in Section 5.1. In Sections 5.2 and 5.3, I triangulate all of my data into two detailed TIS narratives covering two emergent periods (i.e. data- rather than theory-driven):

3) 1959 to 1994 – Gradual Technological Development, and
4) 1995 to 2012 – Commercial Orientation.

These two time periods are divided where a significant upswing in HFC TIS events in both countries begins to occur (which is mirrored in rising event numbers globally). Both periods cover HFC activity in three industrial sectors which have exhibited the greatest number of TIS events in the dataset:

d) Defence and Aerospace,
e) Transport,
f) Stationary Power.

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[56] Additional analysis was made because the DoSH study suggested that TIS event funding and territory were likely influencing the socio-technical processes at work.

In section 5.4, I give my warranted assertions about the German case study based on all of the data presented in this chapter. Section 5.5 concludes the chapter.

5.1 Overview of the German HFC TIS Narrative - 1959-2012

As outlined in Chapter 3, I assembled the German HFC TIS event narrative via the compilation of 1,791 secondary source events (cf. Hekkert et al., 2007a). Events were defined in Section 3.3.1.1 as "instances when changes occur in the innovation ideas, people, transactions, contexts or outcomes while an innovation develops over time [and change] is an empirical observation of differences in time on one or more dimensions of an entity" (Van de Ven et al., 2000, 32). The TIS events narratives for Periods 1 and 2 cover a long time span. The justification for this approach is two-fold: firstly, technological transitions typically take a very long time to occur (Geels, 2002, Geels, 2004), and, secondly, certain social processes like cumulative causation and path dependence are suspected to be at work and it is not possible to be confident which events (and when and where they occurred) will be significant later on (Event History Analysis suggests one should not privilege 'key' events from a *post-hoc* position).

The next two sections recap the event coding and describe the use of text boxes with the narrative.

5.1.1 Event Coding of the German HFC TIS Narrative

Each event was coded in terms of whether the HFC activity made a positive or negative contribution to innovation and diffusion.[57] Events were also coded for the seven TSIS functions based on my modified coding frame (shown in Table 8):

Function 1: Entrepreneurial activities
Function 2: Knowledge development
Function 3: Knowledge diffusion
Function 4: Guidance of the search
Function 5: Market formation
Function 6: Resource mobilisation
Function 7: Advocacy coalition

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[57] Note that several TIS events which get coded in terms of their negative influence on innovation and diffusion, and which occur at the same time, will push the TIS function tallies into minus numbers.

To further investigate whether HFC innovation and diffusion had been affected by patterns of TIS event ownership and territory, extra coding of the TIS events dataset was undertaken. As described in Chapter 3, this extra coding identified:

1) the type of funding for each event, i.e. ‘public only’, ‘private only’, ‘public and private (no partnership)’ and ‘public-private partnerships’ (PPPs),

2) the degree to which ‘private only’ activity involved JVs,

3) the PPP type - based on the typology in Table 4 in Chapter 2, and

4) the town/city and region where events took place.

Quantitative results for this extended TSIS approach are presented graphically in the TIS event narratives in Sections 5.2 and 5.3 below and in the Appendices.

5.1.2 Text Boxes in the German HFC TIS Events Narrative

In the TIS event narratives for Periods 1 and 2 in Germany – Sections 5.2 and 5.3 respectively - the co-evolution of HFC technologies is broken into the defence and aerospace, transport and stationary power sectors. As stated in Section 1.2 of Chapter 1, these sectors were chosen because they represent some of the most prominent early demonstration activity in Germany. Subsequently in the timelines, these sectors also became the most active areas of HFC innovation.

Where I put text boxes into the national TIS event narratives in both periods, my level of analysis is disaggregated from the normal meso- and macro-level approach of the TSIS heuristic to the project level (i.e. the micro level). Within these text boxes I draw on the source material to characterise more fully something of the contestations over HFC activity. At the micro-level, the text boxes typically reveal how actors and individuals sought to access resources that are embedded in particular places. These contestations, and those within and between teams over technological choices, reveal themselves to be more clearly subject to the influence of power relations and expectations (Avelino and Rotmans, 2009, Bakker et al., 2011, Alkemade and Suurs, 2012). Ultimately, this project-level source material offers further insights into the socio-technical processes at work which might otherwise be missed when such data is aggregated using the TSIS approach’s modified Event History Analysis (EHA) methodology.

Finally, the TIS events in the narratives in both periods have their spatial context – both geographical and relational – and this is given greater emphasis than in TSIS studies.

The next section gives the TIS events narrative for Period 1 which runs from 1959 to 1994.

5.2 Period 1: 1959 to 1994 - Gradual Technological Development

In Germany, the period from 1959 to 1994 was characterised by increasingly coordinated policymaking regarding energy, industry and the environment. At times, this evolving multi-level governance was led by some of Germany's Länder (see Table 18 and Table 19) (cf. Poguntke, 2001, Börzel, 2003, Kern, 2008). Also, in 1959, the US space agency NASA committed itself to using AFCs and PEMFCs in its manned space programmes. After each oil and environmental crisis in Period 1, public and private expectations in Germany were high for the governance of change. This was due in part to Germany's status as a coordinated market economy or CME. The federal government was expected to act (cf. Hall and Soskice, 2001). After 1973, Germany adhered to supranational environmental governance from the EEC's Environmental Action Plans (EAPs) and ever more integrated principles and/or strategies from the United Nations, e.g. the Brundtland Report (Brundtland et al., 1987) and the UN Conference on Environment and Development (UNCED, 1992) (see Table 12 in Chapter 4 for outline impacts of these supranational instruments). Another aspect of environmental governance unique to Germany in this period was the rise to political office of the Green Party, Die Grünen, in a number of Länder including the election of Joschka Fischer as Minister of the Environment in the Hesse Land in 1985 (Poguntke, 2001).

The technical challenges in Period 1 included: raising the power output of HFCs, extending their working life, offering energy storage options, improving their efficiency, offering safe operation and reducing unit costs (van den Broeck, 1993, cf. Strasser, 2010, Behling, 2012). The first applications in the defence and aerospace, transport and stationary power sectors were submarines, road vehicles, and off-grid power supplies for remote areas, respectively. Over time, demonstrations were indicating that PEMFCs were more likely reliable and more flexible than AFCs. Leading drivers of HFC knowledge development activity (F2) in these sectors were Germany's Cold War defence requirements, the country's internal and external energy and environmental concerns, and the shared expectations of private actors for future financial returns on their investment in HFC RD&D.

Table 18: Period 1 (1959-1994) – Land-led Policy Measures Affecting HFC Innovation and Diffusion in Germany

Legislative Act / Policy Instrument	Aim	Impact Summary on HFC TIS
Air Pollution Control, Noise and Vibration Abatement Act (NRW) (1962)	Protect neighbourhoods and the general public from dangers or nuisances caused by air pollution in North Rhine-Westphalia.	This Act, which arose because of smog levels in West German cities, also gave a legal basis for systematic air pollution monitoring. Although not rigorously enforced, the Act gave a signal to the transport and stationary power sectors that further regulation was coming and that innovation would be necessary.
Air Pollution Control, Noise and Vibration Abatement Act (BW) (1962)	Protect neighbourhoods and the general public from dangers or nuisances caused by air pollution in Baden-Württemburg.	(as above)
Air Pollution Control, Noise and Vibration Abatement Act (LOS) (1966)	Protect neighbourhoods and the general public from dangers or nuisances caused by air pollution in Lower Saxony.	(as above)
Air Pollution Control, Noise and Vibration Abatement Act (BAV) (1966)	Protect neighbourhoods and the general public from dangers or nuisances caused by air pollution in Bavaria.	(as above)

Table 19: Period 1 (1959-1994) - National Policy Measures Affecting HFC Innovation and Diffusion in Germany

Legislative Act / Policy Instrument	Aim	Impact Summary on HFC TIS
Road Traffic Registration Law (1971)	To limit pollutants (carbon monoxide, hydrocarbons, nitrogen oxides, lead and odorous substances) in the exhaust of spark-ignition engine motor vehicles to one tenth of the average 1969 figures by 1980.	Amongst a range of responses in the West German automobile sector, this legislation prompted Daimler-Benz to completely reorganize its RD&D operation and to focus more of its efforts on reducing emissions (including developing HFC vehicles).
Constitutional Amendment (1972)	To empower the federal parliament to enact general air pollution control legislation.	West German motor vehicle manufacturers anticipated further domestic emissions regulations in the future.
Conference of Environmental Ministers (UMK) (1973-)	To facilitate the harmonized implementation of federal laws.	This coordinating body between the Länder and the federal government meets twice a year to improve national and regional environmental policy integration. This body led to greater coordination of emissions regulations.
Air Pollution Law (1974)	To restrict air pollution, noise, vibrations and similar processes.	The *Bundes-Immissionsschutzgesetz* was formed in response to Länder-level activity. It encouraged vehicle manufacturers to restrict pollution.
Electricity Feed-In Act (StrEG) (1991)	To encourage the sale of electricity back to the national grid from hydropower, wind power, solar power, landfill gas, sewage gas, or biomass.	The *Stromeinspeisungsgesetz* (StrEG) was the first instrument to encourage the rise of decentralised energy production from renewable in Germany. This has since encouraged the further development of renewable energy storage options of which a regenerative fuel cell (RFC) system with its HFC and electrolyser is one.

The leading actors in Period 1 were large, multinational firms led by BASF, Bosch, Daimler-Benz, Howaldtswerke-Deutsche Werft (HDW), Linde, Siemens, Varta and Volkswagen. These firms were based in major urban centres in Rhineland-Palatinate, Baden-Württemberg, Schleswig-Holstein, Bavaria, Hesse and Lower Saxony where highly skilled labour forces already existed and/or related university research was being undertaken. To tackle the significant technical challenges of HFC development, some of these private firms formed JVs to share expertise and spread the financial risk of RD&D. Others worked with the state to form PPPs which offered varying types of support: i) public leverage (of patent portfolios), ii) contracting-out (as seen in defence) and iii) public joint venture (JVs). Indirect state support for HFC RD&D began in Germany in response to the 1973 oil crisis. German federal funding for RD&D into alternative fuels and drivetrains began in 1975 via the *Bundesministerium für Forschung und Technologie* (the Federal Ministry of Research and Technology or BMFT). German university research bodies and corporate actors also sought legitimacy and funding for HFCs via early supranational academic partnerships with the EC (Buchner, 1981).[58] Creating legitimacy for HFC RD&D within the German federal government from the 1970s to the mid-1990s was difficult however, even after the oil crises of 1973 and 1979. As an HFC lobbyist from the *Deutscher Wasserstoff Verband* (German Hydrogen Association or DWV) said to me in interview in 2011:

> "For quite a while there was no federal [HFC] programme in Germany and ... and quite a number of people in the federal administration were indifferent or even hostile towards hydrogen and fuel cells." (Interviewee GLOB1, DWV - 2011)

German national legislation on renewable energy appeared in 1991 with the *Stromeinspeisungsgesetz* (Electricity Feed-In Act or StrEG) (Table 19). Because of the need for storage, this legislation began to spur HFC RD&D into decentralised storage options late in Period 1 (but most activity came in Period 2).

Throughout Period 1, there were low levels of TIS events. Figure 32 shows that these events were dominated by knowledge development (F2). This result suggests a 'technology push' approach to HFC innovation (cf. Nemet, 2009, Hacking, 2013) in which the *Science and Technology Push (STP) motor* was not functioning particularly well (see Figure 41).[59] In Period 1, there was very limited opportunity for cumulative causation beyond knowledge development. Exceptions to this includes two guidance

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[58] Formal data on energy RD&D spend does not include HFCs until 2003 (see Appendix AA).

[59] The TIS event history data coded by function is tabulated in Appendix Z.

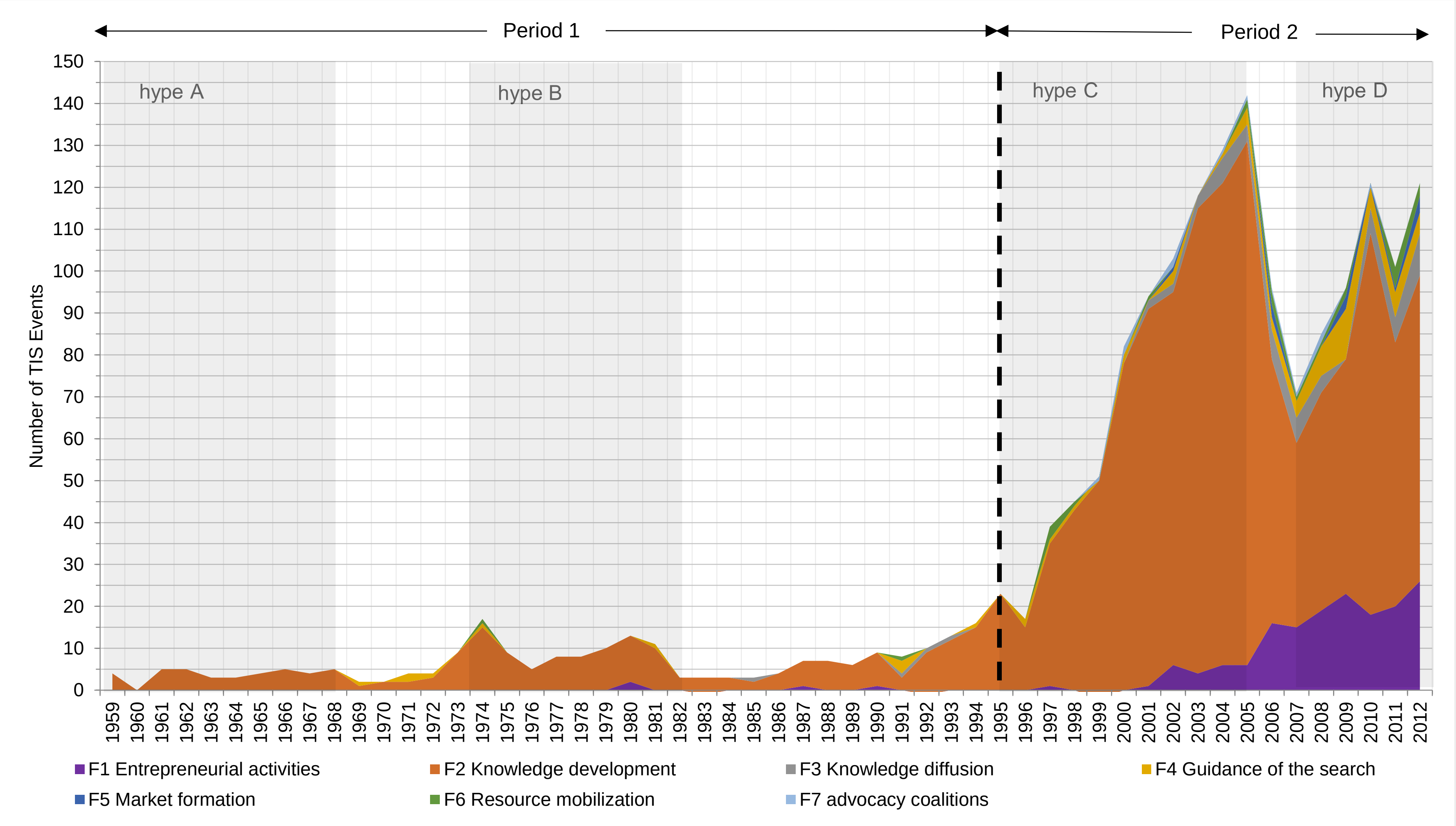

Figure 32: Germany - Annual Totals for HFC TIS Events by Function, 1959-2012

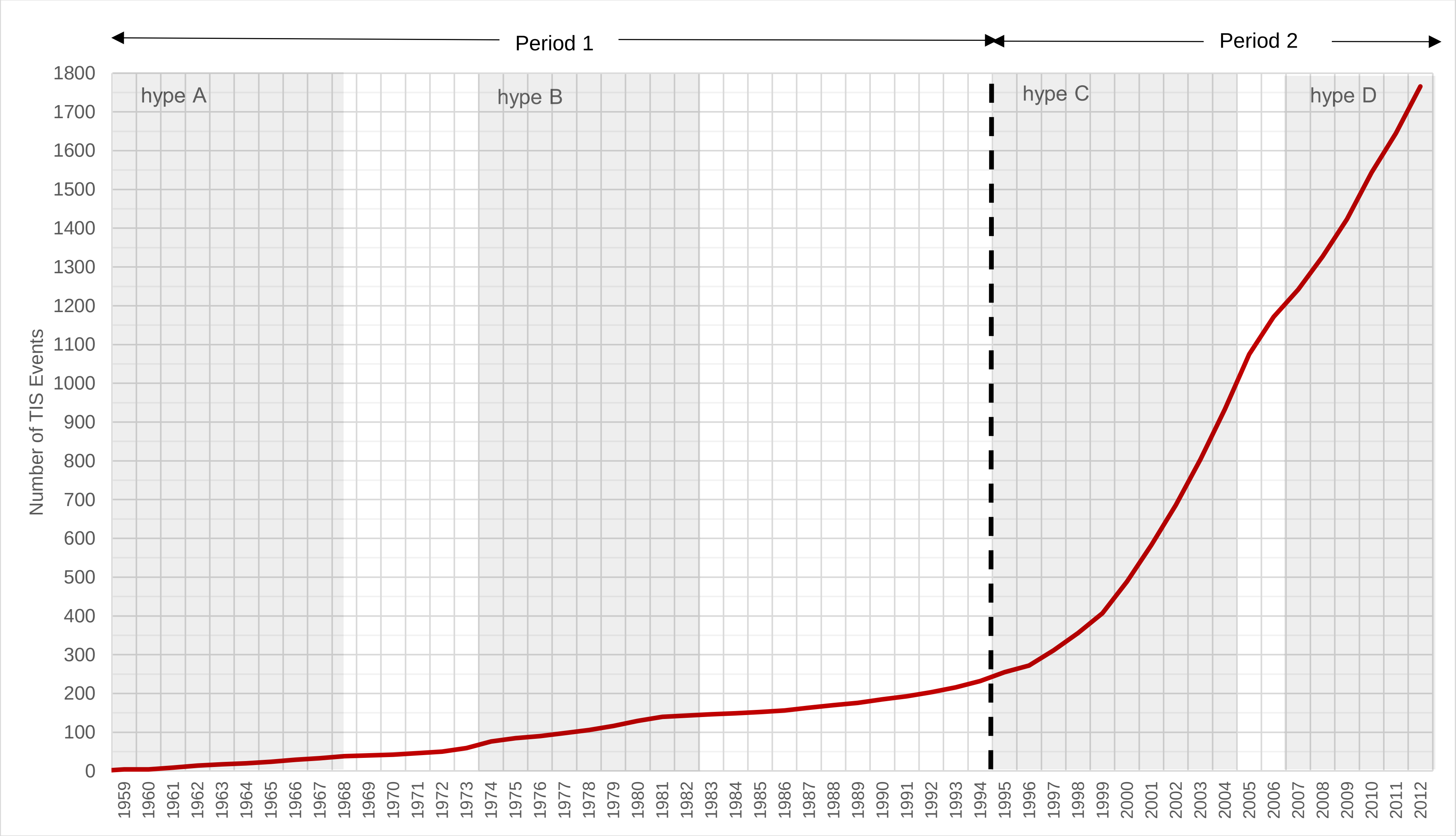

Figure 33: Cumulative Total of All Functional Activity in the German HFC TIS, 1959-2012

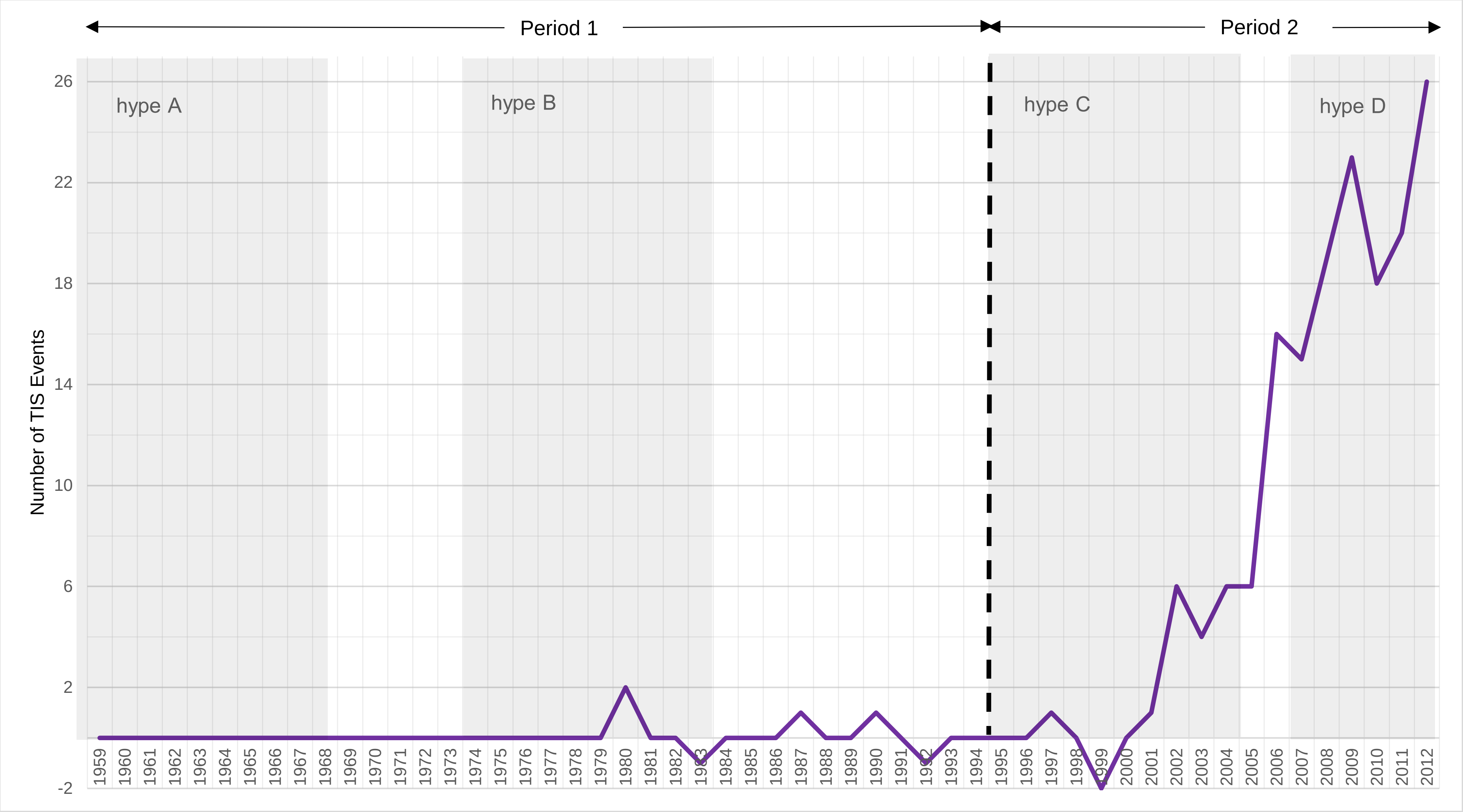

Figure 34: Entrepreneurial Activity (F1) in the German HFC TIS, 1959-2012

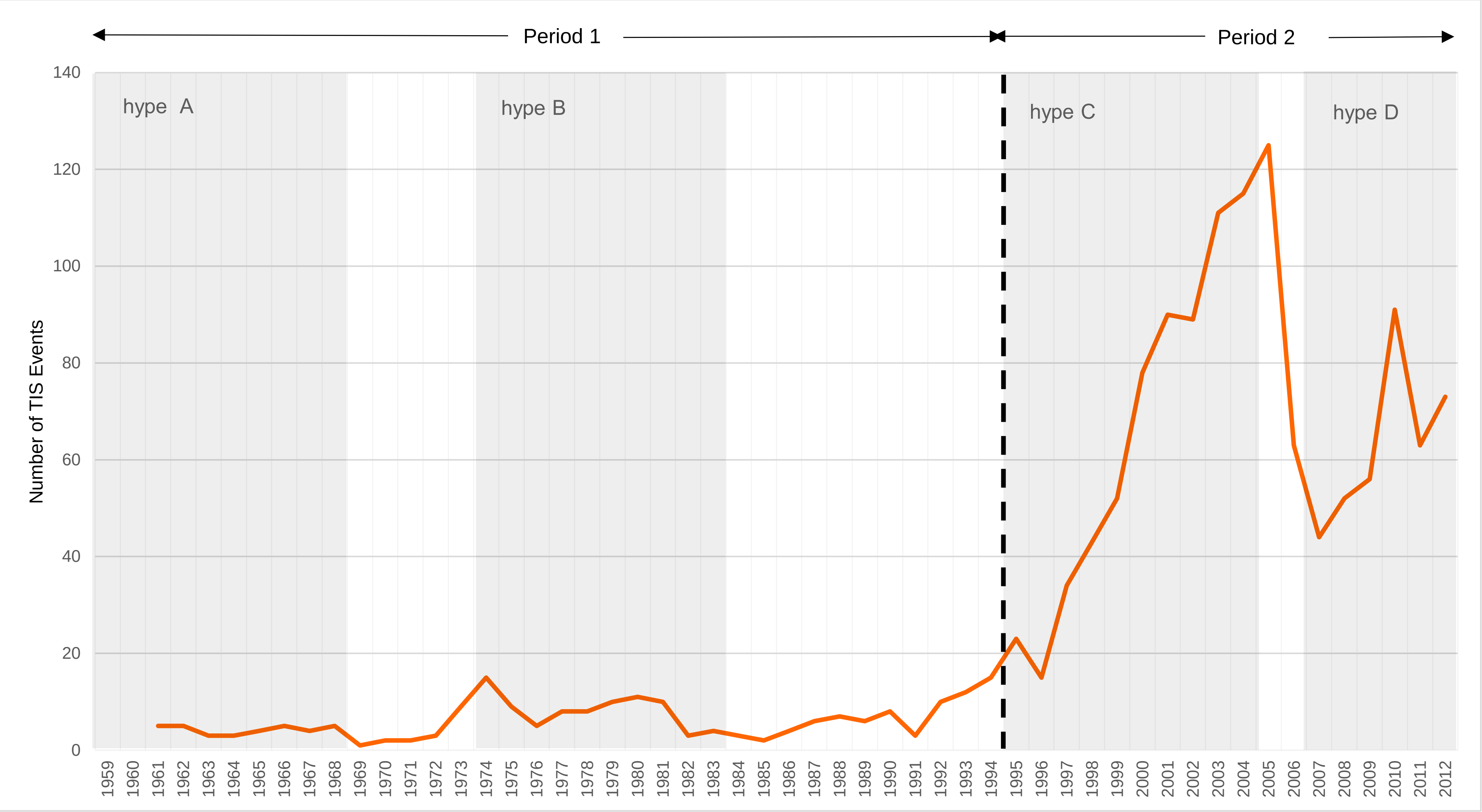

Figure 35: Knowledge Development (F2) in the German HFC TIS, 1959-2012

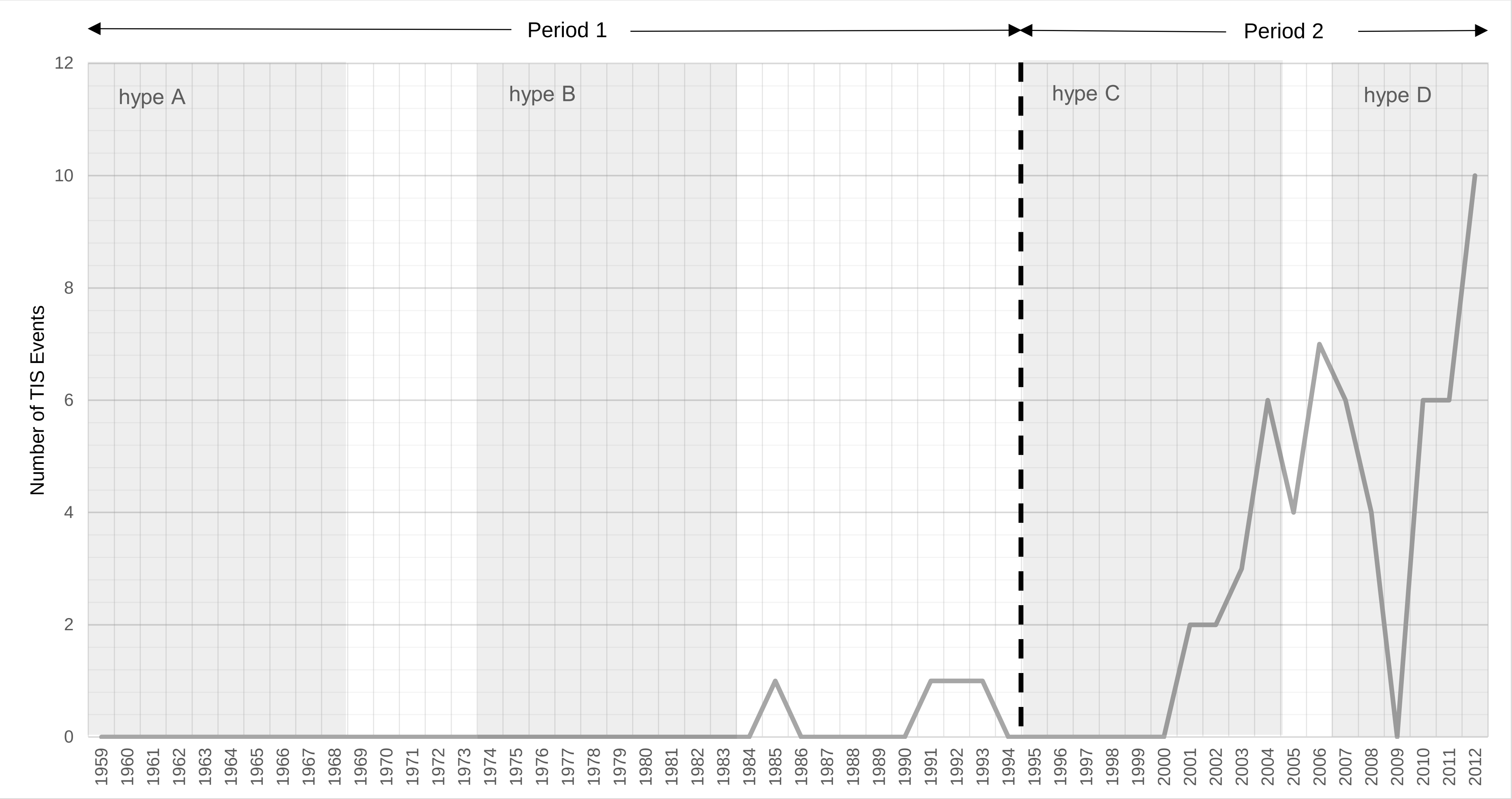

Figure 36: Knowledge Diffusion (F3) in the German HFC TIS, 1959-2012

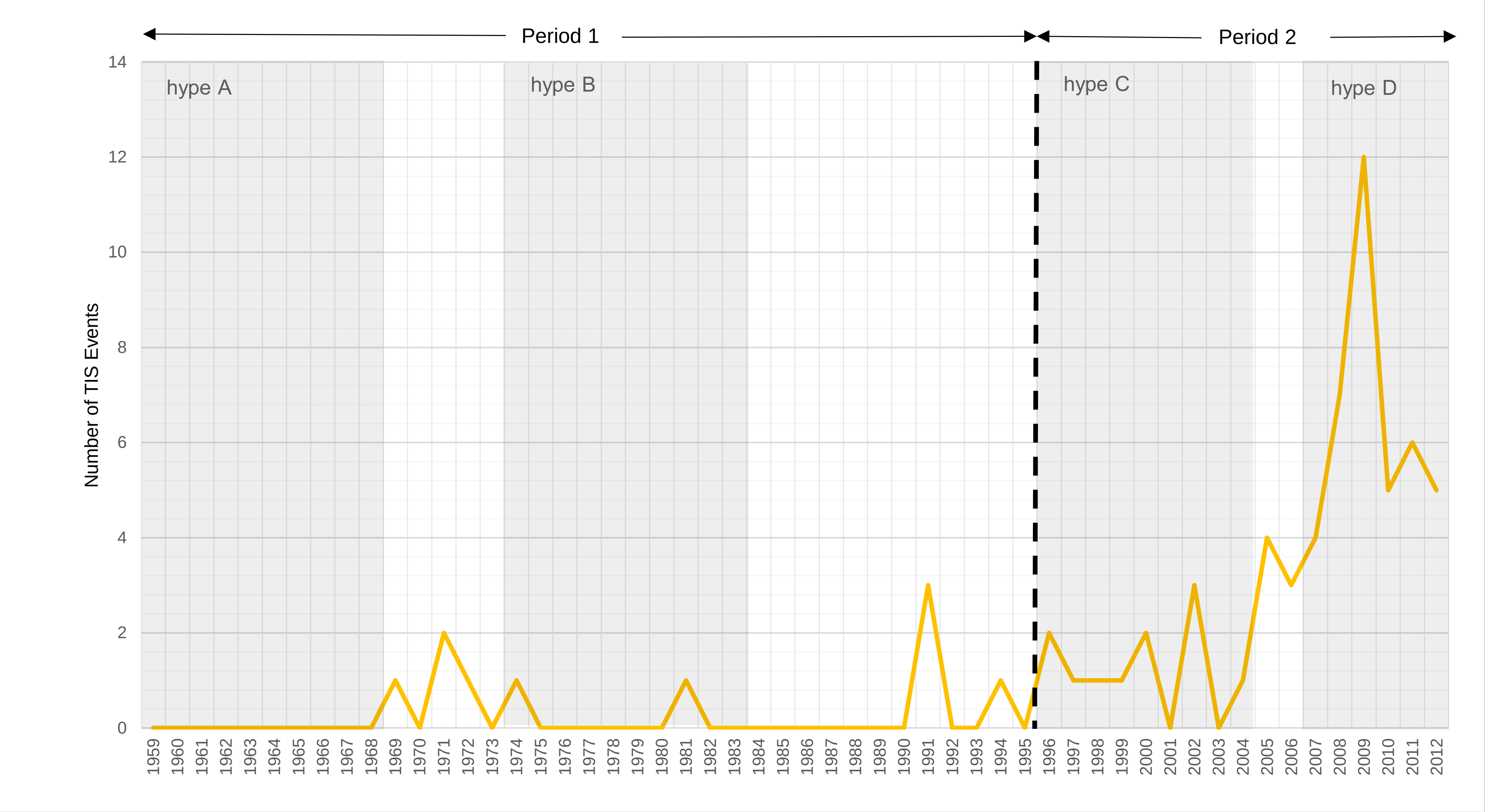

Figure 37: Guidance of the Search (F4) in the German HFC TIS, 1959-2012

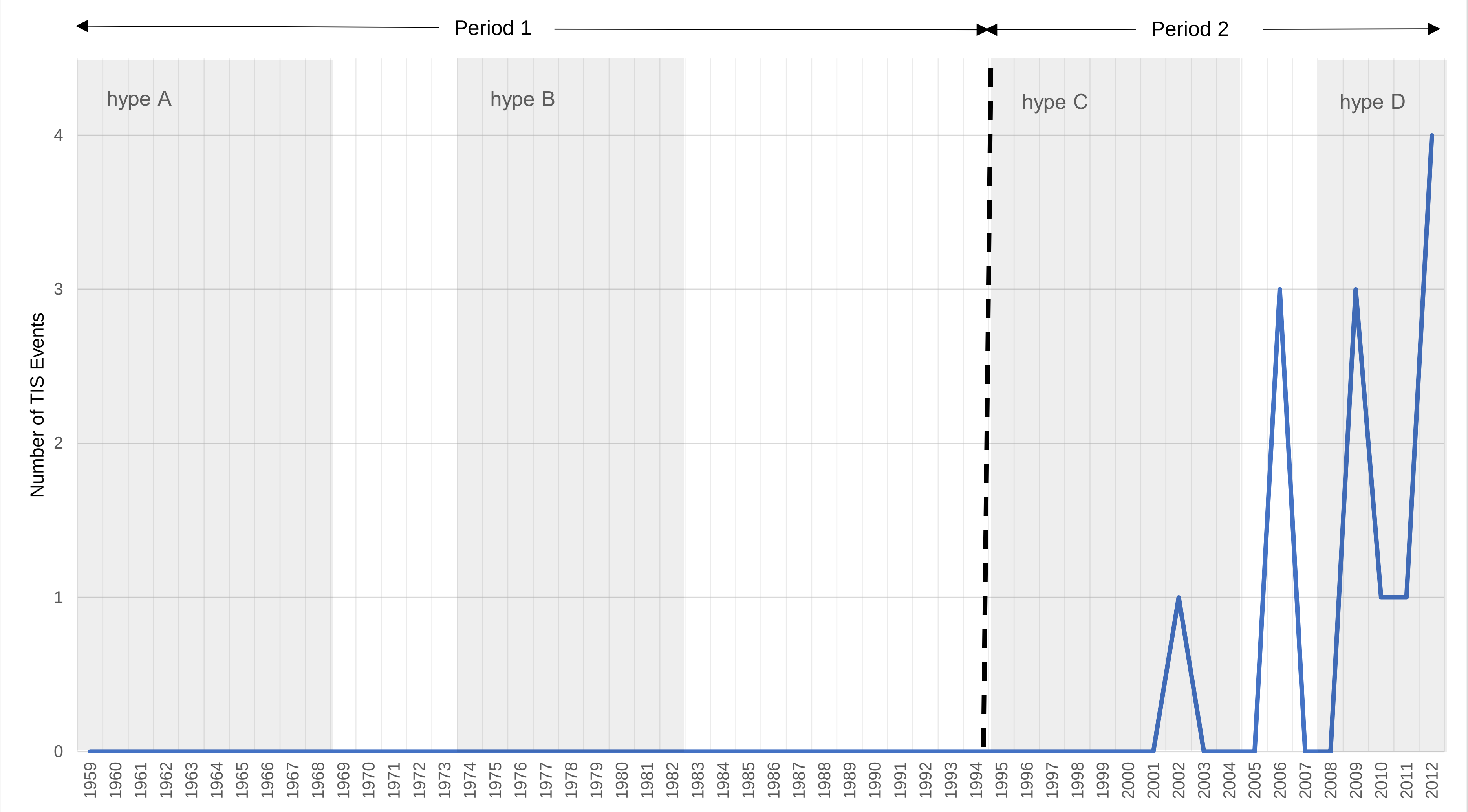

Figure 38: Market Formation (F5) in the German HFC TIS, 1959-2012

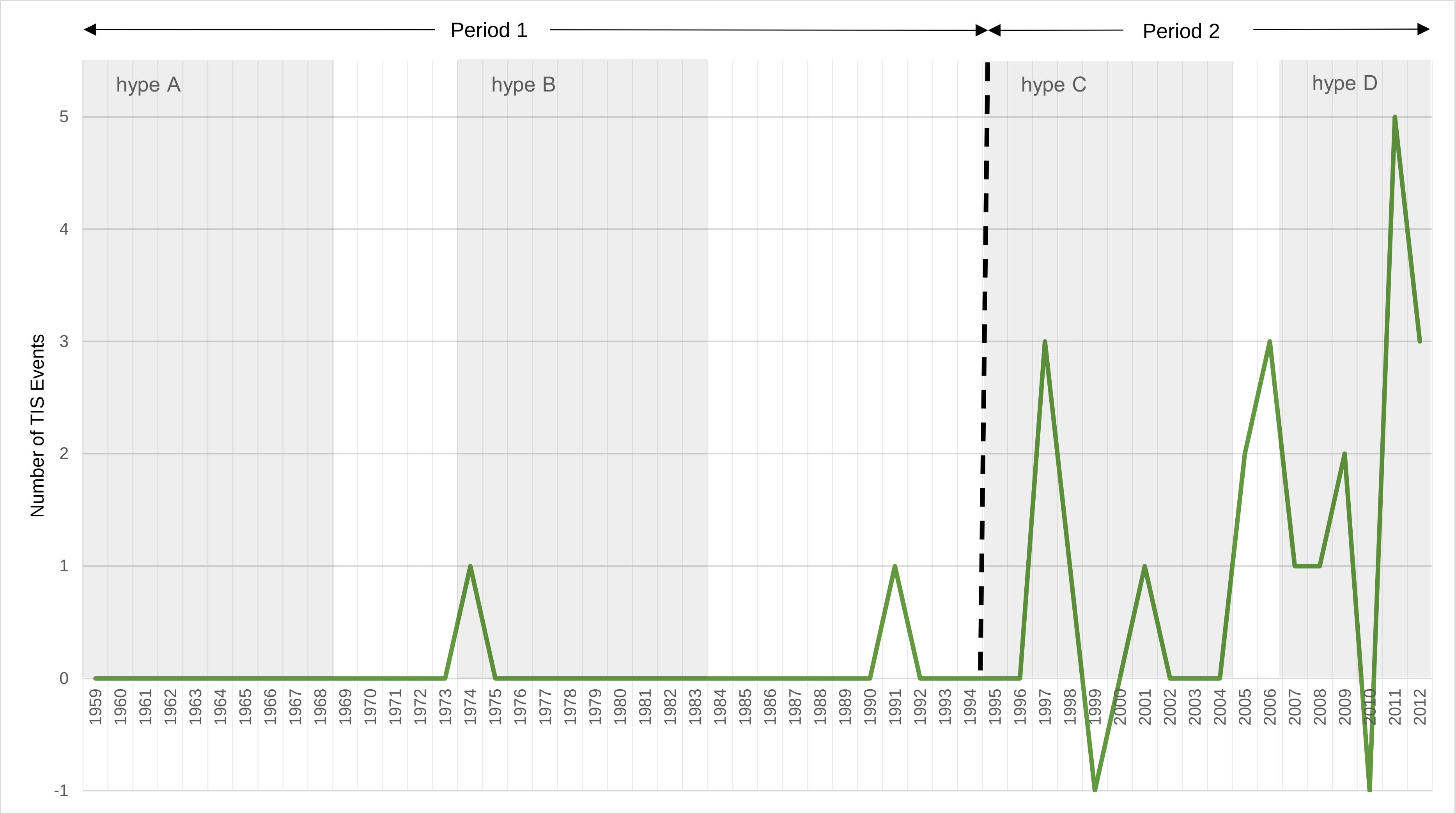

Figure 39: Resource Mobilization (F6) in the German HFC TIS, 1959-2012

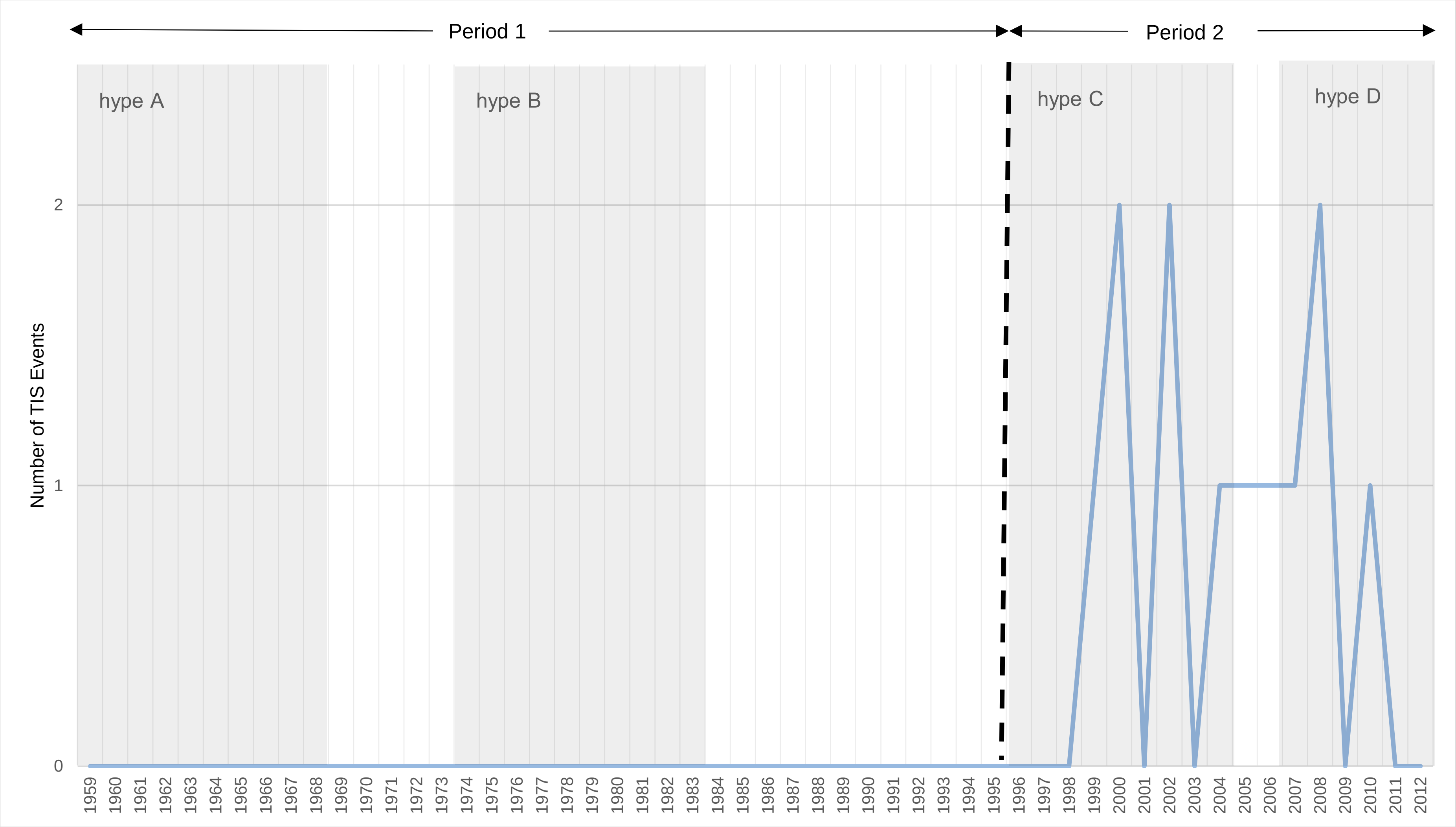

Figure 40: Advocacy Coalitions (F7) in the German HFC TIS, 1959-2012

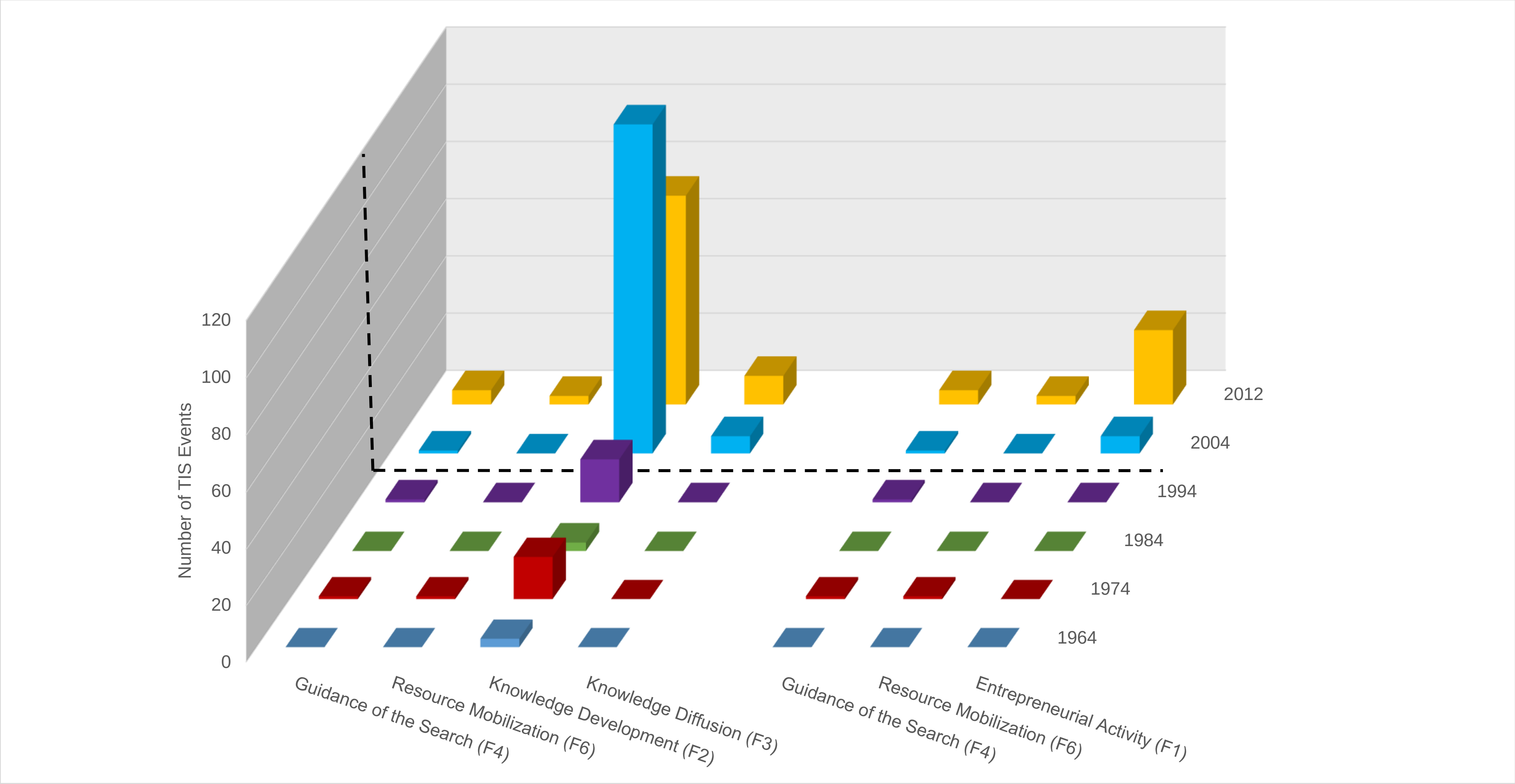

Figure 41: Germany - Science and Technology Push (STP) Motor

of the search (F4) events which appeared in 1971 (Figure 37) – emissions legislation – and, during hype B (1974-1981) (the approach to hype cycles is described in Section 2.3.3):

c) knowledge development (F2) peaking at 15 events in 1974 (Figure 35) and,
d) resource mobilization (F6) getting one event in 1974 (Figure 39).

This increased knowledge development event activity in hype B was not resilient, however, and the level of HFC TIS activity would not pick up again until the early 1990s.[60]

In the next three sections, I reveal a more detailed TIS narrative for Period 1 in Germany in terms of the co-evolution of HFC technologies in the defence and aerospace, transport and stationary power sectors. At times, my level of analysis is disaggregated from the TSIS approach's global, national and sectoral levels of analysis to the project level where HFC activity has a regional context. This where I feel that source material analysed at the project-level offers insights into the socio-technical processes at work (cf. Van de Ven and Huber, 1990, Van de Ven et al., 1999, Poole et al., 2000) that may be missed when data is aggregated (Hekkert et al., 2007a). These parts of the narrative involve examining how resources that are embedded in particular places are made accessible to actors via different organizational approaches to actor networks, whether public, private or public-private.

5.2.1 Defence and Aerospace

In the mid-1950s, NASA undertook a technology assessment (TA) of HFCs versus conventional lead-acid batteries. It found that AFCs and PEMFCs performed well in terms of energy efficiency, reliability, safety, mission flexibility, and development maturity. With aerospace applications in mind, German work on alkaline fuel cells (AFCs) began with Siemens and Varta in a corporate JV which reduced RD&D costs and shared expertise. In 1945, Siemens had relocated from bomb-damaged Berlin to Erlangen for its rapidly growing engineering research community. Varta was based in Kelkheim near Frankfurt. Leading individual research scientists, including August Winsel at Varta and Eduard Justi at Siemens, largely based their approach to AFCs which was based on the work of Bacon's activity in the UK. In 1965, these firms patented an 'Eloflux' AFC system in which the electrolyte flowed through porous

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[60] The German Navy's commitment to HFC-powered AIP propulsion for its submarines and Daimler and BMW's work on HFC mobility were significant exceptions.

electrodes. This permitted a much deeper electrical discharge than lead-acid batteries. Acid depletion could also be avoided.

Demonstrations of the Eloflux system in the late 1960s, led to the *Bundesministerium der Verteidigung* (German Defence Ministry or BMVg) asking Varta for cost-effective improvements to the range and stealth profile of the diesel-electric submarine fleet. The BMVg commissioned an internal technology assessment (TA) of alternative submarine propulsion drives. This covered: i) closed-cycle diesel engines generally with stored liquid oxygen (LOX); ii) closed-cycle steam turbines; iii) Stirling-cycle heat engines with external combustion, and iv) hydrogen-oxygen fuel cells (Psoma and Sattler, 2002). When this TA was completed in the late 1970s, a hydrogen-oxygen fuel-cell-powered air-independent propulsion (AIP) system was considered to have ideal, class-leading attributes. It could run silently, emit little heat, had low electromagnetic properties, extend the diesel-electric battery range, and it released only clean drinking water and an electric current from the electrochemical processes as 'waste'.[61] A submarine was then developed via a contracting out PPP between the BMVg and the German Navy as outlined in Text Box 13.

Text Box 13: Project-Level Narrative - German Navy's Contracting-Out PPP (1)

In 1980, the BMVg entered into a long-term contracting-out PPP with German state-owned shipyard Howaldtswerke-Deutsche Werft (HDW) to develop a prototype AIP submarine with the long-term intention to leverage foreign sales via procurement for the German Navy. This well-resourced PPP included Ingenieurkontor Lübeck (IKL), Ferrostaal and Siemens (with its AFC experience). A demonstration plant for hydrogen production and storage was built. A 100kW AFC system from Siemens was tested in sea trials over two years. In 1985, Siemens then switched to a PEMFC unit (developed via a knowledge transfer agreement with General Electric in the US). By the early 1990s, this new unit operated at a lower (and more end user-friendly) temperature. It also proved more reliable and more flexible in terms of performance compared to the AFC unit. Secondary sources reveal the contestation between the various project partners regarding the technological pathways for HFCs. A pre-existing skilled work force of engineers was based around the shipyards of Kiel and Emden while Siemens' electrochemists drew on knowledge networks based in Erlangen.

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[61] Varta dropped out of its formal alliance with Siemens in 1973.

5.2.2 Transport

In 1970, driven by new regulation (Table 18 and Table 19), Daimler-Benz reorganised its research operations to focus on emissions reductions and alternative drive technologies. In 1971, the company set out a corporate roadmap to achieve more sustainable mobility. There were five options: i) further optimize internal combustion engines (ICEs); ii) improve conventional fuels; iii) use largely carbon-dioxide-neutral, biogenic fuels; iv) refine hybrid drives as an intermediate stage to future drivetrains; and v) investigate zero-emission mobility with fuel-cell vehicles. Joined by Volkswagen and BMW, Daimler's comparative technology assessments (TAs) resulted in uncertainty about which set of alternative fuel and drive technologies would win out in the long run.[62] Initially, automotive engineers had no idea how to comply with the new regulations. This "clearly illustrated the limits of available knowledge." (Daimler-Benz, 2007a, 4). To share expertise and cut RD&D costs, Daimler-Benz and Volkswagen had previously formed *Deutsche Automobilgesellschaft* m.b.H., or DAUG, in 1966.[63] Daimler-Benz also worked with the US-owned Battelle Memorial Institute in Geneva which in 1967 produced the world's first energy storage device based on metal hydrides.[64]

In the late 1970s, BMW opted for a different technological route to HFC mobility and went into a joint venture PPP with *Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt* (DFVLR, later DLR), the state-funded aerospace institute. I outline these events at the project level in Text Box 14.

Text Box 14: Project-Level Narrative - BMW & DLR's Joint Venture PPP

BMW was Daimler-Benz's leading rival German carmaker in terms of HFC RD&D. Its engineers. From 1978, BMW's HFC research team believed that hydrogen internal combustion engines (ICEs) with cryogenic storage of liquid hydrogen (LH_2) had a better potential for future HFC mobility than Daimler-Benz's metal hydride storage tanks. This was because of the invention in 1978 of a cryogenic LH_2 storage tank by two academic researchers, Walther Peschka and Constantin Carpetis. They worked for Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt (DFVLR, later DLR), a state-funded aerospace institute which

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[62] BMW based itself in Munich in southern Bavaria in 1916 where a highly-skilled vehicle engineering workforce already existed.

[63] Daimler-Benz was founded in Stuttgart in 1886. Volkswagen was created in Wolfsburg in 1930. The first joint HFC patent from DAUG came in 1973, the last in 1981.

[64] This practical solution to the technical problem of fuel storage for mobile HFC applications was further developed; the German military sponsored some of Daimler's RD&D.

collaborated with BMW for nearly a decade.

Selecting hydrogen ICEs over Daimler's HFC approach reflected BMW's customer base who prefer more powerful cars. BMW also regarded hydrogen ICEs as a less costly and more reliable route to sustainable mobility because of the costs of complying with the future introduction of catalytic converters. These became mandatory in ICE vehicles in Germany in 1985. From 1979, BMW's researchers developed a series of prototype hydrogen ICE vehicles based on a modified BMW 735i limousine. Each had a small PEMFC as a backup auxiliary power unit (APU). However, by 1985, the driving experience of these vehicles was considered disappointing and BMW did not invest further in HFCs or hydrogen ICEs until the mid-1990s. Secondary sources reveal the important influence of power relations between individual inventors and RD&D managers – enactors and selectors - on the competing technological pathways between BMW and Daimler which were leading towards HFC mobility.

By February 1991, having spent hundreds of millions of deutschmarks of public and private RD&D money on HFC demonstrations, Daimler was in a position to begin a new HFC vehicle project: the 'NECAR' or 'new electric car'. Unveiled in April 1994, NECAR1 became the world's first hydrogen-electric hybrid vehicle. It had a Ballard PEMFC on board, a compressed hydrogen storage tank with gas (GH_2) held at 300 bar.[65] NECAR1 raised very significant and very positive expectations for HFC mobility around the world (Daimler-Benz, 2007a, Daimler-Benz, 2007b). BMW responded by revealing four earlier generations of its different hydrogen mobility route, hydrogen prototypes tested in the 1980s. BMW restarted its hydrogen ICE research in 1994 for fear of losing future hydrogen vehicle market share to Daimler and others.

5.2.3 Stationary Power

By the mid-1960s, German-made direct methanol fuel cells (DMFCs) were being used off-grid for supplying energy to radio and television masts. The alkaline electrolyte consumed sodium hydroxide (NaOH) with the methanol fuel. Regular maintenance to avoid carbon dioxide (CO_2) poisoning was expensive and reducing the rate of electrolyte consumption was the only answer, but this too was expensive. By contrast, the hydrogen-oxygen cells used in Varta and Siemens' Eloflux system did not produce CO_2 and only slowly consumed the electrolyte. The first applied

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[65] NECAR1 had a 50kW cell, a top speed of 56 mph and range of 81 miles.

demonstration of the Eloflux system was with an off-grid television mast in the late 1960s. These AFC units had a wind-powered DC generator powering a high-pressure electrolysis battery. Compressed hydrogen entered at 120-200 bar or 1740-2900 psi (Winsel, 1969, Winsel, 1970).

Despite this early HFC success, RD&D in stationary power applications developed very slowly between the 1970s and 1990s. State funding was crucial to a number of knowledge development projects: HYSOLAR (an academic JV), Solar Wasserstoff Bayern (SWB, a Bavarian JV PPP project), a Solar House (the Fraunhofer Institute for Solar Energy Systems), and Phoebus - a self-sufficient solar-hydrogen-battery (Jülich Research Centre). In general, apart from HYSOLAR, each demonstration showed that energetically reliable systems with low battery capacity were possible and that PEMFCs were more reliable than AFCs and PAFCs.

5.2.4 Summary

Overall, the institutional context of HFC activity in the three sectors described above suggested slowly increasing coordination between energy, industrial and environmental policies. Major German HFC engineering actors innovated as a result of the need to seek regulatory compliance. In the defence and aerospace sector, a distinctly interventionist industrial policy was in evidence (cf. Ades and Tella, 1997, Rodrik, 2013, Mazzucato, 2013). Having identified class-leading submarine propulsion technology, the BMVg reached out to both public and private actors because of the uncertainties involved in developing HFC RD&D. Creating Germany’s first contracting-out PPP involving HFCs also ensured that this highly sensitive (and potentially very lucrative) development would be procured from German firms. Having a pro-active industrial strategy is considered important in this coordinated market economy as an interviewee from HySolutions, a PPP based in Hamburg, confirmed in 2011:

> “We’re … talking about funding schemes here where these projects are ... from German money, so therefore the German Federal Government takes care that whenever German funding money is involved that we have mostly German companies.” (Interviewee GHAM1, HySolutions - 2011)

The policy learning associated with the state procurement of this HFC application via this contracting-out PPP therefore appeared significant: the state could seed innovative activity and encourage future clean technology markets for domestic actors (Mazzucato, 2013). However, it is unclear how widely such knowledge was shared beyond the BMVg at the time. Instead, in the stationary power sector, policy learning experiences about state funding via university research bodies and through the SWB PPP in the State of Bavaria were generally more accessible to public and private RD&D actors.

By the end of Period 1, the technical challenges for HFC-powered submarine propulsion appeared to leading PPP actors to have been largely solved. Siemens and HDW switched from an AFC to a PEMFC unit. However, life-support systems' integration was still required. HDW began looking to take foreign orders for its submarines in the mid-1990s. In transport, by contrast, a dominant design for HFC mobility was yet to emerge (cf. Hekkert and den Hoed, 2004, Ehret and Dignum, 2012). BMW, in particular, were prepared to contest Daimler's emerging FCEV pathway with its hydrogen ICEs (which still require HFC technologies developed via state-funded collaboration). By 1994, Siemens, HDW and Daimler were all beginning to collaborate with the leading global PEMFC supplier, Ballard Power Systems from Canada, to overcome their respective technical challenges.

In the next section, I continue with the German TIS events narrative by describing HFC activity in Period 2.

5.3 Period 2: 1995 to 2012 – Commercial Orientation

The second period in this national case study - Commercial Orientation - began in 1995. The reason for choosing this date was because it was marked by the start of a noticeable rise in TIS events post 1996 (as shown in Figure 32). For the purposes of this study, Period 2 ends in December 2012 when my data gathering for the EPSRC Supergen XIV DoSH study finished. Private HFC RD&D activity in Germany became much more established in Period 2. Strategically-partnered PPPs also rose in this period. This rise was typically as a result of the national and regional coordination of German HFC actors where top-down and bottom-up initiatives were linked to funding from the EC level. At the supranational level, the Kyoto Agreement (cf. UNFCCC, 1997) was a strong external driver of change along with EC energy, industrial and environmental policies which became more coordinated and more sustainable (Baker and Eckerberg, 2008). Stricter environmental governance was also being promoted by Die Grünen who, again led by Joschka Fischer, held national political power as a junior coalition partner in the government headed by Social Democrat Party (SPD) leader Gerhard Schröder between 1998 and 2005. As the interviewee from electricity provider Energie Baden Württemberg (EnBW) noted:

> “The most important way to raise funds is actually strict environmental rules, because that’s, as far as I understand from the car industry, that’s the biggest driver for investment in hydrogen technology.” (Interviewee GBW1, EnBW - 2011)

For Period 2, I outline below the leading structural elements of the German HFC TIS before continuing with the sectoral TIS narrative in Sections 5.3.6, 5.3.7 and 5.3.8. This outline includes the institutions, technologies, actors and actor networks which further contextualise the co-evolution of HFCs. It is worth noting that, at all governance levels, there was a degree of policy learning in Germany about HFC-specific policymaking. This learning was based on the negative events experienced during the blow out of hydrogen hype at the end of ‘hype C’ in 2004/5. In particular, these experiences led to much strengthened and more resilient networked agency via HFC PPPs from 2006 to 2012.

5.3.1 Supranational Institutions

At the global level, HFC TIS events were rising in the 1990s. This shift was led largely by the US, China, Japan, South Korea, Canada and Germany (Huang and Yang, 2013). The Kyoto Protocol in 1997, shown in Table 12 in Chapter 4, led to a recognition at the national and regional levels of signatory countries that longer-term, more coordinated, and more sustainable, planning efforts would be needed to effect a low-carbon energy transition (Helm, 2002, Bulkeley and Kern, 2006). Radical cuts in carbon emissions via HFCs and other clean technologies were lobbied for (cf. Hall and Kerr, 2003) winning the support of the EC President, Romano Prodi. At the European Level, the European Parliament and Council, shown at the supranational level in Figure 42, drove much of Germany’s national legislative changes with Directives and other instruments relevant to energy, the environment, industry and so shaping potential HFC RD&D and infrastructure. Directives typically encouraged neoliberal approaches to progressive decarbonisation in Member States. Market stimulation was tackled chiefly via target setting and tax incentives. Overall, as EC directives became more integrated in terms of their contribution towards sustainable policymaking, they contributed more positively to the institutional landscape that public and private HFC actors in Germany faced. US President George W. Bush made a $1.2 billion commitment to HFC mobility RD&D in 2003, known as the Hydrogen Fuel Initiative (HFI). However, there was a degree of global ‘blow out’ in hydrogen hype amongst many nations’ general publics in 2004/5. In Germany, technological promises made in the late 1990s about future HFC applications, e.g.

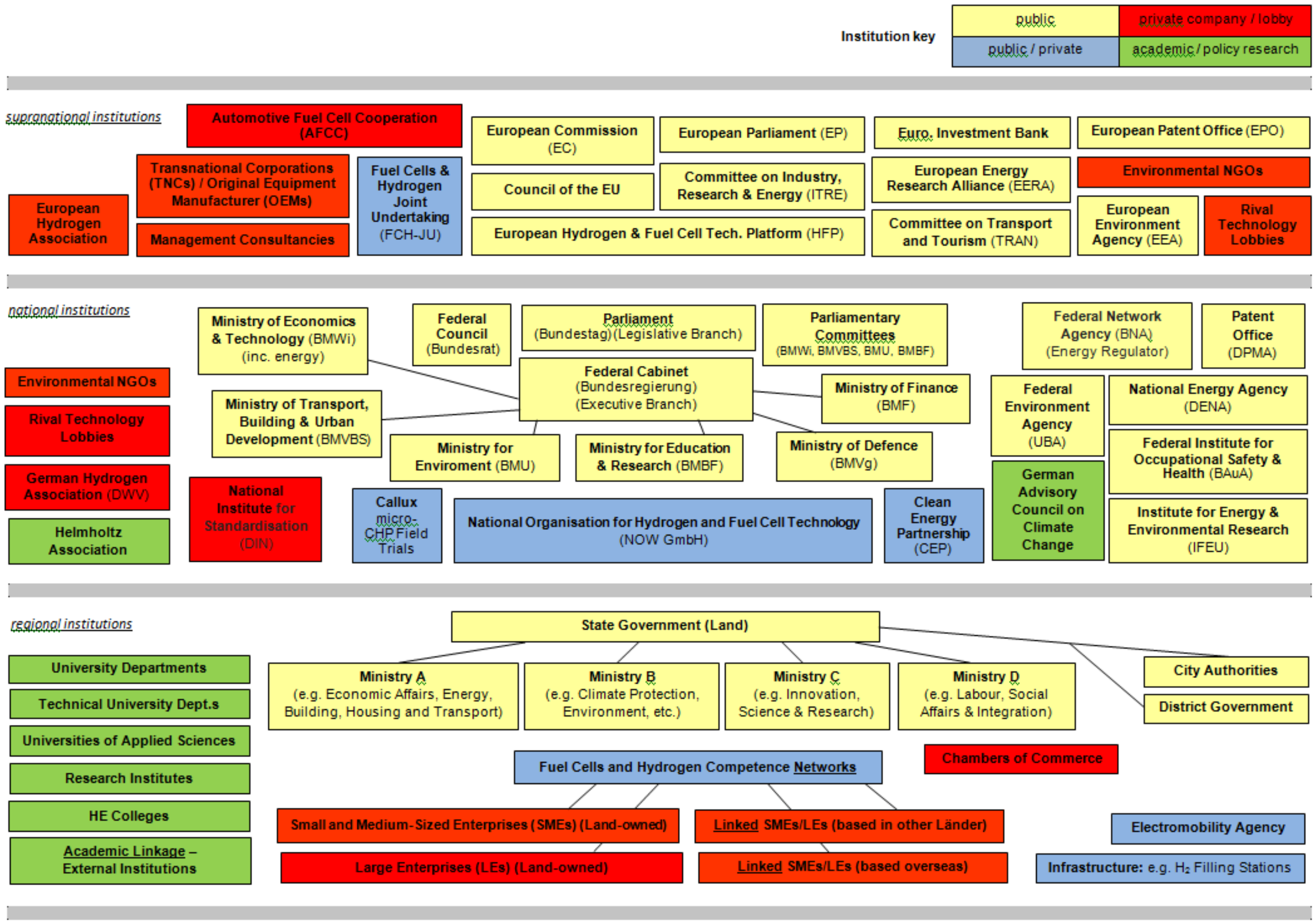

Figure 42: Germany - Multi-level Mapping of Actors Linked to HFC Actors in 2012

vehicles and micro-CHP units, had not been met (cf. Ruef and Markard, 2010). Nevertheless, Prodi's support ultimately led to the creation of an EC-level strategic partnering PPP body, the Fuel Cells and Hydrogen Joint Technology Initiative (FCH-JTI), in 2006. German-based HFC efforts were knocked back from a 2005 peak but public and private financial support continued to grow again towards 2012.

5.3.2 National Institutions

At the national level in Germany, energy and environmental policies in Germany were becoming ever more coordinated and hence more sustainable from the mid-1990s (see Table 19). The federal government entered into another PPP in 1998 with a policy forum known as the Transport Energy Strategy (TES), designed to identify the 'fuel of the future' (Ehret and Dignum, 2012). There was a steady rise in HFC knowledge development (F2) and entrepreneurial activities (F1) from 1996 (see Figure 34 and Figure 35). Such activity reflected in part the increasing federal- and Länder-level interest in using renewables on a larger scale to meet supranational environmental commitments (cf. Gross, 2010). However, in the wake of hype C, i.e. post 2005, German federal bodies (shown in yellow at the national tier of Figure 42) underwent distinct policy learning experiences based on the perceived policy successes and failures since 1998. The resulting HFC-specific road maps, instruments - such as the 'National Innovation Programme (NIP) Hydrogen and Fuel Cells' (see Table 20) - and resources distributed via a dedicated PPP funding body, NOW GmbH, meant the agency and resilience of HFC actors, witnessed as projects at a range regional sites, was greatly enhanced. The impact of the NIP and NOW was described by the interviewee from an HFC enhanced. The impact of the NIP and NOW was described by the interviewee from the German Hydrogen Association (DWV):

> "What was really important was this NIP … [is] it's a ten-year programme, and people who want to invest money, they need a certain safety that the whole thing will not be called off next year, and [Germany has] built a lot in this climate, together with very important and powerful states like for example North Rhine-Westphalia." (Interviewee GLOB1, DWV - 2011)

As the interviewee from NOW stated, the German central government was prepared to support a wide range of projects so long as the socio-technical risks were fully understood by all parties:

Table 20: Period 2 (1995-2012) - National Policy Measures Affecting HFC Innovation and Diffusion in Germany

Year	Policy Measures	Aim	Impact Summary on HFC TIS
1998-2002	Transport Energy Strategy (TES)	Identify the transport 'fuel of the future'. Align leading energy and engineering actors to facilitate HFC RD&D and infrastructure.	This PPP was also a policy forum comprised of powerful domestic-based multinational actors including DaimlerChrysler, BMW, MAN, Volkswagen, Aral, RWE and Royal Dutch Shell. TES members concluded that a transition to more sustainable forms of transport was inevitable via hydrogen. This was a major boost to the legitimacy claims of the HFC technological pathway in the German automotive sector, and resources followed.
1998	Energy Industry Act (EnWG)	Enhance competition, security of supply and sustainable energy production.	The *Energiewirtschaftsgesetz* (EnWG) deregulated the German electricity market and set a target of 25% percent of electricity to come from CHP (large- and small-scale) by 2020. Supported by all German political parties, The EnWG suddenly opened up the market to energy suppliers offering more localised, decentralised power storage and generation.
2000	The Renewable Energy Sources Act (EEG)	Encourage improved energy efficiency via economies of scale over time. This should lead to energy cost reductions.	The *Erneuerbare-Energien-Gesetz* (EEG) provides a significant boost to renewable energy throughout Germany. As with its predecessor, the Electricity Feed-In Act, it encourage the rise of decentralised energy production from renewable in Germany. This has since encouraged the further development of renewable energy storage options of which a regenerative fuel cell (RFC) system with its HFC and electrolyser is one.
2002	Combined Heat and Power Act (KWKG)	Subsidise the CHP share of locally-produced electricity.	The *Kraft-Wärme-Kopplungsgesetz* (KWKG) further promotes innovation required for decentralised energy production and storage via CHP.
2002-	The Clean Energy Partnership (CEP)	Test the suitability of hydrogen as a fuel.	A joint initiative of government and industry lead-managed by the German Ministry of Transport and Industry. CEP's demonstration projects have added to learning about HFC technologies while its infrastructure investments make Germany more market ready.
2005	Energy Act (EnWG)	Enhance competition, security of supply and sustainable energy production.	The *Energiewirtschaftsgesetz* (EnWG) impacts HFCs across the board because it requires all electricity to be labelled according to: i) type of energy source and ii) the provision of greater information on electricity sources to allow consumers to make informed decisions about suppliers.

Table 20: Period 2 (1995-2012) - National Policy Measures Affecting HFC Innovation and Diffusion in Germany

Year	Policy Measures	Aim	Impact Summary on HFC TIS
2006	National Innovation Programme (HFC Technologies) (NIP)	Align and coordinate HFC actors in terms technology pathways, RD&D, standards and infrastructure.	This 10-year-long market-focused RD&D road map (2006-16) was created by the Federal Ministry of Transport and Digital Infrastructure (BMVI). It aligns HFC actors and structures their activity via the creation of NOW GmbH.
2008-	National Organisation for Hydrogen & Fuel Cells (NOW GmbH)	Implement the National Innovation Programme (NIP) (2006).	This influential 'selector' body has entered into a range of strategic HFC PPPs thanks to a budget of €1.4 billion in match funds for demonstration and infrastructure projects (up to 2016 when NOW's future operation is renegotiated). To maximise available funding, NOW sought to coordinate project partners at supranational, national and regional levels.
2009	Combined Heat and Power Act (KWKG)	Subsidise CHP electricity that is not used for general supply in a grid, but is fed into non-public grids or is used for self-supply.	This *Kraft-Wärme-Kopplungsgesetz* (KWKG) further promotes innovation required for decentralised energy production and storage via CHP.
2009	H_2Mobility (PPP)	Encourage investment in HFC infrastructure, market coordination & roll out of mass-produced vehicles.	Significant infrastructure investments – chiefly hydrogen refuelling stations - have been made in anticipation of HFC vehicle sales (market entries since renegotiated by individual vehicle manufacturers from 2015 to between 2017 and 2020).
2009	*Konjunkturpaket II* programme	Offer regional regeneration funding.	This *National Economic Stimulus Package* has helped kick-started public and private investment in some hydrogen refuelling infrastructure.
2009-2015	Vehicle Tax Exemption	Exempt vehicles producing 80mg/CO_2/km or less from road tax.	This federal-level exemption drives innovation, cost reductions and market entries for a range of low- and ultra-low emission vehicles including fuel cell electric vehicles (FCEVs) and fuel cell vehicles (FCVs).

Table 20: Period 2 (1995-2012) - National Policy Measures Affecting HFC Innovation and Diffusion in Germany

Year	Policy Measures	Aim	Impact Summary on HFC TIS
2010	*Energiewende*	Facilitate a transition to an energy portfolio dominated by renewable energy, energy efficiency and sustainable development.	The hoped for impact of the *Energiewende* on the HFC TIS is: i) to encourage the domestic economy via HFC sales and exports, ii) to encourage regional economic regeneration, iii) to reduce dependence on fossil fuels and nuclear power, iv) to help energy production to decentralise via storage, and v) to help the country achieve its supranational low-carbon treaty commitments.
2011	Nuclear Power Phase-out	Progressively phase out nuclear energy production.	On the one hand this measure encourages a more diverse energy mix and decentralised energy production which benefits HFC innovation. But nuclear hydrogen could also be a relatively abundant future feedstock.

> “There is no innovation without risk and these are reasonably big steps still and … we know we need the risk. Just what we have to evaluate, and people have to really show, [is that] they understand the risks. And then … [if what] we see as a risk … is acceptable, we support it.” (Interviewee GFIN1, NOW GmbH - 2011)

In Chapter 6, I comparatively analyse the timing of the German hype cycles – which the long-term commitment of the NIP and NOW’s managers have attempted to overcome - with those in the UK.

5.3.3 Regional Institutions

In the face of negative federal evaluations for HFC prospects in the mid-1990s, Bavaria pursued its own industrial roadmap involving HFCs. The *Bayerisches Staatsministerium für Wirtschaft, Infrastruktur, Verkehr und Technologie* (Bavarian Ministry of Economic Affairs, Infrastructure, Transport and Technology or StMWIVT) created a PPP, the *Wasserstoff-Initiative Bayern* (Hydrogen Initiative Bavaria or WIBA) in 1995. WIBA used public leverage to attract foreign direct investment in urban clusters and JVs to fund HFC demonstration projects. Improving international competitiveness, preparing applications for market launch, jobs and attempting to ensure gains in future market share were all stressed (WIBA, 2015). This led the federal government to work with competence networks in Hamburg, Baden-Württemberg, Hesse and North Rhine-Westphalia in pursuing similar HFC-specific policy initiatives to Bavaria from 2002 onwards.[66] As in Bavaria, these state-supported networks encouraged local knowledge exchange about HFC RD&D and were involved in top-up funding of market-oriented projects (cf. Musiolik and Markard, 2011, Musiolik et al., 2012). The interviewee from Ford of Europe in Aachen said of the HFC network in North Rhine-Westphalia:

> “We are ...working together with the institutes of the universities with private companies, so little and medium ones, and also with the big OEMs ... And so you can also talk then on these meetings with people ... in other industry sectors, and this is ... very interesting ... There might be some very interesting ideas which you can also maybe collect ... copy and paste onto your vehicle technology.” (Interviewee

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[66] A national-level HFC lobby, the German Hydrogen Association (DWV), formed in 1996.

Table 21: Period 2 (1995-2012) – Land-level Policy Measures Affecting HFC Innovation and Diffusion in Germany

Year	Land	Policy Measures	Aim	Impact Summary on HFC TIS
1995	BAV	Hydrogen Initiative Bavaria (WIBA)	To encourage regional growth	In 1995, the Bavarian State Ministry of Economic Affairs, Infrastructure, Transport and Technology began using a range of PPP instruments to promote HFC RD&D including public leverage JVs and strategic partnering.
2000	NRW	North Rhine-Westphalia Fuel Cells & Hydrogen Network (NBW-NRW)	Encourage regional HFC clustering.	Funded and run by the NRW administration, the NBW-NRW supports HFC innovation and diffusion via a range of PPP activity from public leverage to JVs and strategic partnering. It manages a competence network.
2002	HES	Hydrogen & Fuel Cell (H2BZ) Initiative Hesse	Encourage regional HFC clustering.	Funded and run by the HES administration, the H2BZ supports HFC innovation and diffusion via a range of PPP activity from public leverage to JVs and strategic partnering. It manages a competence network.
2006	BW	Cluster Strategy	Encourage regional hi-tech clustering.	The BW administration focuses on public leverage and knowledge exchange for HFC companies. It offers financial support for cluster projects, supports the internationalisation of those projects, as well as events, studies, management support, publications and information.
2007	BW	Fuel Cell & Battery Alliance Baden-Württemberg (BBA-BW)	Encourage regional HFC clustering.	Funded and run by the HES administration, the H2BZ supports HFC innovation and diffusion via a range of PPP activity from public leverage to JVs and strategic partnering. It manages a competence network.
2008	NRW	Energy and Climate Strategy	Reduce energy-related CO_2 emissions.	The target set - 81 million tonnes by the year 2020 as compared with 2005 - is ambitious and has acted as an incentive to cleantech innovation.
2008	NRW	Hydrogen HyWay Programme	Support regional HFC infrastructure.	This PPP helps HFC investment in hydrogen filling stations along the route of a hydrogen pipeline that goes from Aachen northwards through Cologne, Dusseldorf and Essen and on to the Ruhr.

Table 21: Period 2 (1995-2012) – Land-level Policy Measures Affecting HFC Innovation and Diffusion in Germany

Year	Land	Policy Measures	Aim	Impact Summary on HFC TIS
2008	BW	Renewable Heat Act	Mandate renewable energy use in residential buildings.	This legislation has encouraged regional HFC RD&D and sales of stationary power systems.
2008	BW	Fuel Cells Challenge Research Programme	Provide project support for HFC RD&D.	The Ministry of Environment, Nature Conservation and Transport of Baden-Württemberg provided €3 million via PPP JVs up to 2010. This de-risked HFC RD&D investment in the region.
2008	HES	Cluster Policy	Encourage regional hi-tech clustering.	The HES administration focuses on public leverage and knowledge exchange for HFC companies. It offers financial support for cluster projects, supports the internationalisation of those projects, as well as events, studies, management support, publications and information.
2009	NRW / BW / HES	*Electromobility* Master Plan	Support electric vehicle RD&D.	The national electromobility programme supports demonstration projects in eight Länder. Electromobility is a key objective in regional plans for more green jobs. The long-term roadmap supports RD&D for vehicle manufacturing in both public and private institutions.
2009	NRW	Cluster Strategy	Encourage regional hi-tech clustering.	The NRW administration supports the clustering of hi-tech firms by linking research facilities and making public funds available.
2009	BW	State Infrastructure Programme	Support regional HFC infrastructure.	The State Ministry for the Environment, Climate and Energy Economy of Baden-Württemberg has funded HFC projects including the hydrogen filling station in Freiburg completed in 2012.

Table 21: Period 2 (1995-2012) – Land-level Policy Measures Affecting HFC Innovation and Diffusion in Germany

Year	Land	Legislative Act / Policy Instrument	Aim	Impact Summary on HFC TIS
2011	NRW	Wind Power Decree	Increase wind energy generation from 3% to at least 15% by 2020.	This decree further promotes decentralised energy production and storage for renewable in which HFCs offer some innovative solutions.
2011	BW	Climate Change Mitigation Strategy 2020PLUS	Reduce the region’s greenhouse gas emissions by 30% by 2020.	The long-term goal is to emit only 2 tons per capita by 2050. To achieve these targets, the strategy encompasses 145 measures to improve energy efficiency, boost use of renewable energies and reduce emissions in all relevant sectors of the economy. This includes HFCs.
2012	NRW	Climate Protection Action Plan	Substantially increase in renewable energy generation	With a focus on decentralized energy production as well as the increased influence and independence of citizens, targets included increasing wind energy production to 15% by 2020.
2012	BW	Climate Protection Act	Cut GHG emissions at least 25% compared with 1990 and by 90% until 2050.	In terms of mobility, BW has developed a concept for “integrated environmental mobility” by foot, bicycle and public transport. This and electromobility plans are a major focal point of this state’s future energy policy. This policy was expected to encourage HFC RD&D innovation and market rollout in the vehicle industry based in BW.
2012	HES	Energy Future Act (Draft)	100% Renewables by 2050	This legislation was expected to accelerate decarbonisation efforts in certain sectors including transport. This will speed up RD&D and market rollout efforts in electric vehicles and FCEVs.

> GMNC2 – Ford of Europe, 2011)

Similarly, the interviewee from Energie Baden-Württemberg (EnBW), a large energy supplier, said of the HFC networks they are involved with:

> "If a small cell is more efficient than a large gas turbine then it might, then it might be a competing technology for our investments, and therefore we are interested in this sort of information. And that's why we join [networks] … knowledge creation or the development of components is not so interesting … [T]hat's why it's so easy for us to collaborate with all the technology companies because they open the book for us and they know … we don't compete with them, [there's] no problem … to show their [technologies] … [so] I think we get a realistic picture about the status of the technology and about the capabilities and about the ambitions of the various companies involved." (Interviewee GBW1, EnBW - 2011)

A leading HFC industry lobbyist said in 2011 that bottom-up initiatives in regionally-based networks had aligned with top-down efforts:

> "It was of great value that there were states which supported the topic … ten or fifteen years ago it was Bavaria. Today, it's North Rhine-Westphalia ... Hessen ... Baden-Wurttemberg [and] Hamburg." (Interviewee GLOB1, DWV - 2011)

Figure 32 and Figure 33 show that, hype C ended in Germany in 2005. Another upswing - hype D - swiftly started in 2007 and activity likely built on gains made during hype C. Figure 35 shows that knowledge development activity (F2) in orange peaked at 125 events in 2005 and again at 91 in 2010. Entrepreneurial activity (F1) peaked at 26 events in 2012 (Figure 34). Resource mobilization (F6) peaked at 5 events in 2011 (Figure 39) and market formation was at 4 events by 2012 (Figure 38). Guidance of the search hit a peak of 12 in 2009 (Figure 37). Similarly, knowledge diffusion peaked at ten events in 2012 (Figure 36). However, the remaining function – advocacy coalitions - dipped sharply from small peaks of two events in 2000, 2002 and 2008 to zero in 2012 (Figure 40).

Overall, this suggests that post-2004 knowledge development activity was beginning to be reinforced by activity from other functions in the STP feedback loop (Figure 41).

Similarly, by 2012, feedback was beginning to be seen in the *Entrepreneurial motor* (Figure 43) (the analysis of the ‘motors of sustainable change’ are outlined in Section 3.3.1.5). The only function in the loop of functions in Figure 43 – F1, F7, F6, F1, F4, F5, F1, F2, F3 - that had no data by 2012 was advocacy coalitions (F7). Given that HFC lobbying actors are active in Germany, this particular result might reflect problems with event selection and coding. However, this result could also reflect the fact that HFC lobbying efforts are relatively small compared to those of other, much larger energy-based lobby groups. The *System building motor* (Figure 44), and the *Market motor*: (Figure 45) both suggest that, in loops where knowledge development was dominant, positive feedback with other functions might well be occurring by 2012. I next turn to the organisational context of the TIS events which was revealed by my extra coding and the interview data.

5.3.4 Organisational Context: Private JVs and PPPs

After the leads taken by WIBA in 1995 and TES in 1998, better-resourced German HFC actors in Period 2 embarked upon further private JV activity and a range of PPPs. This activity then coincided with (and partly fed) rising global expectations in hype C (1998-2005). Post-2005, there was a rapid rise in strategic partnering PPPs based on policy learning from negative outcomes in hype C (Interviewee GFIN1, NOW GmbH – 2011). One of the interviewees from Ford of Europe, in Aachen, said:

> “[At] the end of the 90s, several companies ... were saying, ‘Oh by 2004, we will see a fleet of fuel cell vehicles on the road,’ … I think we [made] a big mistake in over-promising ... People think: ‘Oh hydrogen, oh again, oh they keep promising’. So it’s something I think we didn’t do very well.” (Interviewee GMNC3, Ford of Europe - 2011)

From 2006 – hype D – private JV and PPP activity was even more numerous and more functionally diverse than the TIS events in Period 1. Approaching 2012, this suggests that HFC path creation was occurring with dominant designs for certain applications emerging (cf. Garud and Karnøe, 2001, Simmie, 2012, Binz et al., 2016). To further investigate how HFC innovation and diffusion may have been affected by patterns of actor ownership, extra coding of the TIS events dataset was undertaken. This coding identified:

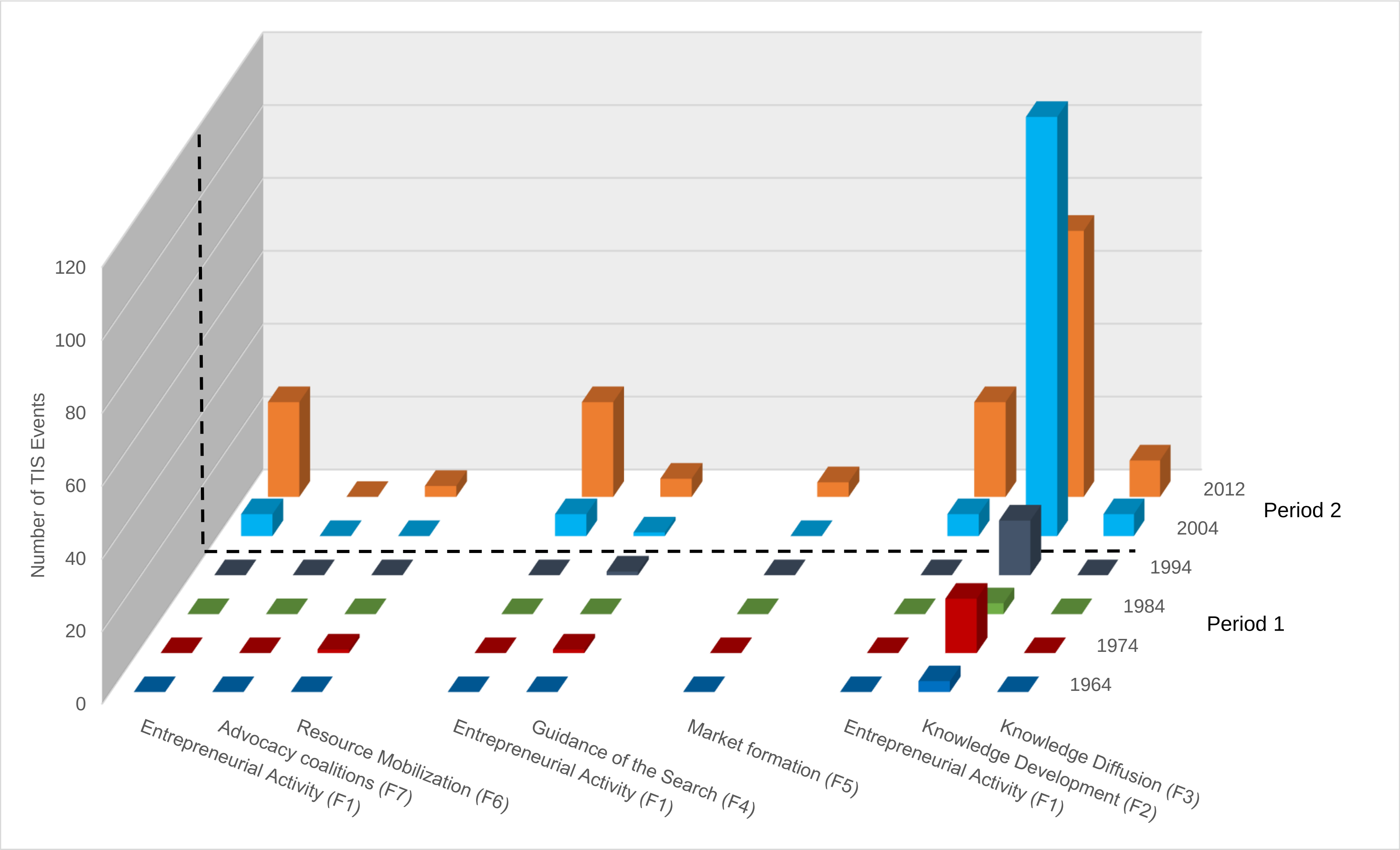

Figure 43: Germany - Evidence for the Entrepreneurial Motor, 1964-2012

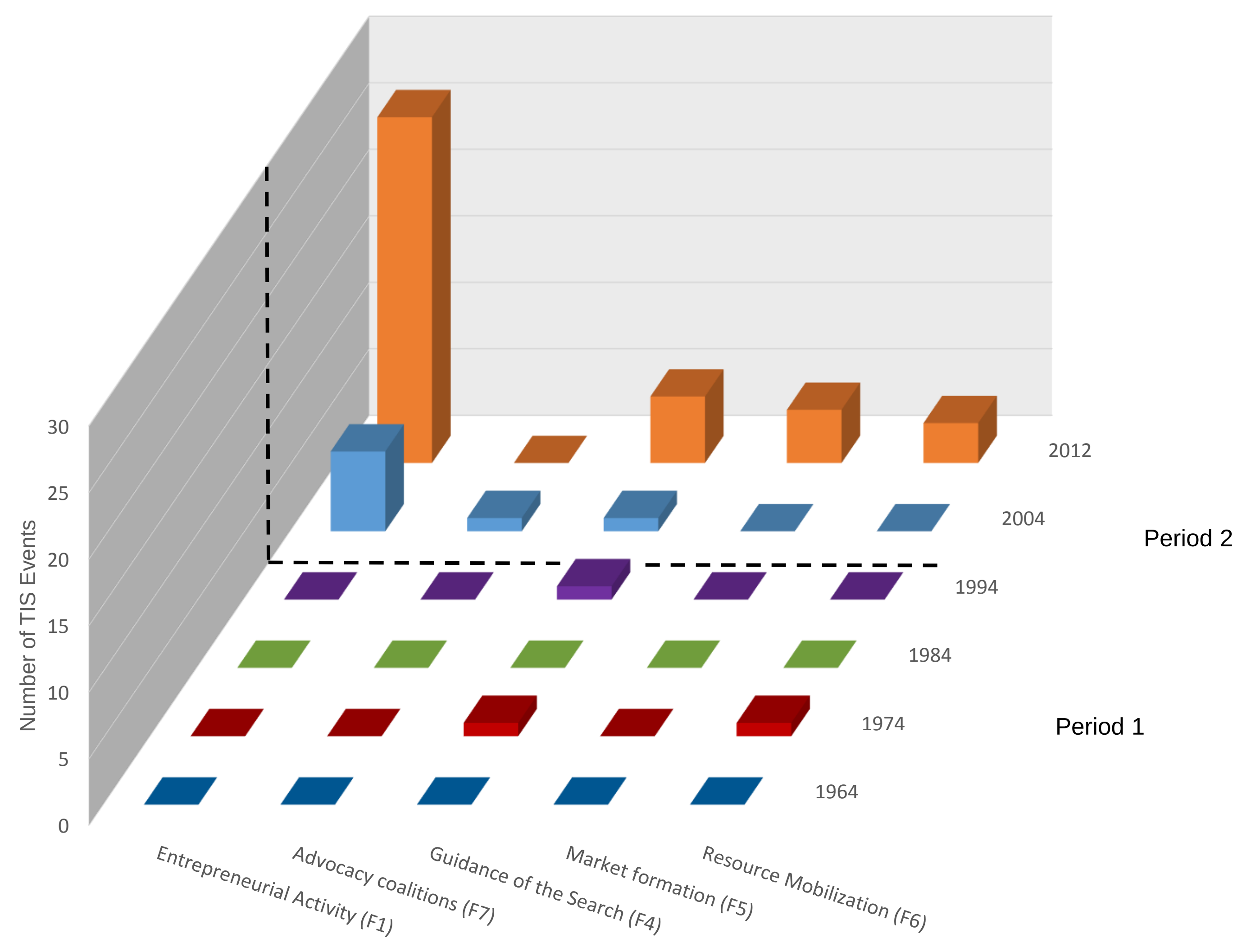

Figure 44: Germany - Evidence for the System Building Motor, 1964-2012

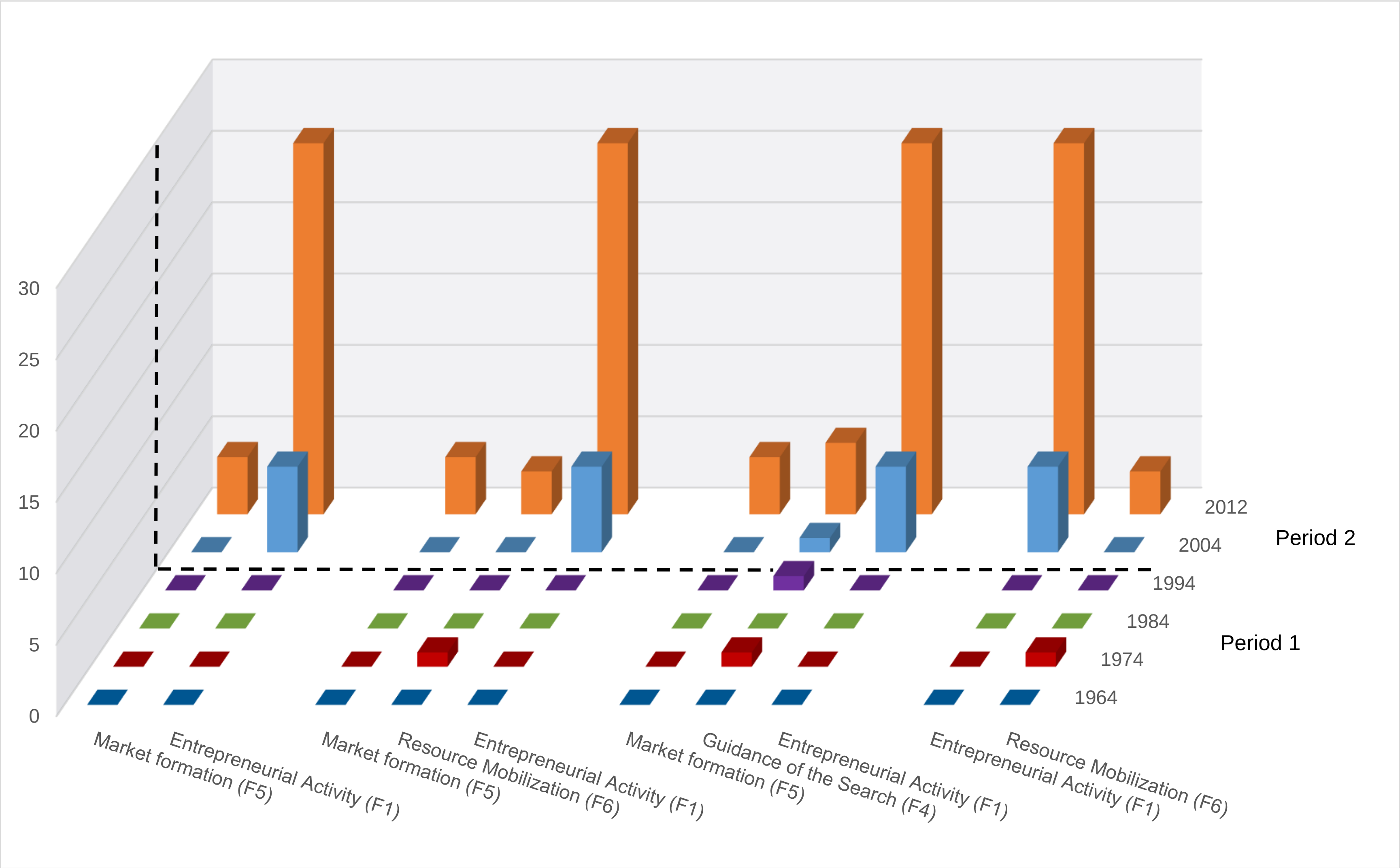

Figure 45: Germany - Evidence for the Market Motor, 1964-2012

- the type of funding for each event, i.e. ‘public only’, ‘private only’, ‘public and private (no partnership)’ and ‘public-private partnerships (PPPs),
- the degree to which ‘private only’ activity involved JVs, and
- the PPP type - based on the typology in Table 4 in Chapter 2.

Figure 46 and Figure 47 show that private-only funded TIS events led what little activity there was in Period 1. Private activity similarly dominated the rise in all funding post 1992.[67] It seems unlikely that state support for PPPs was not influencing this private spending in terms of indirectly de-risking HFC activity. Figure 48 and Figure 49 reveal that, of the different types of PPPs highlighted in the typology in Table 4 in Chapter 2, the rise of strategic planning PPPs post-1998 added the greatest number of TIS events in Germany in Period 2.[68]

In terms of the context for investment in HFCs in Germany in 2012, the interviewee from Australian-based CFCL said:

> “Companies [in] Germany … tend to have long term views. There’s more venture capital in the UK than in Germany, which tends to be more short term. At the moment, the way the markets are, there’s more money amongst high net worth individuals [in Germany], ‘angel’ investors … than there is amongst institutions, simply because the institutions have become very risk averse with the financial crisis, whereas the individuals find that they can’t get a return, if you’ve got money on deposit and so forth, they can’t get any kind of return … It makes a lot more sense for individuals now to make investments, a lot of which can be tax effective … particularly earlier stage companies or AIM listed companies … and I think the institutional is more difficult because of the way they’re structured. There’s a completely different funding culture in Germany, so … in Germany there’s more of a debt culture than an equity culture. So when you’re looking at fundraising, it tends to be a different form and … you tend to see family officers and corporate officers, i.e. large industrial companies who are prepared to invest in things, which is very difficult to find in the UK.” (Interviewee GMNC5, CFCL - 2011)

Similarly, spatially-specific factors were also linked to uneven rates of growth in TIS

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[67] Data coded according to the funding status of TIS events is tabulated in Appendix AK.

[68] The data coded according to the PPP typology is tabulated in Appendix AL.

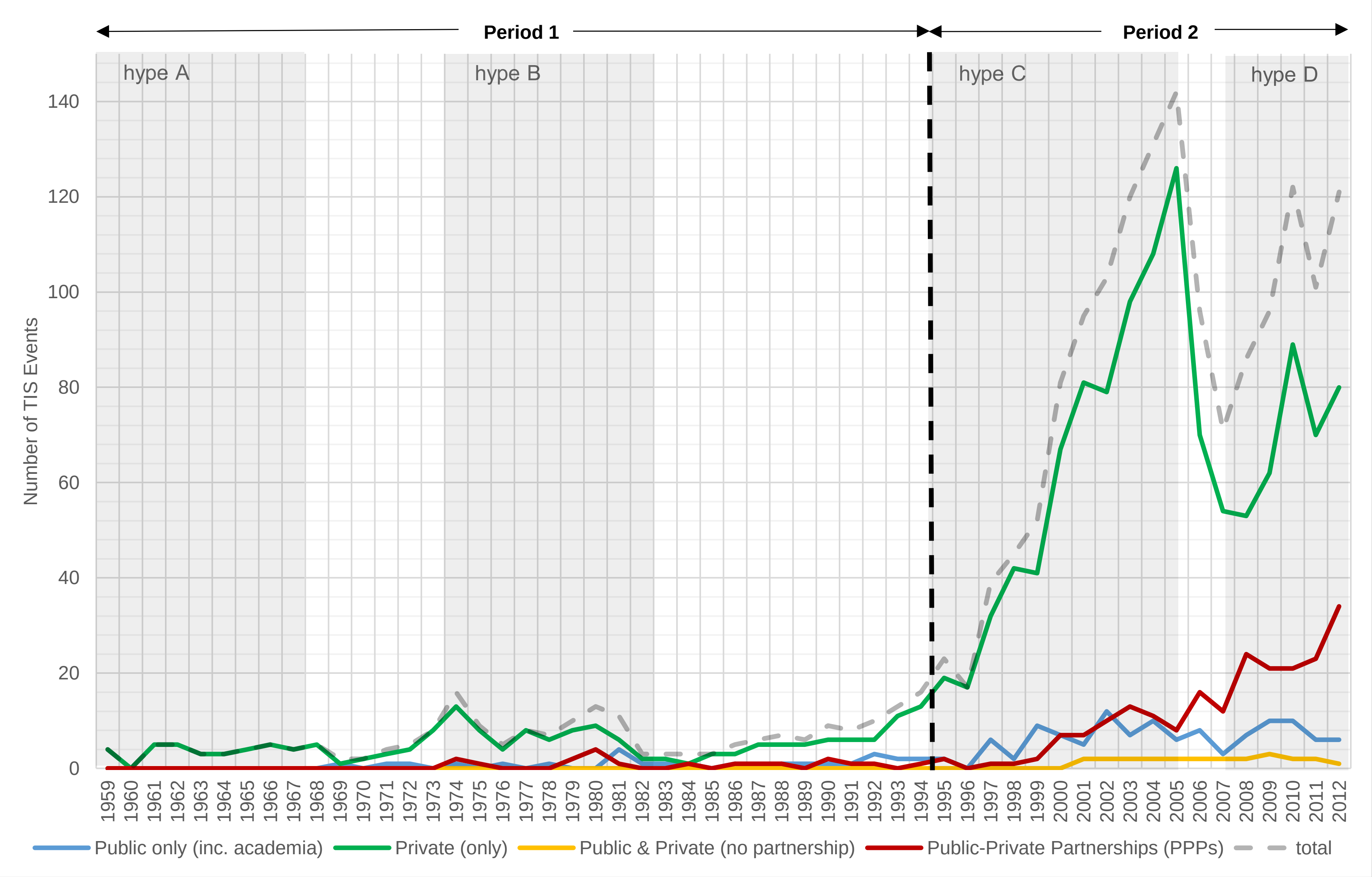

Figure 46: Germany – Annual Totals of All TIS Events by Actor Funding Type, 1959-2012

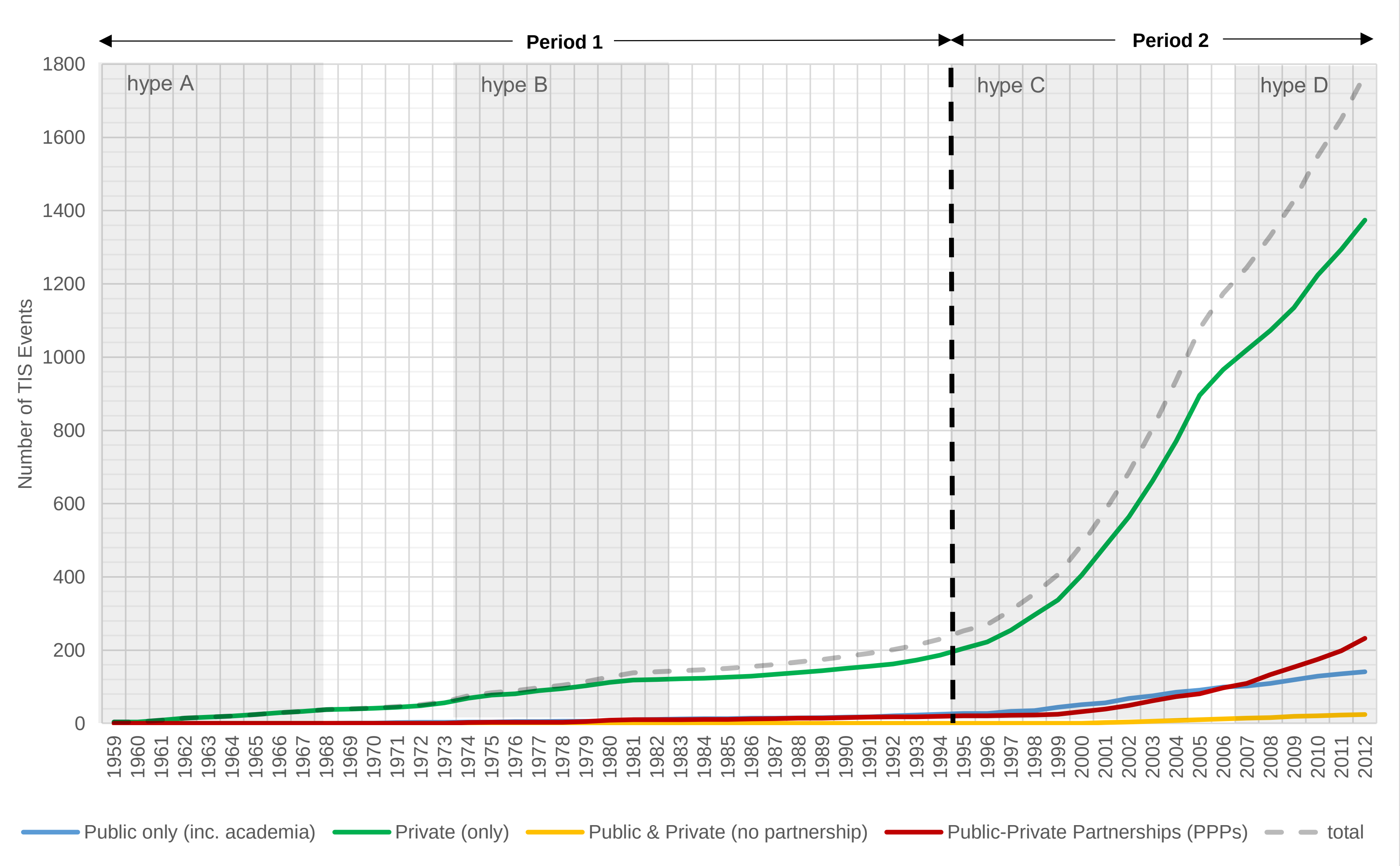

Figure 47: Germany – Cumulative Totals of All TIS Events by Actor Funding Type, 1959-2012

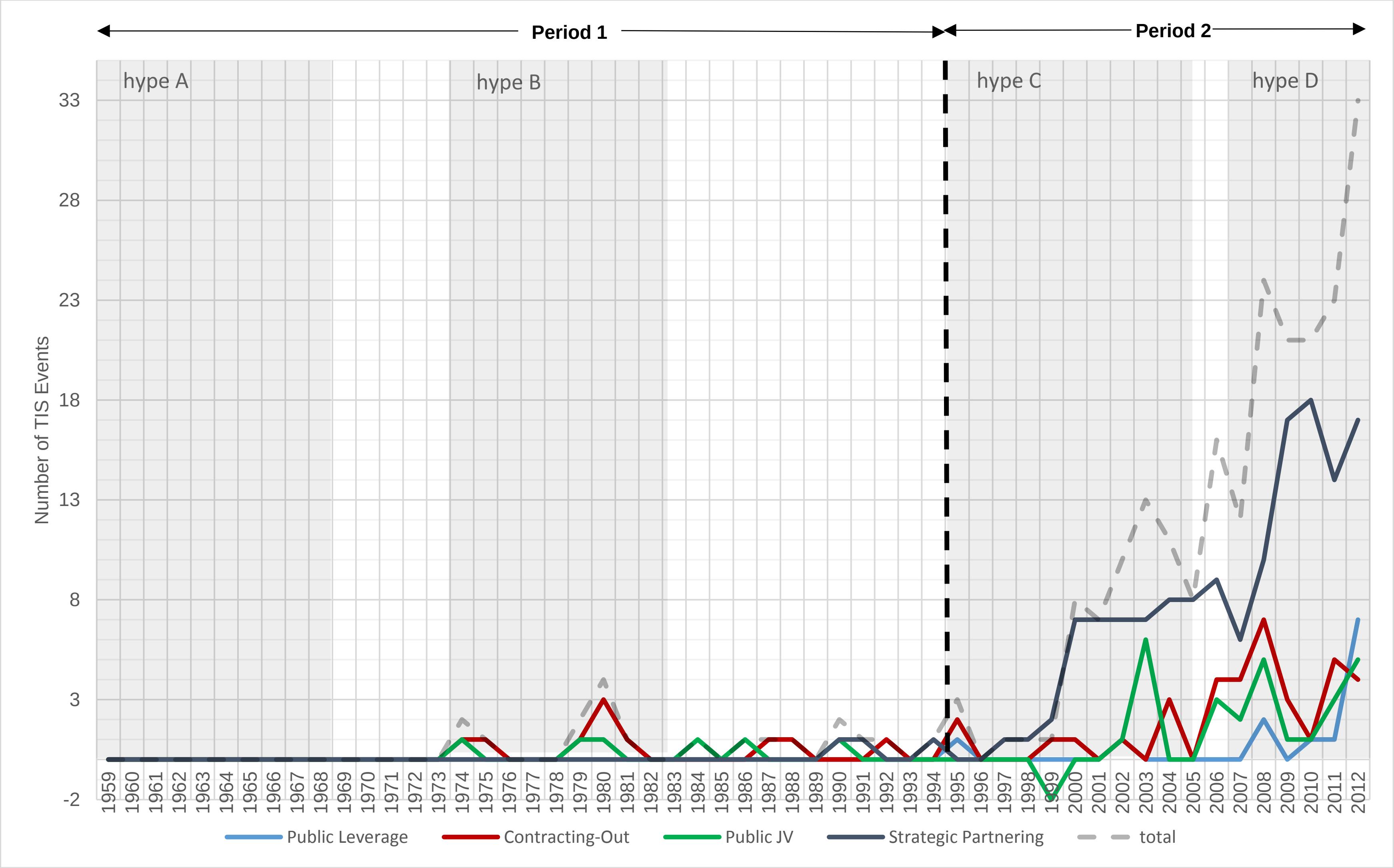

Figure 48: Germany – Annual Totals of Public-Private Partnerships (PPPs) by Type, 1959-2012

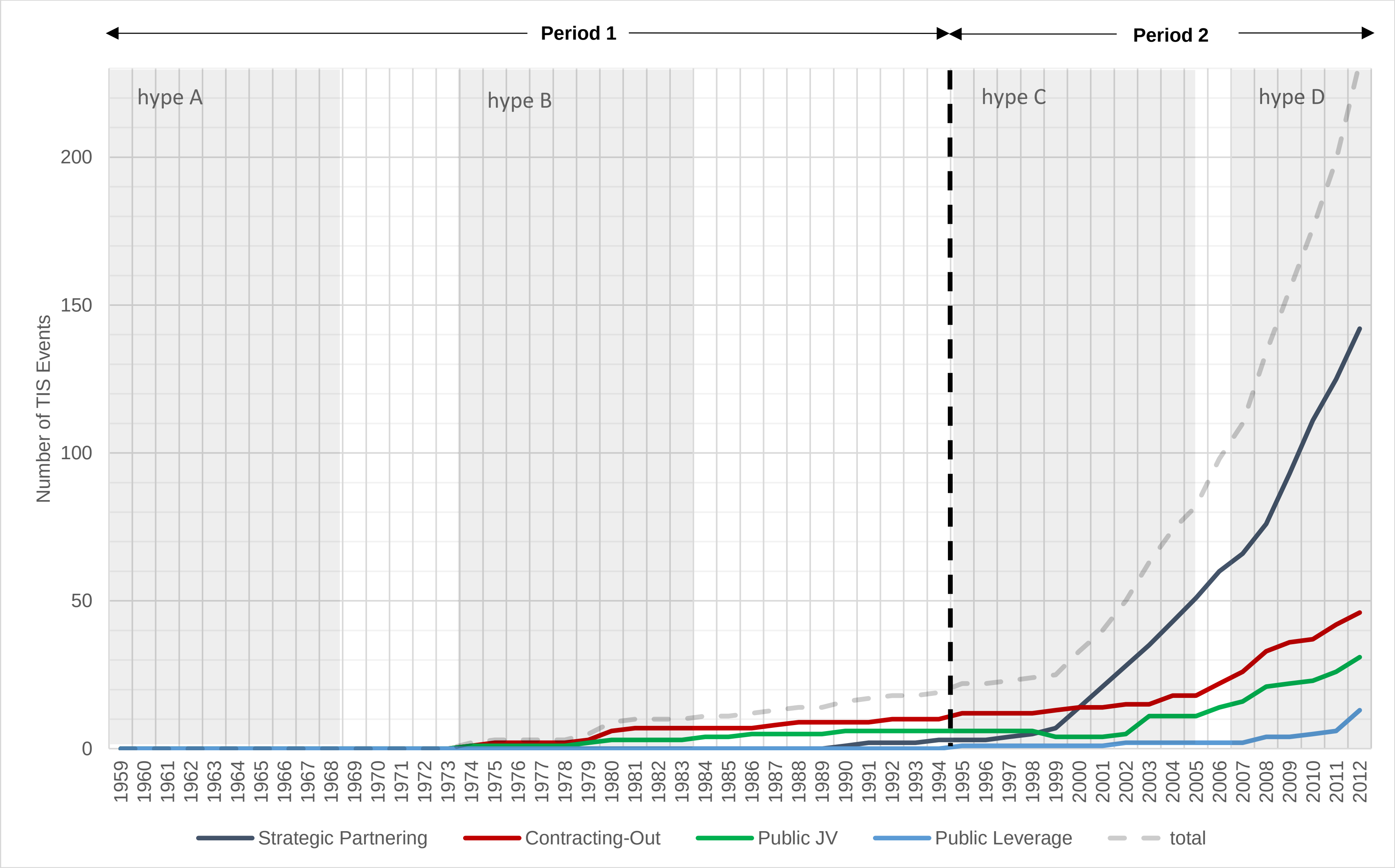

Figure 49: Germany – Cumulative Totals of Public-Private Partnerships (PPPs) by Type, 1959-2012

events, as I describe in the next section.

5.3.5 Spatial Context

Coding for the spatial context for all German HFC TIS events was examined. Actor lists revealed 101 higher education bodies and research institutes and 346 corporate HFC actors active in December 2012 (Appendices AM and AN respectively). The importance of links between these two groups of actors was emphasized by the lobbyist from the German Hydrogen Association (DWV):

> “It’s … very important, in particular in the development phase, because every new product is based on research which has … at some time been done at the universities … [F]or example, safety is an important topic and a lot of the safety knowledge on hydrogen has been generated by the nuclear industry and in the relevant research institutes like in Karslruhe and in Jülich and the whole field now profits a lot from this … money is becoming scarce and no university and no professor can survive only from … state funding. So they have to go outside and find the money where it is coming from” (Interviewee GLOB1, DWV - 2011)

The Länder with the greatest concentration of estimated employee numbers working with HFCs (set against numbers for all other employment) were: Hamburg, Hesse, Baden-Württemberg, North Rhine-Westphalia, Berlin and Bavaria in that order (Appendix AO). When plotted geographically, the uneven distribution of these two sets of actors - research bodies and companies – is revealed (Figure 50). The greatest concentrations of actors mirror the distribution of leading urban areas (with academic and engineering workforces), e.g. Hamburg, Stuttgart, the Rhine-Ruhr, Berlin and Munich. Appendix AP uses the Multi-Distance Spatial Cluster Analysis tool (based on Ripley’s K function) in ArcGIS software to reveal that each of these two actor groups, on their own, were clustered in statistically significant ways over a range of distances.[69] Interviewees, like the one from Daimler in Stuttgart, for example, highlighted some of the actors and institutions at work in that cluster:

> “Stuttgart is … [in] one of the hydrogen regions in Germany … We will have two

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[69] Observed K function values in red in Appendix AP are larger than expected K values in blue making the distributions more clustered than if the distribution was random.

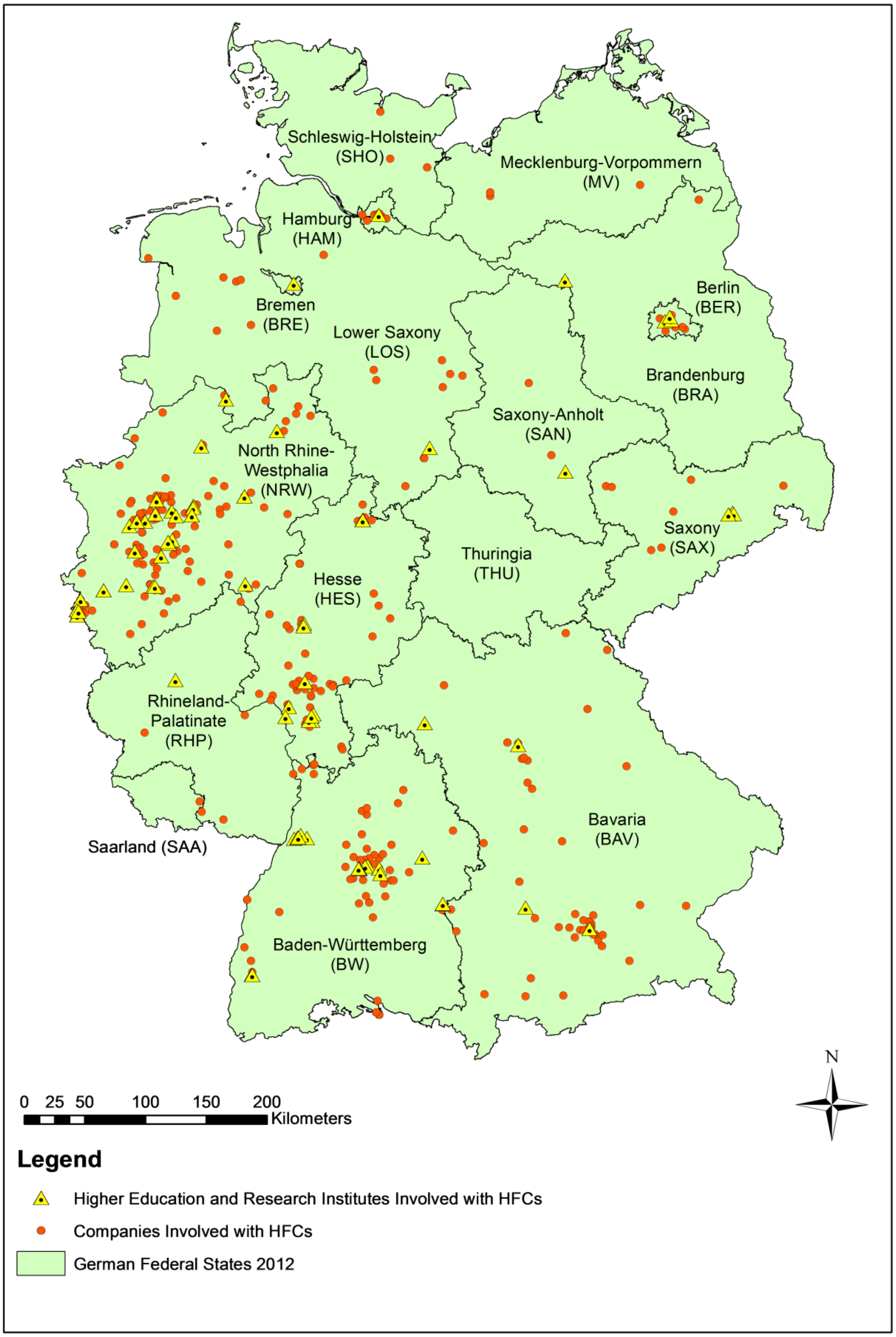

Figure 50: Germany - Geographical Distribution of HFC Actors in 2012

> public [fuel] stations in a couple of weeks, and the entire industry here is … very car oriented because of Porsche being here, because of Bosch being here, Siemens, and then Daimler … So that means that there's a lot of support for new technologies in general … [O]n top of that we just got a new local Government, which is run by a green party … [I]t's the first one in Germany." (Interviewee GMNC4, Daimler - 2011)

Similarly, in North Rhine-Westphalia, for example, an HFC cluster is growing around the small city of Helden and other HFC firms have located in the region because they expect to interact and network (Interviewee, GLOB1, DWV - 2011).

When analysed in Stata14's statistical software package for the interpoint distance distribution (IDD) (Appendix AQ), both of these distribution patterns – HFC firms and Higher Education bodies undertaking HFC research - are correlated with each other in a statistically significant way.[70] Such correlations do not imply causation and need to be interrogated further. However, I then triangulated this 2012 snapshot of where German HFC actors were located with the longitudinal records by region of knowledge development activity (F2) and entrepreneurial activity (F1). From this, Figure 51 suggests that path dependence was in evidence with knowledge development: activity first established in Period 1 appearing to be advantageous in terms of greater activity in Period 2 in three leading regions – Baden-Württemberg, Hesse and Bavaria.[71] This same regional breakdown was also applied to entrepreneurial activity (F1) (Figure 52) and PPP TIS events (Figure 53).

I then checked to see if there were correlations between the TIS events I coded 'yes' for strategic partnering PPPs and those coded for knowledge development (F2) and entrepreneurial activity (F1). The results, shown in Appendix AU, suggest a weak to moderate positive relationship between strategic partnering PPPs and knowledge development (0.38) and between strategic partnering and entrepreneurial activity (0.46).[72]

In terms of regional differences, I also compiled market data on HFC firm size, employee numbers and ownership patterns as indicators of the dynamism, maturity and resilience of the evolving German HFC TIS. In terms of estimated firm size, Appendix Z

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[70] Chapter 3 describes the use of a 'Mahalanobis distance', or 'M statistic', between distributions of two sets of points. Stata14 outputs in Appendix AQ include chi^2 and Monte Carlo runs.

[71] Knowledge development TIS event data (F2) by region is tabulated in Appendix AR.

[72] The strongest correlation by a small margin was between F1 and F2 at 0.49.

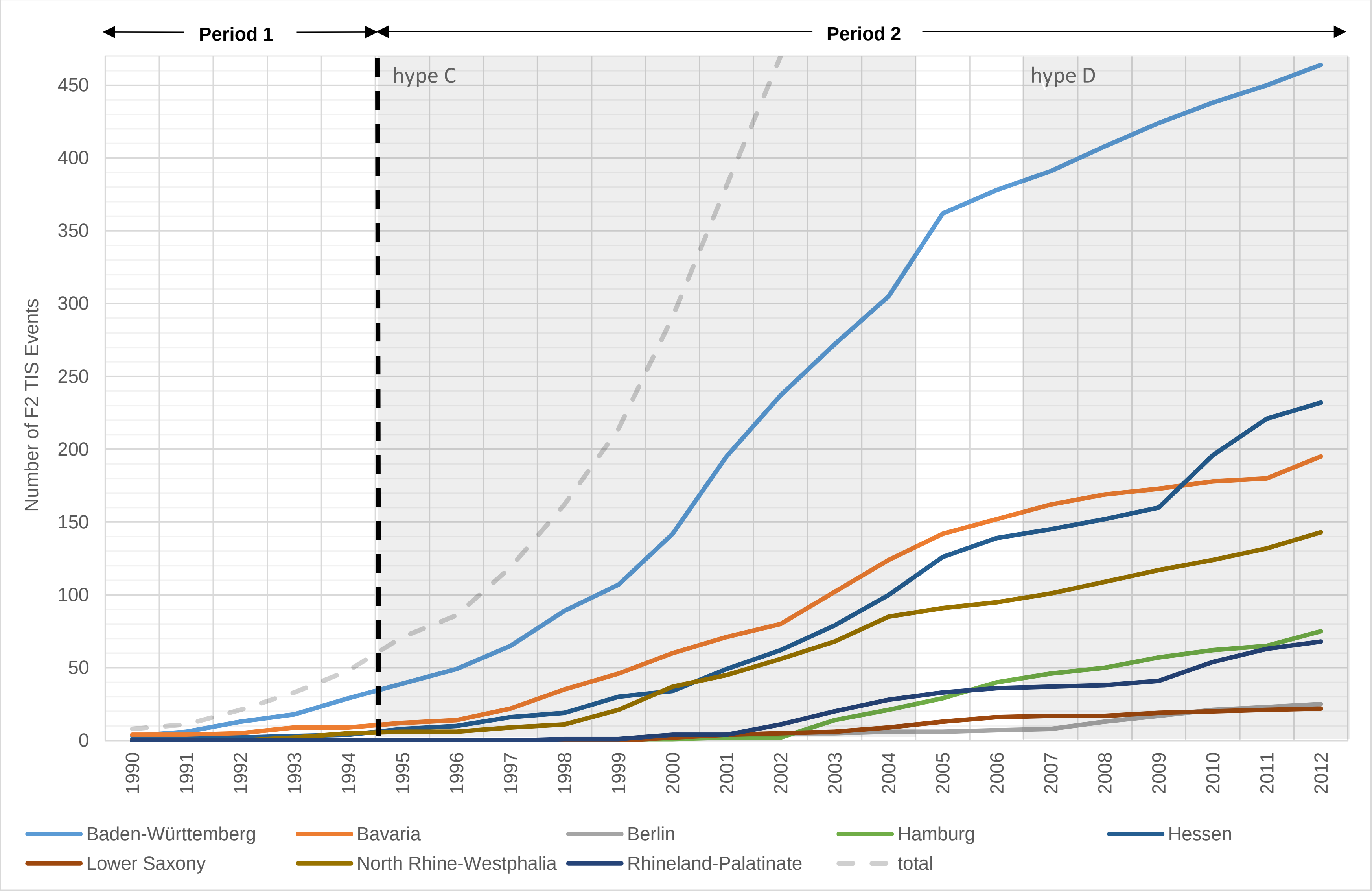

Figure 51: Germany – Cumulative Totals of Knowledge Development (F2) in Selected Regions, 1990-2012

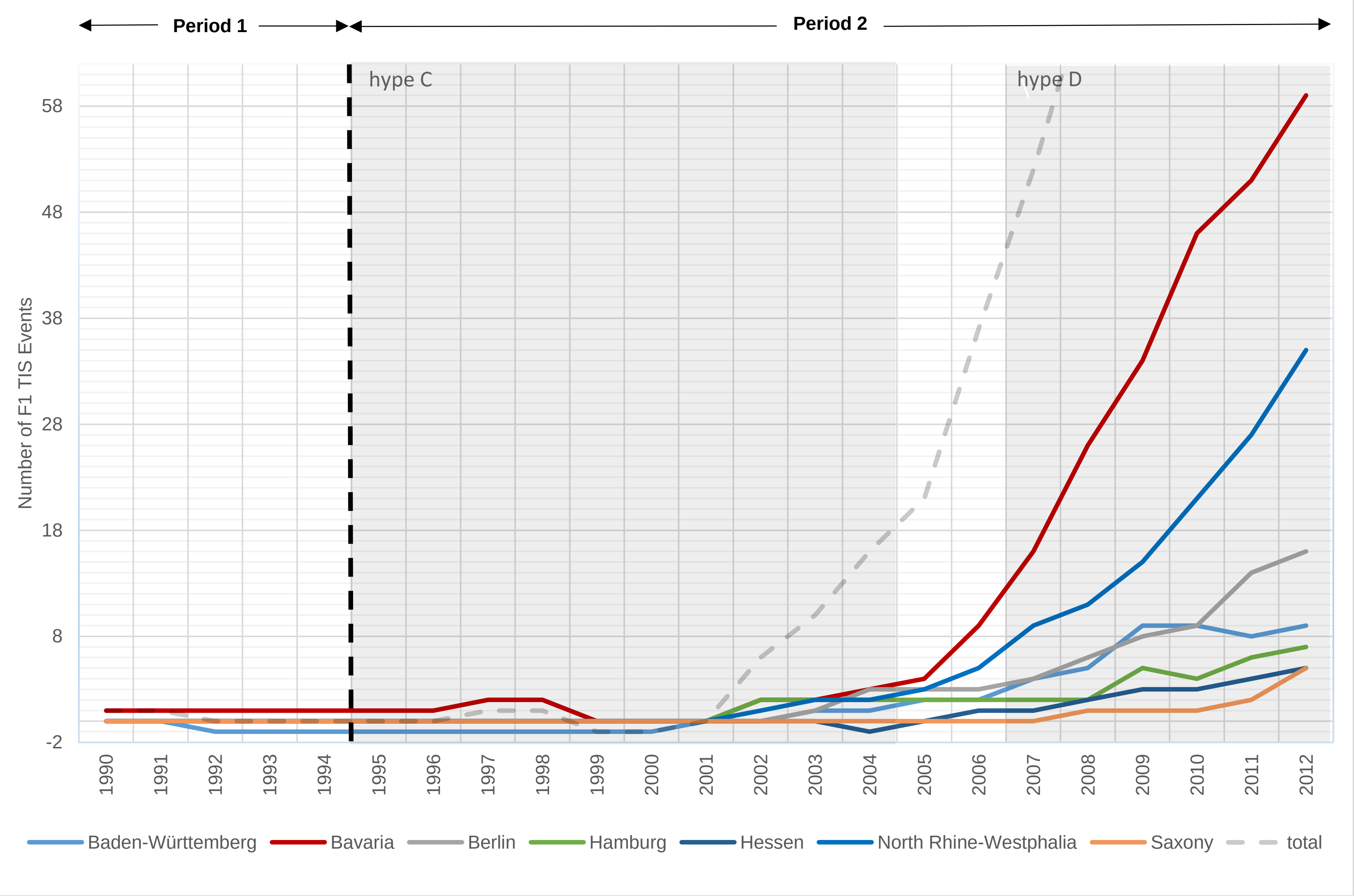

Figure 52: Germany – Cumulative Totals of Entrepreneurial Activity (F1) in Selected Regions, 1990-2012

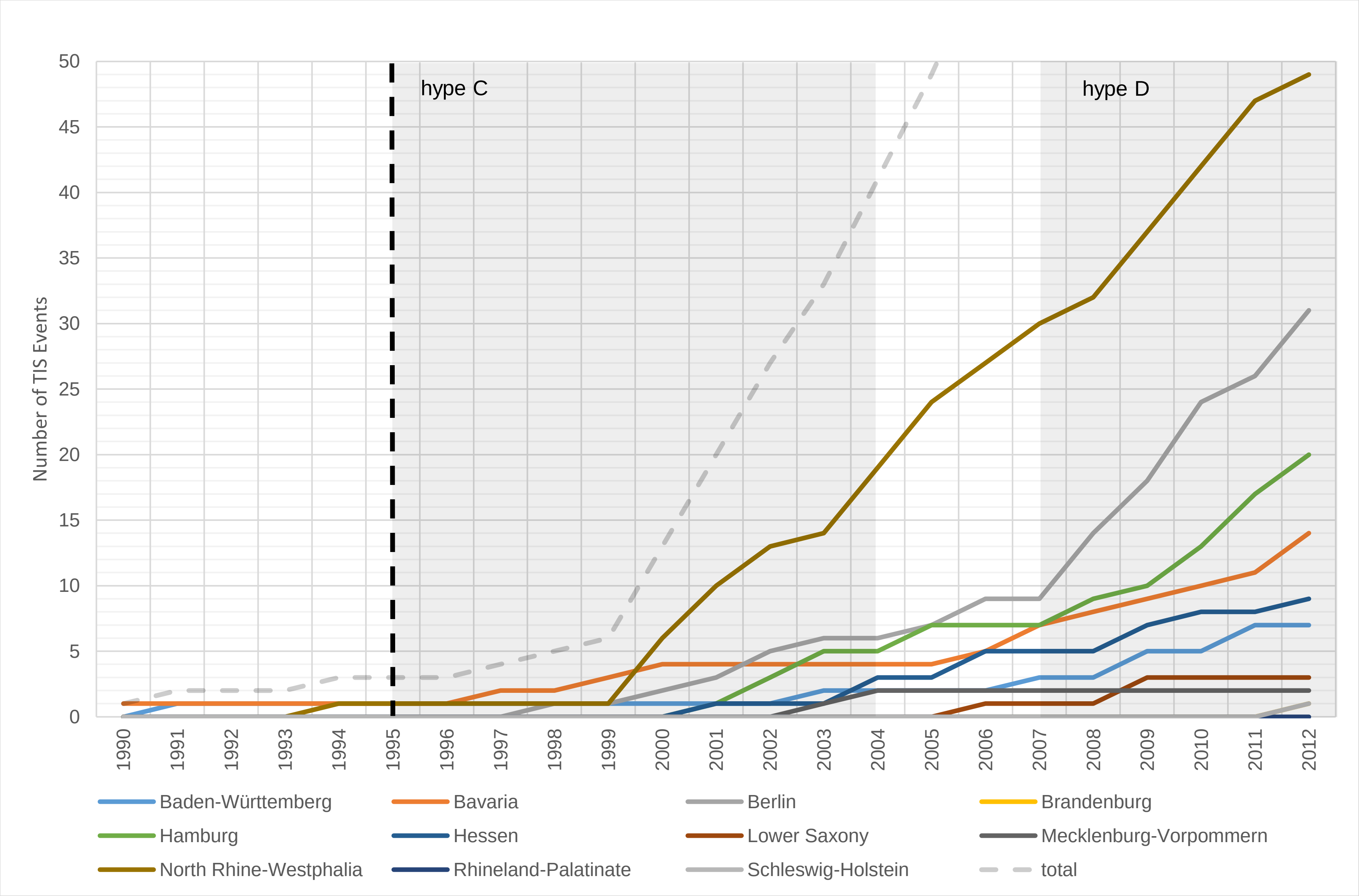

Figure 53: Germany – Cumulative Totals for Regional Diffusion of PPP Activity, 1999-2012

indicates that, out of the 284 corporate actors in the six most active states of in 2012 (not including Berlin[73]), the ratio of small companies (1 to 250 employees) to larger ones (251+ employees) was roughly 1:1. The smaller HFC companies' activities may have impacted on the total estimated employment of around 2,994 individuals compared to 4,289 by larger ones. This suggests a relatively balanced economic structure in the HFC TIS where neither firm size was dominant. The interviewee from Energie Baden-Württemberg (EnBW) in Karlsruhe notes an emerging degree of symbiosis between different-sized HFC companies:

> "Over the last 20 years, the big companies have spent lots of money on fuel cell development ... and now they are looking for ... the small companies who have solved their problems. And so as soon as one of the smaller companies is having a good idea ... they're being bought up by the large company. And that fits well because usually the small companies are looking for funds and partners anyway. So all our smaller fuel cell developing companies are actually in talks with larger institutions." (Interviewee GBW1, EnBW - 2011)

In terms of estimated total employees working for, *or associated with*, corporate HFC actors, German-owned companies to foreign-owned ones in 2012 was roughly 9:1 suggesting that Germany is a good institutional environment for creating and nurturing home-grown HFC firms. Nevertheless, in the TIS narrative, foreign ownership of HFC firms, large and small, is shown by the comments from the EnBW interviewee above, to be a key part of the dynamism seen in all the three sectors as HFC actors move their applications closer to the market.

Overall, the TIS event data suggests that the rise in TIS activity in Period 2 during hypes C and D was stronger, more functionally diverse and potentially more resilient than that of hypes A and B in Period 1. In fact, with an increase in all functional activity in Period 2 (Figure 32), the potential for positive feedback *between* functions was growing significantly (based on the results or the motors in Figures 41, 43, 44 and 45). This potential appears to have led to the beginnings of a system-wide commercial 'take off' by 2012 (cf. Suurs and Hekkert, 2012). My market data and extended coding of the TIS events adds to this picture by offering further insights into *where* and *how* innovation and diffusion occurred (i.e. in JVs/PPPs and unevenly in space). These extended indicators at least hint at micro-level socio-technical

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[73] Berlin's profile was considered to be overly representative of corporate headquarter operations.

processes being influenced by socio-economic processes such as path dependence. However, to more fully warrant such an assertion would require further investigations at the micro level which is beyond the scope of this thesis: Activities 2 and 4 specifically refer to the use of Innovation Studies approaches, specifically evaluating the use of the TSIS heuristic with HFCs. The micro-level influence of actor agency is most evident at the regional and sub-regional (i.e. project) levels (cf. Van de Ven and Huber, 1990, Van de Ven et al., 1999, Poole et al., 2000). However, these levels of analysis are not currently well developed in the TSIS approach which seeks an aggregated picture of change.

In order to contextualize the co-evolution of HFCs in Germany, I use the next three sections to describe how, in a narrative fashion, actors, individuals, networks, institutions and technologies interacted in the three sectors from 1995 to 2012.

5.3.6 Defence and Aerospace

The German Defence Ministry, the BMVg, undertook a desk study in 1995 about the costs and benefits of future fleets of Type 212 and 214 diesel-electric submarines with air-independent propulsion (AIP) submarines (the former for the German Navy, the latter for export) from HDW, Siemens and partners. The results of the study were positive. As I describe in Text Box 15 below, Ballard then joined HDW's contracting out PPP just as plans for a submarine hydrogen refuelling plant in Kiel began to be developed.

Text Box 15: Project-Level Narrative - German Navy's Contracting Out PPP (2)

Further testing and demonstration involved the Canadian PEMFC developer, Ballard Power Systems, in 1996/7. Ballard used one of its own air-breathing fuel cell modules which could readily go into mass production. The construction of the first full-scale hydrogen fuelling plant for submarines was completed in Kiel in 1999. The first Type 212 submarine sea trials took place in 2000 and 2001. The BMVg and HDW actively avoided any public overhyping of what the HFC-powered AIP drive could achieve. In an impressive feat of engineering, on May 1st, 2002, HDW delivered the first of six 212 Class diesel-electric submarines with fuel-cell-powered air-independent-propulsion (AIP) to the German Navy on time (the sixth and final Type 212 submarine for the German Navy was launched in 2013). The HFC AIP drive included two 120kW PEMFC modules from Siemens. Each of these could achieve nearly four times the performance of their predecessors for the same weight and dimensions. Appendix T shows that, with foreign orders and licensing, I estimate that AIP technology has so far been worth more than €10bn in turnover to German manufacturing industry. The full cycle of project development took over forty years. This might seem particularly long but it resulted in a significant technical achievement given the relatively low levels of HFC RD&D activity underway in 1959 (Psoma and Sattler, 2002).

Secondary sources reveal that there was relatively little contestation over technological pathways once the dominant design was agreed on and that was thanks to Ballard's input. For HDW, Siemens and others in Germany, networked linkage with Ballard – located in Burnaby, Canada, i.e. outside of the German national 'container' (as far as the TSIS approach is concerned) - involved a mix of knowledge flows via phone, other electronic communication and periodic face-to-face meetings.

Other market activity in the defence and aerospace sector came from SFC Smart Fuel Cell AG, based in Munich. Around the Millennium, this firm went into volume production with its range of direct methanol fuel cell (DMFC) auxiliary power units (APUs). These units can provide remote backup power on the battlefield in all temperatures. In 2002, the company started series production with around 1,000 units produced. But, due to technical difficulties with production, it continued prototyping with an exchangeable 125ml fuel tank which gave up to 100W in terms of power output. This learning experience at the manufacturing stage, along with SFC's JV with LG Chem in Korea, allowed the company to mass produce further products: the 'EFOY' appeared in 2006, the 'Jenny' in 2007 and the 'Emily' in 2009. These have been publicly procured for US and German soldiers via contracting-out PPPs and by the end of 2012 had sold tens of thousands of units.

Overall, the evidence from this and previous periods in the defence and aerospace sector, suggests that, when the federal state has a technological vision or road map, it can align actors and de-risk their activities in HFC PPPs. Decades-long governmental support with the submarine AIP drive, for example, sends the signal to researchers and entrepreneurs of "a credible and safe environment in which new energy sources and technologies can develop and mature." (Fouquet and Pearson, 2012, 4). This niche support helped to avoid the 'technology Valley of Death' - between the laboratory and the marketplace - through further coordination of state procurement and export efforts for these new HFC applications particularly for smaller firms with fewer resources marketplace - through further coordination of state procurement and export efforts for these new HFC applications particularly for smaller firms with fewer resources.

5.3.7 Transport

Automotive actors involved with HFCs converged on PEMFC propulsion with pressurised gaseous hydrogen storage as a dominant design in Period 2. This favoured Daimler's approach to HFC mobility. While private HFC activity dominated all sectors (Appendix L), strategic partnering PPPs (Appendix P) were particularly important in aligning competing corporate interests and de-risking investment in automotive infrastructure.

In 1997, DaimlerChrysler formalised its links to Ballard. A private JV, DBB Fuel Cell Engines GmbH, was designed to help recover investment costs through joint licensing of HFC technology.[74] This actor formation gave a powerful signal around the world about Daimler's long-term market intentions. Ford Motor Company soon joined these actors in another strategic fuel cell manufacturing JV, the Fuel Cell Alliance[75] and in 2001, Volkswagen, having restarted its HFC RD&D programme in 1996, unveiled the Bora HyMotion, a 75kW demonstration vehicle. In 2002, DaimlerChrysler introduced sixty all-new A-class 'F-cell' vehicles.

Public HFC activity included the formation of a strategic partnering PPP, the Transport Energy Strategy (TES), by the German federal government. Designed to identify the 'fuel of the future', TES comprised powerful multinationals including DaimlerChrysler, BMW, MAN, Volkswagen, Aral, RWE and Royal Dutch Shell who announced that a transition to sustainable mobility was inevitable. They selected hydrogen as the most-promising fuel. This offered significant legitimacy to the HFC automotive technological pathway and investment resources followed. In 2002, TES ended and was replaced by the Clean Energy Partnership (CEP) another strategic partnering PPP based in Hamburg. CEP was designed to break the HFC infrastructure 'chicken-and-egg' dilemma by delivering a network of hydrogen fuelling stations in advance of HFC vehicle sales. The interviewee from Vattenfall said of the political situation in the city-state of Hamburg in 2011:

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[74] This was in Kirchheim unter Teck near Stuttgart. PEMFC stack production remained at Ballard's headquarters in Vancouver.

[75] In 1991, Ford built the FFA in Aachen. This $35 million RD&D site, close to four academic research institutes, prototyped HFCs. In 1999, DBB became XCELLSIS GmbH, an FCA subsidiary. Two thirds of the XCELLSIS investment came from DaimlerChrysler, one third from Ballard. Engineers at Ford's US HQ in Dearborn, Michigan, had previously worked with Ballard.

> “The political will in Hamburg is very, very big, to have hydrogen and to foster participation in those projects, but at the same side it’s quite complicated to apply and get funding from the Hamburg state … Those projects [are] very expensive ... and I think the thinking … is … ‘so why should we fund this as well?’” (Interviewee GHAM2, Vattenfall - 2011)

This is where the federal-level HFC coordinating and funding body, NOW GmbH, has had significant influence. Between 2008 and 2011, for example, NOW spent 55% of its match-funded budget, totalling €216 million, on subsidizing German electric and HFC transport projects. This activity has helped in part to overcome private concerns about funding linked to delays in revenues for smaller- and medium-sized enterprises (SMEs) linked into HFC supply chains. The interviewee working for North Rhine-Westphalia Fuel Cells and Hydrogen Network (NBW-NRW) based in Düsseldorf said in 2011:

> “If you are a supplier for Daimler or also for CHP, you are doing the development maybe for five years, you have to wait another five years until you can earn money with this. And this is a problem for the small companies, and there we need help … We … are in a stage of funding [difficulty]...” (Interviewee GNRW1, NBW-NRW - 2011)

In September 2009, a Memorandum of Understanding (MOU) underpinning another strategic PPP was signed between the German government and the country’s automotive multinational corporations (MNCs) to invest in HFC infrastructure. These actors also separately signed up to an ‘H2Mobility’ programme agreeing to roll out mass-produced HFC vehicles by 2015, the importance of which was outlined by the interviewee from NOW GmbH.[76]

> “Nothing has been reported, but you’ve got all these big companies and more companies, and they’re calculating all these production pathways, and it’s highly secretive … it’s … company information … You get all these … competitors working together because they know they … cannot do it on their own, they know they need to … align the roll out of vehicles and of infrastructure because … you have to … solve the … chicken and egg problem. And they also must know

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[76] Daimler, Ford and Renault have since signed an agreement to develop a common platform for fuel-cell electric vehicles (FCEVs) to be sold from 2017.

> whether the risk for them is worthwhile. I believe generally it's the first time ever such a large scale coordinated effort between industries has been made … And this is just a knowledge base. It's a huge effort, it hasn't to my knowledge ever been like this." (Interviewee GFIN1, NOW GmbH - 2011)

The HFC lobbyist from the German Hydrogen Association (DWV) also pointed out that, in terms of technological pathways, electric vehicles and fuel cell electric vehicles are not in competition:

> "Many of these people in the battery electric fields are personally identical with the people in the fuel cell fields because the car companies are doing both! And as a matter of fact a fuel cell car is also a battery car, only the battery is smaller and the way the power comes into the battery is different. And well, the competition between fuel cell and battery is, happens mainly in public perception, not in reality." (Interviewee GLOB1, DWV - 2011)

By 2011, Daimler-Benz was able to say that, after four decades of RD&D, it had overcome the key technical hurdles of HFC mobility: performance and range.[77] A senior R&D manager working on HFC vehicles for Daimler-Benz in Stuttgart said in interview:

> "I think that the technical hurdles have been overcome a while ago. I think now it's more scaling it up to higher volumes and really bringing it into the market … The only … remaining piece of the puzzle is really to make it cheap and affordable … To do that you need simply commitment and you need high volumes." (Interviewee GMNC4, Daimler-Benz - 2011)

The interviewee from Vattenfall described the importance of the knowledge coming from working with new infrastructure:

> "We are gathering everyday experience from refuelling and running the stations. And from that we derive ... new demands for the ... technology. We also experience [the] limitations of the current legislations or rules … It's a constant process" (Interviewee GHAM2, Vattenfall - 2011)

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[77] Appendices J and K show that Daimler's knowledge development (F2) peaked at 18 events in 2003 and 2005 before tailing off to 2 events in 2012.

In late 2012, Daimler-Benz was aiming for a market launch of its HFC vehicles in 2017, having re-evaluated the ability of other German HFC actors to get the refuelling infrastructure in place by 2015. Achieving this revised timetable would continue to involve its skilled labour force, its still-evolving actor networks (partnering with Ford and Nissan to reduce production costs through standardisation), supranational, national and regional state support and the technical success in low-volume production runs of its intended B-class 'F-cell' launch vehicle.

However, an interviewee from Vattenfall, one of the energy majors involved with the CEP, was involved in building a large hydrogen filling station (HFS) in Hamburg's HafenCity inner city redevelopment site. This person said:[78]

> "We don't have a mass market for the infrastructure side … [It] is far away from that, and the costs in consequence are much too high ... So we have to deal with that. And then … the gauging of hydrogen to … be able to refuel a certain amount which can be taxed in turn is not possible at the moment." (Interviewee GHAM2, Vattenfall - 2011)

These activities of Daimler, Vattenfall and others all indicate, nevertheless, that by 2012 a significant and more coordinated shift was underway in the transport sector towards market preparedness for HFC mobility.

5.3.8 Stationary Power

In terms of stationary power, neoliberal energy market reform in the energy sector began in Germany in 1998 (see the Energy Industry Act in Table 21). Technological promises were made by German and overseas CHP manufacturers as well as energy giants that HFC micro-CHP units would be in every house and office within a few years. These rising public expectations became unsustainable from 2004 onwards when the technical hurdles proved to be more difficult. One interviewee from North Rhine-Westphalia's Fuel Cells and Hydrogen Network (NBW-NRW) was unequivocal:

> "This was a big disaster. At the end of the 90s … there was a big advertisement campaign by RWE [79] … indicating you can buy your fuel cells for your CHP system at home in the supermarket, or in the market for CHP or for heating systems … It has not [happened]." (Interviewee GNRW1, NBW-NRW - 2011)

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[78] This HFS opened in February 2012.

[79] Rheinisch-Westfälisches Elektrizitätswerk (RWE) AG is an energy multinational based in Essen.

The interviewee from Ceramic Fuel Cells Ltd (CFCL) said in 2012:

> "We never make claims about things we can't do … [S]ome people ... still haven't learnt that lesson ... we've seen other people make that mistake and we've said we're not doing that." (Interviewee GMNC5, CFCL - 2012)

Despite the public loss of faith in stationary power HFCs after this peak in hype, there was a continued private faith in the potential of 3rd generation fuel cell technologies: PEMFCs and SOFCs described in Table 1 in Chapter 1. What has made a significant difference is the number of multi-actor PPPs running extensive technical field trials. More realistic assessments of the management of HFC innovation in stationary power have been made via state guidance, for example, via NOW. State support in the pre-commercial phase for stationary power appears crucial. According to the contributor from Ceramic Fuel Cells Ltd:

> "One very, very important pre-requisite is that you do have a solid commitment from the Government, because … the early phase of such roll out of infrastructure will always be a non-profitable phase ... you need some sort of risk management or risk mitigation, something that takes away all the fear and pain from the investors." (Interviewee GMNC5, CFCL - 2012)

German domestic micro-CHP unit manufacturers in 1999 included Vaillant GmbH, Viessman GmbH and Staxera GmbH. Overseas actors who entered the German market after 1998 included the UK's Baxi Group, the Swiss SOFC manufacturer Sulzer Hexis and Australia's CFCL. At the start of this period, the challenges that still needed to be overcome were socio-technical and so have implications for theorizing innovation and diffusion:

1) keeping the electrical efficiency of the system as high as possible,
2) ensuring the long-term reliability of individual power units over thousands of hours of operation,
3) finding a dominant design, and
4) keeping costs low.

Access to skilled staff, raw materials, markets and government grants were important factors that determined the location of both domestic investment and foreign direct investment. A major federal-government-backed PPP, the ‘Callux’ micro-CHP field trial, started in 2008 (and finished in 2015).[80]

The leading domestic heating technology manufacturer, Vaillant GmbH, benefitted from two levels of governance, national and supranational. It had European-level RD&D funding in 2004 and 2007, for example, for major international research actor networks. Strategically, Vaillant was simultaneously looking at domestic and commercial markets by patenting its own SOFC-powered micro-CHP heating unit and gathering new data on PEMFC performance in micro-CHP units. However, by the end of 2012, a dominant micro-CHP design for domestic markets – where the biggest potential sales lie - still needed to emerge from field trials.

The Australian-based HFC firm, CFCL, saw the potential of locating inside the German market in the 2000s and began investing there in 2006, as I describe in Text Box 16.

Text Box 16: Project-Level Narrative: CFCL’s JVs and Public Leverage PPP

Ceramic Fuel Cells Ltd (CFCL) in Melbourne, Australia, had a proprietary SOFC-powered micro-CHP system which it had designed at its own RD&D facilities (FCB, 2005). In the 1990s, CFCL researchers had found a way of using ceramic fuel cells to electrochemically convert natural gas into electricity at up to 60 per cent electrical efficiency. CFCL’s focus was on residential markets of Europe, the US and Japan and in the late 2000s prepared to market its ‘BlueGen’ micro-CHP unit. Foreign ownership meant that links to the parent company’s fortunes might be stronger than the impact of interactions with German actors and institutions. Learning processes amongst other regionally-based companies could have been highly limited. Instead, the company swiftly made a number of strategic supplier and RD&D alliances. It opened offices in Heinsberg on the Dutch border in North Rhine-Westphalia thanks to public leverage efforts in 2006. When CFCL received its first volume order from the Netherlands), it invested €12.4 million in the construction of a manufacturing plant in Heinsberg. This was supported by a further grant from the state government in North Rhine-Westphalia worth €3.2 million. In interview, a senior CFCL manager in Germany said: “What we’re trying to do is sell products … The strongest factor at the moment is Government policy because … we’re [only] talking about sales in the 100s rather than the 1000s. So German policy has a huge impact.” (Interviewee GMNC5, CFCL - 2012). By the end of 2012,

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[80] Callux actors, and others, were expected to start selling micro-CHP units from 2016.

CFCL was leading the German HFC micro-CHP market with sales at pre-commercial volumes. Primary and secondary sources reveal the precarious nature of accessing resources, both human and financial. Organisationally, these micro-level power struggles lend themselves to socio-technical analysis of private JVs and PPPs via the enactors and selectors heuristic. CFCL revealed a well-orchestrated strategy to embed itself into regional HFC knowledge exchanges, supply chains and manufacturing networks in North Rhine-Westphalia.

In terms of the most significant PPP in the sector, the Callux field trial of 800 demonstration micro-CHP units was set up thanks to the federal-level NIP policy in 2006. Callux has so far operated over two phases and its funding is coordinated by NOW GmbH. The aim was to find a dominant micro-CHP unit design and to help prepare the route to market for HFC actors. NOW GmbH’s facilitation role has so far involved evaluation and selection of projects to be supported, the linking of R&D with demonstration projects, the setting up of international cooperative ventures, and communication and knowledge management. Callux is a PPP of actors based in Germany, but some are foreign-owned. This powerful actor network includes heating manufacturers (Baxi Innotech, Vaillant, Viessmann and Hexis), energy suppliers (EnBW, E.ON/Ruhrgas, EWE, MVV Energie and VNG Verbundnetz Gas), as well as the Center for Solar Energy and Hydrogen Research (ZSW) in Stuttgart. Total funding for the project was €86m, with the *Bundesministerium für Verkehr, Bau und Stadtentwicklung* (the Ministry for Transportation, Building and Urban Affairs or BMVBS) contributing around €40 million. In terms of the competing HFC CHP technologies, Baxi Innotech and Vaillant tested their PEMFC micro-CHP units. Hexis tested its SOFC products. By 2012, half way through the trial, both PEMFC- and SOFC-powered micro-CHP units were functioning well after a million hours’ worth of operation. The second stage of the trial focused on the pathway to the market with training, support and maintenance of the units.

5.3.9 Policy Context/Summary - German HFC TIS in 2012

In terms of the HFC TIS narrative in Germany in Period 2, the evolution of certain technological pathways was characterised by increasingly coordinated multi-level governance of energy, industry and environmental policies (shown in Table 21). Privately financed RD&D activity dominated the TIS (Figure 46), yet HFC PPPs steadily emerged and strategic partnering in particular was used to coordinate and accelerate demonstration projects. In transport, experimental evidence continued to suggest that PEMFCs were ‘winning’ the technological evolution between the competing HFC systems outlined in Table 1. However, the picture was more nuanced in defence with niche applications like SFC Smart Fuel Cell’s DMFC-powered APUs successfully going into mass production. In terms of knowledge sharing via JVs, leading actors in all three sectors had been linked at one time or another to the leading global PEMFC manufacturer, Ballard Power Systems, based in Canada.

The technical challenges in transport were shifting from the lab to the production line and the deep pockets of private enterprise remained as important as ever:

> “We are much closer to commercial application of hydrogen fuels technologies. [Y]ou’ve got more actors involved in the thing. We’ve got … more powerful actors involved. We [have] also got an interest from additional industry sectors… It needs big companies to go for large numbers, and so the future very much depends on what the large car companies like Daimler or Toyota are really up to … If they are going, if they are really going, pushing to the market, then all the other smaller companies, if their inventions and innovations, they are going to be successful, if not it’s hard for a small company to be the integrator, to develop a full system which can be run in a car.” (Interviewee GFIN1, NOW GmbH - 2011)

The Daimler interviewee felt the national government still has an important role in the HFC emerging marketplace in terms of infrastructure and competition:

> “Commitment to higher volumes is definitely very important because [otherwise], none of the infrastructure companies will invest ... to make sure that the costs go down ... The commitment could come from the industry, but it probably needs some backing from the Government. And I think another very important factor is competition ... You need at least four or five [oil] companies who are really into the technology and have a couple of years of experience ... otherwise the best company in terms of technology will simply just set the price.” (Interviewee GMNC4, Daimler-Benz - 2011)

However, a globalised industry perspective which recognises the relative power and leverage of actors is required when examining the potential relationships between national governments and multinationals:

> “You will find that the companies which are driving [HFC] development are global … because Daimler may be a German company but they … [are] in North

> America and also in East Asia. And Toyota may be a Japanese company, but they have factories in the UK … So the distinction between the national borders, they become less and less important.” (Interviewee GLOB1, German Hydrogen Association, DWV - 2011)

In Period 2, pure science research at universities and institutes was said to be declining in favour of private HFC activity:

> “It’s really about innovation and innovation is more than just about novelty. It’s about bringing novelty to the market. [This is when] you need a stronger input by industry ... There are sixteen institutes for large-scale basic research ... and they have a lot of expensive equipment [and] resources ... and this is what you need. If you have only one professor in [a] chair, this is difficult in a technical area really to advance a lot because ... a research programme requires a lot of budget.” (Interviewee GFIN1, NOW GmbH - 2011)

The interviewee from Daimler-Benz confirmed this view is held in the German HFC transport sector:

> “I think we’re beyond [open source sharing with universities]. I think at this point in time it’s all in-house and maybe you have, I mean you do have a few suppliers, but it’s not basic research anymore.” (Interviewee GMNC4, Daimler-Benz - 2011)

Also, a number of interviewees reported that the defence and aerospace sector had already produced commercial HFC products and that the transport and stationary power sectors would do so relatively soon after 2012.

In summary, by 1998, the main planned applications in the three most active sectors – defence and aerospace, transport and stationary power – were submarines, motor vehicles, and remote power/back up power/micro-CHP units, respectively. Evidence from demonstrations and testing continued to suggest that PEMFCs would win out in technological terms in defence and aerospace, and transport because the lower operating temperatures help with user comfort and safety. However, certain stationary power applications also favoured high temperature solid-oxide fuel cells (SOFCs) (see Table 1 in Chapter 1) and it was recognised that further field testing would be needed before a dominant design would emerge for domestic markets. A barrier emerging in Period 2 is an emerging skills shortage in the HFC TIS. Young people in Germany were increasingly opting out of more traditional science and engineering careers and going into the media, for example (Cremer, 2011):

> “Already nowadays we have a lack of engineers here … And this is a problem … and we try to do anything against it … supporting these activities to bring young people into the scene and to motivate an interest in technology.” (Interviewee GNRW1, NBW-NRW - 2011)

Apart from HFC unit costs, another barrier mentioned by the interviewee from Daimler-Benz is the oil and gas industry and the path dependence of its associated infrastructure:

> “We’re trying to be active in a business environment that has been and is still occupied by the very, very mighty oil industry. So that makes it extremely hard to either convince the oil industry to be part of that, or to convince others to take over some of that role from the oil industry … you definitely need partners … to solve the chicken and egg dilemma [of infrastructure provision] … [When it comes to HFC mobility] we’re the ones pushing the car, but the government is sitting in the driver’s seat and steering it, and then the oil company is reaching for the brake pedal!” (Interviewee GMNC4, Mercedes-Benz - 2011)

With such barriers in mind, the interviewee from an HFC lobbying group in Germany nevertheless concluded that:

> “[The German government] has created a general climate which is very favourable and which is also the reason why Germany … is one of the most important centres of development” (Interviewee GLOB1, DWV - 2011)

In the next section, I give my warranted assertions about German HFC TIS activity based on triangulating all the data sources presented in this chapter.

5.4 Findings / Assertions – Evolution of the German HFC TIS

In this penultimate section, I give my findings, or warranted assertions, about the German case study in the context of Activity 2 (cf. Smith, 1997). Text Box 4 in Chapter 1 says that Activity 2 involves “characterising HFC innovative activity in the UK and Germany between the 1950s and 2012 via two case studies that draw on qualitative and quantitative data and are informed by innovation theory”. Events and processes should focus on *how*, *when* and *where* they occur. I divide my warranted assertions below into what was revealed about the German HFC TIS via the TSIS indicators of Hekkert et al. (2007a) and secondly what was revealed by my extended indicators.

The TSIS approach helped me to identify a longitudinal picture of structural, functional and technological co-evolutionary change in the German HFC TIS. From this perspective, institutional governance of the TIS was largely shaped by regime-level legislative responses – whether supranational, national and regional - to external landscape-level events (cf. Geels, 2010). From 1959, German public and private actors in two periods of activity organized themselves into increasingly powerful and sophisticated private JVs and PPPs (cf. Soecipto et al., 2015). Such projects in Periods 1 and 2 were generally resilient (cf. Walker et al., 2004, Fiksel, 2006). HFC actors were largely motivated to reduce the inherent financial risks of RD&D. German HFC research was world-class in both periods (Huang and Yang, 2013). What was less evident from the TSIS approach was: i) how the emerging HFC technological pathways in each of the three sectors of interest were contested in both periods (in particular how such contestations were subject to power relations between individuals and actors) (cf. Avelino and Rotmans, 2009), and ii) the utility of consolidated spatio-temporal TIS event data (cf. Louis, 1982, Onwuegbuzie and Teddlie, 2003) in terms of the impact of an expanded dataset on understandings of the nature of causality between events (Coenen et al., 2012, Binz et al., 2014).

5.4.1 TSIS Indicators

In terms of the TSIS indicators, an emergent division in the rate and number of TIS events from 1996 onwards. This division suggests the beginnings of a system-wide transition towards more sustained positive feedback (cf. Hekkert et al., 2007a, Suurs and Hekkert, 2012). Rises and falls in functional activity were revealed by the motors of sustainable change approach which proved to be dominated by knowledge development in both periods. HFC innovative activity during the resulting hype cycles (C and D) was linked directly and/or indirectly to global oil, environmental, political crises as well as to financial speculation. Resilience was in evidence in Periods 1 and 2 although Period 2 revealed more resilient activity than in Period 1 (cf. Walker et al., 2004, Fiksel, 2006). German scientists and engineers, were initially led by *key individuals*, August Winsel at Varta and Eduard Justi at Siemens (cf. Ehret, 2004). They started making significant progress in overcoming a number of technical barriers associated with HFCs. In spite of specific barriers to innovation and diffusion, chiefly in the functional areas of guidance of the search, resource mobilization and advocacy coalition areas, these actors entered into corporate JVs and early PPPs (involving public leverage and contracting-out). In an institutional environment dominated by the state funding of nuclear RD&D, German HFC actors managed to increase knowledge development activity during hype B. But this diffusion was constrained in large part by reduced access to resources following on from the drop in oil prices post-1979. This shift delegitimized HFCs in the eyes of German policymakers and made acquiring resources, especially public funds, difficult for actors (cf. Unruh, 2000, Garud et al., 2010). The influence of individual private project managers, for example at Daimler-Benz, was crucial in terms of actors choosing to continue with their HFC programmes (Ehret, 2004).

In Period 2, by contrast, the resilience of German HFC RD&D actors was revealed by the TSIS approach's motors to be greater (cf. Walker et al., 2004, Fiksel, 2006). Up to 2012, actors continued to try to reduce financial uncertainties, boost the recombination of knowledge and organize the coordination of RD&D and plan for manufacturing with the pro-active support of the state. Positive feedback appeared to be occurring, particularly from 2002 onwards (see motors' results in Figures 41, 43, 44 and 45), as both public and private activity increased (cf. Hekkert et al., 2007a, Suurs and Hekkert, 2012). By 2012, Germany's HFC TIS functions appeared particularly well varied with tallies in every category except advocacy coalitions. Noticeably, German HFC transport actors in Period 2 built on their historic comparative advantages in working with HFCs in Period 1. The rise in knowledge development post-2002 was stronger in the transport sector than in defence and aerospace (and stationary power) and there were many new entrants (cf. Ehret and Dignum, 2012). A new period of hype – D - was building up from 2007 onwards giving further longitudinal evidence of the uneven timing of socio-technical processes chiefly in terms of *where* cumulative causation was likely occuring in the German HFC TIS.

5.4.2 Extended Indicators

The extended indicators enriched the picture of HFC innovation and diffusion by going beyond the TSIS's neofunctional approach to increase the emphasis in analysis on 1) *organizational funding*, specifically PPPs because of their ability to increase actor agency (Hodge and Greve, 2005, Roehrich et al., 2014), and on 2) *geographical location* because of the contribution to spatio-temporal understandings of causation (Coenen and Díaz López, 2010, Coenen and Truffer, 2012).

Firstly, in terms of event ownership, these extended indicators reveal that Germany has deployed a number of HFC PPPs ranging from public leverage to strategic partnering (see the typology in Table 4 in Chapter 2). Early German contracting-out PPP efforts with HDW and partners succeeded and showed resilience in large part because of the German Ministry of Defence's ability to commit to a long-term partnership (cf. Fouquet and Pearson, 2012). The lack of policy interest after the fall in oil prices in the 1980s revealed relatively weak networked agency and few prospects for innovation and diffusion. However, in Period 2, Germany witnessed a very significant rise in private HFC activity (Figures 46 and 47, Interviewee GFIN1, NOW GmbH - 2011). There was also an evolution in PPP activity – suggested by the typology in Table 4 in Chapter 2 - from public leverage and contracting-out and more towards strategic partnering (Figures 48 and 49). Hypes A, B, C and D coincided with the periods of greatest change in German TIS event numbers (i.e. when collective agency was at its greatest). Sectorally, HDW and Siemens were working in defence as part of Germany's 1st PPP with submarine propulsion. The resilience of this activity was strong because Germany's defence policy was linked to a long-term industrial policy. State procurement linked to defence contracting-out PPPs in Period 2 suggests a recognition by the German state of the need to protect these HFC niches which involve class-leading technologies (cf. Rodrik, 2013, Lember et al., 2014a). The extended organizational data on the transport sector revealed that, in Period 2, the emergence of the German HFC Mobility PPP in 2009 came on the back of Daimler, chiefly, having worked on HFCs for several decades. In the stationary power sector in Period 2, PPPs were used to help find dominant HFC designs. In all three sectors, there was evidence of state-led path creation.

Secondly, my other extended indicator covering geographical location permitted data consolidation to occur with my neopragmatic methodological framework (cf. Louis, 1982, Onwuegbuzie and Teddlie, 2003). I thus merged the time-dependent and spatial data to create an expanded dataset which reveals a very uneven *spatio-temporal* picture of innovation and diffusion by region between 1959 and 2012. This aspect of the evolution of the HFC TIS was linked in part to uneven structures of spatial governance – i.e. relative levels of devolution in the German federal system - and a 'varieties of capitalism' assessment of Germany as a coordinated market economy (cf. Hall and Soskice, 2001).

In terms of territorial analysis, the three Länder where most knowledge development activity first took place in Period 2 – Baden-Württemberg, Bavaria and Hesse, in that order – were the ones where TIS events first occurred in Period 1. This suggests there was a degree of path creation and path dependence at work (Grabher, 1993, Garud et al., 2010). Relative regional growth with many new entrant regions mainly occurred after 2002 (Figure 51) as HFC knowledge development activity diffused to North Rhine-Westphalia, Rhineland-Palatinate and Hamburg. In each state, there was long-standing access to academic/industrial research centres and/or a workforce with specific engineering and research skills. There was multi-level governance to support access to local resources. However, activity in these new regions grew more slowly than in the dominant one, Baden-Württemberg, whose high levels of activity were due to the dominant impact of Daimler within the historic centre of the car industry clustered around Stuttgart (cf. Mans et al., 2008). Such regions fared better over time thanks to historic global and local academic-industry links – i.e. ‘global-local’ connections - underpinning the institutional embeddedness of clustering activity (cf. Braczyk et al., 1998, Heidenreich, 2004, Heidenreich, 2012a).

Regional growth differentials in knowledge development (F2) (Figure 51) and entrepreneurial activity (F1) (Figure 52) were shown to at least correlate in a weakly positive fashion with the regional use of strategic partnering PPPs (Figure 53). This relative pattern of diffusion suggests that the large HFC actors active in Period 1 were likely building on their historic competitive advantage (but finding the precise socio-technical processes at work from aggregated data is difficult). The longitudinal evidence of regional shifts in knowledge development, where early innovation leads to later diffusion, is suggestive of a degree of path dependency based on historic competition for access to resources (Grabher, 1993, Morgan, 2013). To more fully warrant such an assertion would require further investigation of innovation and diffusion at the micro level, i.e. the project-level, which is beyond the scope of this thesis.

Ultimately, the consolidated spatio-temporal indicators suggest that the beginnings of cumulative causation is likely in evidence in Germany by 2012 and is occurring unevenly in time *and* space (Coenen et al., 2012, Binz et al., 2014). The first regional movers from Period 1 drew on access to historically unevenly grouped human and financial resources in pre-existing centres of industry. However, post-2000, state-backed HFC activity has also encompassed attracting investment in ‘hoped for’ HFC clusters with global and local academic-industry linkage (cf. Mans et al., 2008). In the German TIS narrative, linkage was shown to be geographical *and* relational and appeared to underpin the embeddedness of resources in historical and some new clusters (cf. Braczyk et al., 1998, Heidenreich, 2004, Heidenreich, 2012a). The ‘extended indicators’ help to achieve a better understanding of the nature of HFC innovation because they reveal that individuals at the project level – who are networked in teams, funded in distinct ways and located in particular places – do have an impact upon how events play out on the ground (Van de Ven et al., 1999, Poole et al., 2000) and so need to be factored into conceptions of causation (cf. Ehret, 2004). This use of extended indicators recalls the realist approach known as methodological situationism which suggests that social systems are created in local areas and that actor behaviour is shaped by a response to immediate situations (Duncan, 1989, Day and Murdoch, 1993, Massey, 1993, Massey and Jess, 1995, Murdoch and Marsden, 1995). Proponents claim that, contrary to neofunctionalism, locality is not the result of general structural processes, but is rather the outcome of networked associations in actor-space. This point underpins the critique of neofunctionalist innovation models made by Coenen et al. (2012) which I return to it in Chapter 7.

5.5 Conclusion

To conclude this chapter, I note that I have completed the second half of Activity 2. This involved describing *how*, *when* and *where* innovation and diffusion activity occurred in the German HFC TIS between the 1959 and 2012. I then offered warranted assertions about the emergent trends in the German HFC TIS based upon the triangulation of all data sources. Constructing this national HFC TIS events narrative has also allowed me to reveal how, methodologically, the TSIS indicators and my extended indicators have performed in terms of offering insights into the nature of socio-technical change with HFCs in Germany. My warranted assertions about the German HFC TIS now feed into a comparative analysis of both case studies in Chapter 6. I compare what the TSIS functional analysis and my extended indicators have revealed about HFC socio-technical processes in both countries. Based on the warranted assertions given at the end of Chapter 4 and here, I now assess in Chapter 6 which socio-technical processes appeared most important to the evolution of these two HFC TISs. This chapter's results also feed into Chapter 7's methodological and policy discussions.

Chapter 6: Findings from UK & German HFC TIS Comparison

6.0 Introduction

In this chapter, comparative findings from the two case studies are given in order to answer my second research question:

2) Which socio-technical factors have had the most influence on the nature and pace of HFC innovation and diffusion in these national cases and why?

Chapter 1 established how hydrogen fuel cells (HFCs) are a disruptive technology with the potential to help policy makers adapt to climate change by decarbonizing national, regional and local energy systems (Hardman et al., 2013). In Chapter 2, I gave a theoretical critique of the use of Innovation Studies' approaches. This critique was divided into four interlinked and emergent themes involving the Innovation Systems, Systems Innovation/Technological Transitions and the Sociology of Expectations strands of theorizing. These themes cover: a) micro-macro conceptions of actors' agency and structure, b) system delineation, c) system indicators, and d) policy guidance. I also suggested that, in the policy debate over whether or not HFC innovation could be encouraged anywhere (Mans et al., 2008), specific knowledge gaps exist about the nature of HFC innovation and diffusion. Then, in Chapter 3, I proposed a neopragmatic research design to investigate HFC innovation and diffusion in the UK and Germany. The research design was informed by the Technologically-specific Innovation Systems (TSIS) heuristic from Innovation Studies, an approach I had used in a prior study (cf. Hekkert et al., 2007a). Four modifications to the TSIS heuristic were made with this thesis to help overcome the methodological concerns that I had found whilst identifying knowledge gaps. These modifications included two extended indicators used with Event History Analysis, the organizational funding of events and their geographic location. This additional data added greater confidence to my warranted assertions – or meta-inferences - about the nature of the socio-technical processes at work with HFCs which are made at the ends of Chapters 4 and 5 respectively (cf. Smith, 1997). By the end of Chapter 5, I had answered Research Question 1 which sought evidence of *how*, *when* and *where* the innovation and diffusion of HFC technologies took place in the UK and Germany between the 1950s and 2012.

In this chapter, I have triangulated data from the expanded and consolidated datasets and about the evolution of the UK and German TISs. This helped me to identify the leading socio-technical processes involved with HFC innovation and diffusion in the UK and Germany. Just as in Chapters 4 and 5, these findings (warranted assertions) go beyond the seven TSIS indicators to include my extended coding of *organizational funding* and *spatio-temporal* aspects of agency and structure which the evidence suggests are linked to the socio-technical processes known to be at work (Hacking and Eames, 2012, Contestabile et al., 2013).

In terms of the structure of this chapter, I briefly summarize the comparative UK-German analytical picture in both periods in Section 6.1.1 below. I do this via the TSIS heuristics' seven functions of innovation. In Sections 6.1.2 and 6.1.3, I look at the comparative results of my extended indicators. In Section 6.2, I integrate all available evidence (and previous warranted assertions) and identify the socio-technical processes which appear most important to HFC innovation and diffusion on the basis of the evidence from both countries. Finally, these new warranted assertions, based on comparative analysis, feed into the methodological and policy analyses in Chapter 7 (cf. Tashakkori and Teddlie, 2003, Plano Clark and Creswell, 2011).

I begin Section 6.1 below with a short comparative summary of the TSIS indicators for each country.

6.1 Comparative Analysis Summary

In this section, I re-establish the structural and functional themes of my analysis before getting into the comparative analysis below.

As per the TSIS approach, the structural themes remain the institutions, technologies, actors and networks as seen with the national TIS narratives. The focus on the seven functions of innovation also remains the same (cf. Hekkert et al., 2007a, Suurs and Hekkert, 2012). Ultimately, in answering Research Question 2, the analysis provided below will also reveal the potential added value of my extended indicators to the TSIS heuristic's methodological approaches (which I discuss in Chapter 7).

6.1.1 Findings from Comparative Analysis of TSIS Indicators

In Chapters 4 and 5, I undertook TSIS analysis for HFC activity in both countries (cf. Hekkert et al., 2007a). I achieved this analysis through coding HFC TIS events both in terms of positive and negative contributions to innovation and diffusion and in terms of the seven functional indicators. As Figure 54 and Figure 55 reveal comparatively, both countries showed systemic shifts from relatively low HFC activity in Period 1 to relatively higher activity in Period 2. However, as these comparative figures suggest, the UK and Germany were clearly on different technological pathways over time with

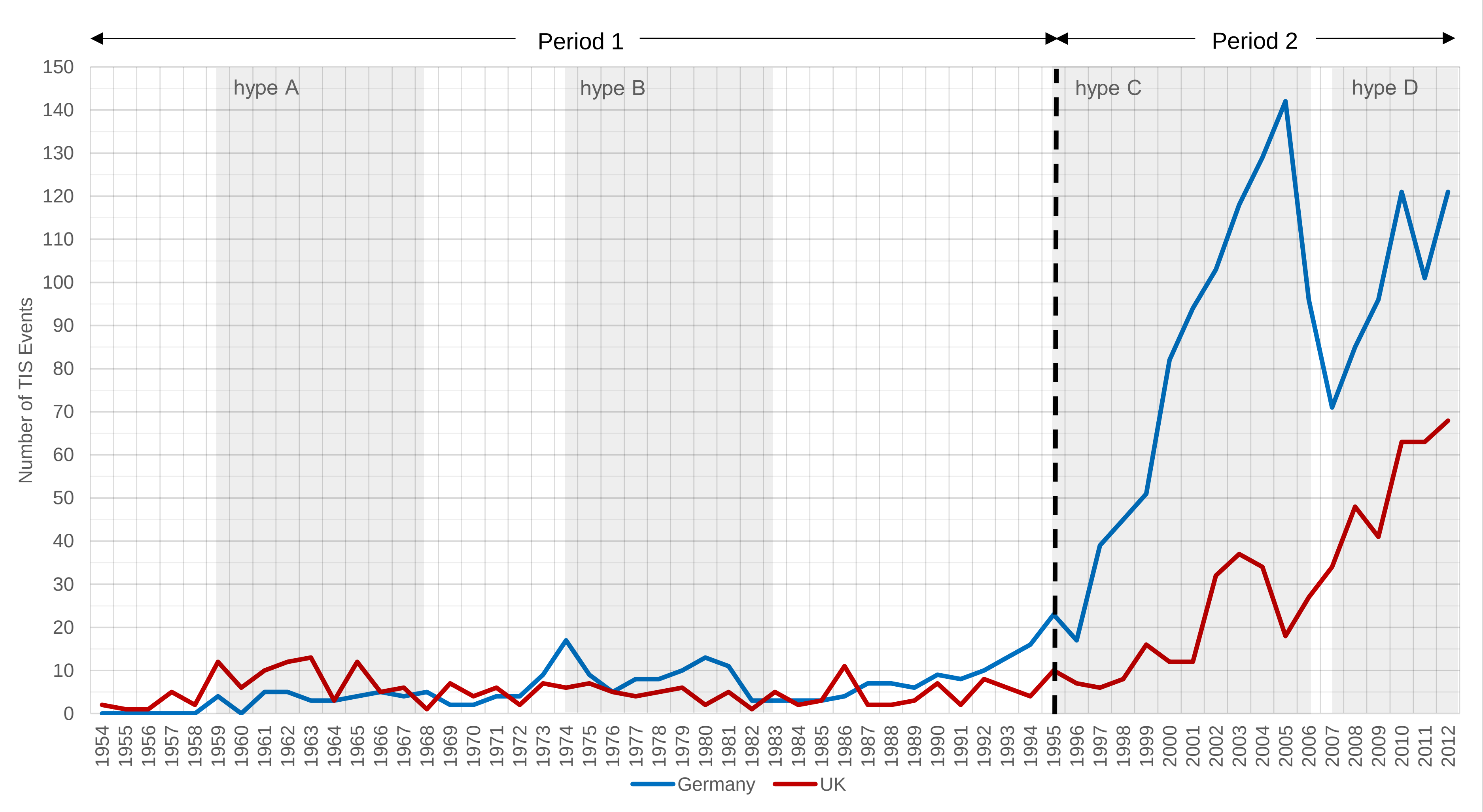

Figure 54: Annual Totals of All HFC TIS Events for the UK and Germany, 1950s-2012

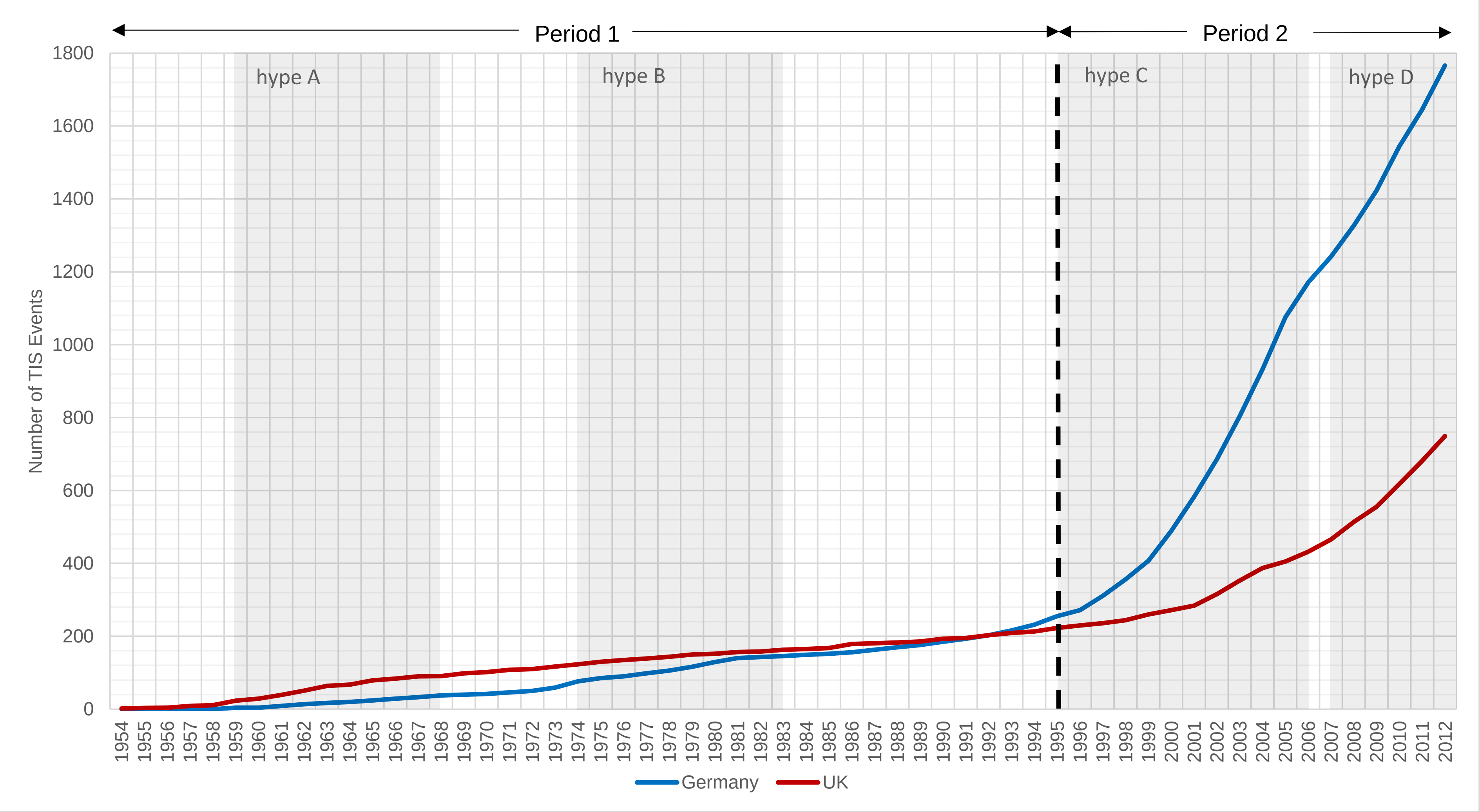

Figure 55: Cumulative Totals of All HFC TIS Events for Germany and the UK, 1950s-2012

the development of a range of HFC technologies (cf. Williamson, 2010, Contestabile et al., 2013).

Throughout each national TIS event narrative, there were coincident periods of global hype – A to D - indicating the specific impact of external global events on both of these national TISs (these hype periods are shown for the UK in Figure 10 in Chapter 4 and for Germany in Figure 32 in Chapter 5) (cf. Fenn and Raskino, 2008, Bakker, 2010a, Ruef and Markard, 2010, Konrad et al., 2012).[81] Such external events included oil crises, environmental concerns and political events (sometimes in combination). The TSIS approach anticipates rapid innovation in response to these system shocks followed by longer periods of incremental change (Hekkert et al., 2007a, Suurs, 2009, Suurs et al., 2009, Suurs and Hekkert, 2012). This was largely borne out by the two TIS narratives. In terms of the TSIS analysis, both countries also appeared to show similar 'motors of sustainable change' beginning to appear in Period 2 (as shown for the UK in Figures 19, 21, 22 and 23 and for Germany in Figures 40, 42, 43, 44 and 45). Comparative empirical evidence of such a shift has not been reported elsewhere.

In terms of analysis of the TIS events' numbers and functions, Germany had roughly four times as much overall activity in Period 2 while the UK's TIS events were more qualitatively varied than Germany's by 2012. The increasing number and diversity of functions witnessed in both countries when moving from Period 1 to Period 2 revealed an increased level of relative resilience of TIS activity in the later post-hype phases (cf. Walker et al., 2004). In Period 1, for example, hypes A and B produced some limited functional diversity in the UK and Germany respectively beyond a steady low-level stream of knowledge development activity. However, this activity was rarely resilient. In both countries, HFCs were locked out of energy policy to a greater or lesser extent between 1974 and 1994 (this lock out process was stronger for actors in the UK).[82] By contrast, the HFC activity in hype D from 2007 in both countries appeared much more resilient. HFCs had a recognised place in energy policy and proponents were apparently building on the gains made in hype C (i.e. post-1995) when cumulative causation between functions appears likely to have begun to be involved (Figures 21, 22, and 23 for the UK and Figures 43, 44 and 45 for Germany).

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[81] See Section 2.3.3 for a discussion of hype cycle literature.

[82] Appendices D and AA show respective breakdowns of UK and FRG energy R&D spending between 1974 and 2012. In both cases, there was heavy historic spending on nuclear R&D.

Overall, in terms of answering Research Question 2, the uneven timing of the socio-technical processes underpinning HFC innovation and diffusion appears to be closely linked to:

a) the institutional context where, in response to external events, ever-increasing top-down and bottom-up regulation was appearing, and
b) whether or not cumulative causation was contributing to system resilience.

However, a degree of methodological situationism was also in evidence in Chapters 4 and 5 – for example with high fuel costs driving the demand for innovation in the Scottish Isles and the clustering of research and entrepreneurial actors in urban centres - and this was impacting the socio-technical processes revealed in the UK and Germany by the TSIS heuristic (cf. Duncan, 1989, Massey and Jess, 1995, Hacking and Eames, 2012, Coenen and Truffer, 2012).

In the next two sections, I therefore give the comparative results of the extended coding of organisational funding and geographical location which was designed enhance the TSIS methodological approach.

6.1.2 Findings from Comparative Analysis of Organizational Funding Indicators

In this section, I examine the first of my extended indicators, the organisational funding of TIS events. In order to answer the second research question about which socio-technical processes were most important, I want to assess what impact funding type had on the socio-technical processes underpinning HFC innovation and diffusion in each country. The impact of funding type is highlighted in the discussion below in terms of barriers to and enablers of innovation and diffusion in these HFC TISs. My additional institutional coding was based on distinctions for all TIS events between funding that was: a) public only, b) private only, c) public-private partnerships (PPPs), and d) public and private funding (with no partnership). The events coded for PPPs were then further categorized into my own typology that revealed increasing sophistication over time. The PPP typology in Table 4 in Chapter 2 shows that these categories, in general terms, evolved in sophistication from public leverage to contracting-out, to joint ventures (JVs), and ultimately to strategic partnering (cf. Skelcher, 2005). This suggests a greater recognition by these two states that, over time, the emergence of a set of clean technologes like HFCs from protected niches into the marketplace still needs significant and nuanced state coordination with public and private actors. Such multi-level coordination leading to a transition is more overtly recognised in heuristics like Strategic Niche Management than the TSIS (cf. Kemp, 1994, Kemp et al., 1998b).

In the context of funding type, Figure 24 and Figure 25 in Chapter 4 reveal that private and PPP funding of HFC TIS events in the UK involved roughly similar numbers of TIS events over time. This was contrasted by the situation in Germany, shown in Figure 46 and Figure 47 in Chapter 5, where, post-1995 private funding far outstripped PPP funding (particularly during hype C). Of all the TIS events coded as ‘PPPs’, the UK outdid Germany with its total TIS event numbers. However, the UK and Germany showed very similar rises in strategic partnering PPPs from 1998 up to 2012 (see Figure 26 and Figure 48 respectively). These rises appear to reflect global rises in HFC knowledge development activity as indicated by increasing patent filings in the US, China, Canada, South Korea, Japan, for example (Huang and Yang, 2013). Also, in both the UK and Germany, strategic partnering appeared similarly positively correlated to knowledge development (F2) and entrepreneurial activity (F1).[83] These correlations, in conjunction with the other TSIS analysis above, imply that the socio-technical processes involved in strategic partnering PPPs – trust building, knowledge sharing, legitimacy building, devising road maps, appointing political champions, de-risking efforts, etc. - are effective ways for the state to be involved in promoting innovation and diffusion of HFC technologies (see Table 4 in Chapter 2 for the typology of PPPs).

An analysis of the reasons why these similarities and differences have existed comes down, at least in part, to a ‘varieties of capitalism’ explanation outlined in Sections 1.4.5 and 2.5.2.1 (cf. Hall and Soskice, 2001, Mikler, 2009). In this case, the spatial context - whether at the national and/or regional levels – appears to have had an influence on the socio-technical processes at work something few HFC studies note. Both private and state-led HFC activity in Germany occurred in a coordinated market economy, or CME. HFC activity took place in the context of a country where, historically, non-market relations, collaboration, credible commitments and deliberative calculation on the part of firms are important. Firm innovation and investment behaviour in Germany depends on long-term employment strategies, rule-bound behaviour and durable ties between firms and banks (cf. Hall and Soskice, 2001, Kang and Park, 2011). This context-specific socio-economic situation, supports and enables patient capital provision, in general, and makes firms more

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[83] In the UK, the correlations were 0.36 and 0.42 respectively (Appendix X) and in Germany they were 0.49 and 0.46 respectively (Appendix AU).

likely to be incremental innovators because they have the resources to methodically improve upon innovations over longer time frames. In this context, German firms are thought to be more likely to focus on specific or ‘co-specific’ assets whose value depends on the active co-operation of others. By contrast, the UK can be usefully portrayed as a liberal market economy, or LME, much closer in financial practices to the US than continental Europe. In the UK, HFC firm activity takes place more in terms of arms-length, competitive relations, competition and formal contracting, and the operation of supply and demand in line with price signalling. In the UK, in general, fluid labour markets fit well with enabling easy access to stock market capital and the profit imperative. Crucially, this national approach to capital is thought likely to make firms act as radical innovators in a range of high-tech and service sectors (Hall and Soskice, 2001). Nevertheless, the UK’s strengths can also act as barriers. The financial footing of these UK-funded actors, for example, can be precarious given relatively shorter term investment horizons on the part of institutional investors (cf. Kang and Park, 2011).[84]

Returning to the empirical TIS event narratives, early in Period 1, the UK national economy was behaving more like a CME. In the 1960s and 70s, however, public leverage efforts failed to encourage UK actors to more fully develop demonstrations based on Bacon’s AFC patents. Resilient activity in Period 1 in both countries only occurred via contracting-out PPPs with defence actors in very narrowly defined niches, i.e. submarines, something not analysed in secondary sources. This niche activity was well resourced and centred on finding class-leading technologies with strategic advantages. Sustainability gains were considered incidental. These submarine technologies were protected in their niches over the very long term by specific Cold War defence requirements (cf. Kemp et al., 2001, Kemp et al., 2007b, Mazzucato, 2013). This made these PPPs ideal for incremental innovation (cf. Fouquet and Pearson, 2012). Historians have suggested that the problem in Period 1 was that in the UK - at least up to 1974 - civil servants involved in HFC PPP activity lacked sufficient commercial acumen (Eisler, 2009, Wilson, 2012). Advantageous terms for patent licensing and successful project-level direction amongst private PPP partners were relatively poor, as was the case with the state-supported joint venture, Energy Conversion Ltd. Between 1974 and 1994, relatively little could be achieved at all - publicly and/or privately in both countries - because of the relative degrees of lock out for HFCs from national energy policy (cf. Unruh, 2000). After the oil crises of

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[84] According to Kang and Park (2011), the logic of firm dynamics in CMEs revolves around ‘switchable assets’ whose value are best realized if they are deployed in multiple ways.

1973 and 1979, HFC actors had assets and resources cut as political priorities for energy shifted with formal energy policies. The result was that 1974 to 1994 was a time of relatively weak networked agency, i.e. poor resilience, for HFC actors in both countries (cf. Walker et al., 2004, Fiksel, 2006). The TIS event data, which was coded for the seven TSIS functions and for funding status of TIS events, reveals that there were few prospects for diffusion of HFC technologies up to the end of Period 1. Unlike in Period 2, almost all the knowledge development that did take place in Period 1 in both countries was enabled by large, private engineering multinationals who could afford, alone and/or in JVs, the long-term and costly commitment needed with HFC RD&D.

My extended coding regarding organisational funding also reveals that the UK and Germany witnessed an evolution over time from public leverage PPPs towards strategic partnering ones in the PPP typology (Figure 26 and Figure 48 respectively). Explaining this shift, which is not reported elsewhere, similarly involves the place-specific nature of each country's approach to capital (cf. Hall and Soskice, 2001, Mikler, 2009). In the UK, Period 1 witnessed more coordinated state activity involving public leverage and some formal contracting-out, but by 2012 a more neoliberal approach with many strategic partnering PPPs had become the norm for state involvement in HFC RD&D and infrastructure provision (Figure 26). In Germany, broader national moves towards a more liberal market approach to capital, encouraged in part by Directives at the EC level, were witnessed in the 1990s and 2000s with the rise of strategic partnering shown in Figure 48. However, the state's role in attracting private investment to the HFC sector appeared proportionally more effective in Germany with less PPPs: by 2012, private TIS events cumulatively represented 78% of all German TIS events, compared to the UK's figure of 49%.[85] Of the two countries, the greatest agency was exercised by the state in the UK: hypes C and D coincided with the periods of greatest PPP activity there (cf. Soecipto et al., 2015, Verhoest et al., 2015).

This PPP activity, when analyzed sectorally, also highlighted context-specific barriers to and enablers of change. In defence, in the UK, a first mover, contracting-out PPP between the Navy and CJBD Ltd emerged in 1958 to supply submarine electrolysers. This was thanks in part to a technology transfer with the US military. However, further diffusion of submarine HFC technology by CJBD was limited in the 1960s to the production of a single electrolytic water treatment plant on Guernsey

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[85] In the UK, by 2012, 358 TIS events out of 725 (49%) were privately funded compared to 1,374 out of 1,771 (76%) for Germany.

after which time the UK shipbuilding industry collapsed forcing the Navy to bring CJBD in-house. That particular HFC effort, plus VSEL's attempt to develop HFC-powered air-independent propulsion in the 1980s and 1990s, ended for external economic and political reasons respectively. A specific barrier in both cases, typical of many LMEs, was the UK state's lack of a *long-term* industrial policy (cf. Rodrik, 2007, Rodrik, 2013). In Germany, by contrast, HFC defence activity succeeded thanks to the long-term commercial vision of the German Ministry of Defence (BMVg). The BMVg linked the delivery of its future naval defence requirements to exports via planned public procurement and a contracting-out PPP. This PPP, coordinated by a state-owned shipbuilder, provided increased agency (and hence greater access to human and financial resources). Nevertheless, by 2012, there were several HFC defence contracts in both countries each linked to state procurement and each with the longer-term potential to diffuse HFC technologies further by bringing down unit costs (cf. Eames and McDowall, 2010).

In the transport sector, the TIS narratives revealed quite stark structural differences between the two countries. These differences are based chiefly upon the fact that Germany had a consistently successful home-grown vehicle industry since at least the 1970s whereas the UK did not (at least from the late 1970s to the late 1990s). This meant that when very significant HFC PPPs like the Germany's 'HFC Mobility' programme, launched in 2009 (Table 21), it was different in scale and potential. This difference was thanks to its networked partnership as compared to its UK counterpart PPP, 'UK HFC Mobility', launched in 2012. The UK has no equivalent homegrown multinational motor vehicle manufacturer with the resources to match Germany's Daimler and its HFC path creation. The TIS narrative in Chapter 5 made clear that Daimler pioneered many innovations in HFC mobility and stuck with continuously investing in HFC RD&D right up to 2012 thanks to much state support (cf. Mazzucato, 2013). Again, in the transport sector, comparative analysis of these sorts of socio-economic enablers and barriers partly comes down to the varieties of capitalism approach (cf. Hall and Soskice, 2001, Mikler, 2009). The empirical evidence of Chapters 4 and 5 suggests that, nationally and regionally, different approaches to capital helped to determine the historic growth (or lack of it at times in the UK) of each country's transport sectors (cf. McNicol, 1999, Ehret and Dignum, 2012). Such differences centre on the levels of state support given to HFCs and the commitment to a long-term (green) industrial policy involving each country's vehicle industries (cf. Rodrik, 2013). Both of these elements were in evidence in Germany between 2000 and 2012, but only the former has existed in the UK.

While both states have attempted to create/support HFC technological pathways for mobility applications in Period 2 through the use of PPPs, not picking winners, choosing ‘technology pull’ rather than ‘technology push’ policies, etc., the German central state was shown via its TIS events narrative to be much more ‘hands on’ with funding and coordinating activity than the UK central state was in the same time period. This was thanks in large part to the influence of Die Grünen on the ‘red-green’ alliance with the SPD up to 2005, and subsequent political pressure by the greens both in the Bundestag and in several Länder, like Baden-Württemburg, where a red-green coalition was established with the rightist Christian Democratic Union (CDU) in 2011 (Interviewee GMNC4, Daimler – 2011). In both cases, the Greens seek stricter environmental governance and have been prepared to champion renewable energy and storage schemes linked to HFCs.

Finally, in the stationary power sector, the PPPs that I identified in Periods 1 and 2 in both countries were helping to establish dominant designs. This was occurring both during hype A in Period 1 and in the lead up to 2012 (cf. Hekkert and den Hoed, 2004). Such state-led path creation which, latterly in Period 2, was more well-organized and well-coordinated in Germany than in the UK (cf. Garud et al., 2010, Binz et al., 2016). During hype A in Period 1, the UK joint venture (JV) PPP, Energy Conversion Ltd, set out to develop an HFC micro-CHP unit. Unfortunately, this PPP ended without making the hoped-for advances in large part for a lack of government coordination of its commercial partners. Chapter 4’s TIS narrative revealed that, in the UK, there had been no roadmap to successfully bind the commercial partners’ divergent interests together and there was no political champion at a senior level (cf. McDowall, 2012). Without legitimacy and resources, Energy Conversion Ltd.’s HFC unit lost out to competing technologies. Ultimately, partner confidence ebbed away and this HFC RD&D work was brought entirely into government control at Harwell. By contrast, in Germany, PPP activity on HFCs and stationary power started between academic and industrial actors in Bavaria in 1980s. By 2012, the state body NOW GmbH was involved in well-coordinated and well-resourced, state-led path creation via the Callux field test (cf. Garud et al., 2010, Morgan, 2013). This technology assessment was helping with a potential branching point, i.e. determining whether SOFCs or PEMFCs were the most appropriate technological design for domestic micro-CHP units.

Overall, in terms of answering Research Question 2, coding for the organisational funding of TIS events revealed important new information about each country’s TIS evolution. Resilient activity in Period 1 only occurred via contracting-out PPPs with defence actors in very narrowly-defined niches (cf. Fiksel, 2006, Walker et al., 2004).

More resilient activity occurred in Period 2, where certain actors such as Daimler built on activity in Period 1. This suggests Daimler had the agency (based on its networked power) and the technical ability and financial resources to begin to convince other actors from the incumbent regime of HFCs' legitimacy (and so begin to develop new HFC technological pathways through actor enrolment in HFC networks) (cf. Latour, 1987). Actors including component manufacturers in the vehicle supply chain – typically near Daimler's Stuttgart base – have, over time, become progressively more involved in this car maker's plans to launch a commercial HFC vehicle (Interviewee GMNC4, Daimler – 2011). However, the oil majors appeared to the interviewee from Daimler, GMNC4, to be wary of change in 2011 despite signing industry-wide Memoranda of Understanding (MOUs) and joining PPPs like the Clean Energy Partnership in Germany. Certainly, HFC actors in both countries were forced to overcome the energy policy lock-out for HFCs begun in the 1970s despite notable technical advances in the 1960s (cf. Unruh, 2000).

In looking at organizational distinctions between each country, place was also shown to matter in terms of the differing approaches to capital (Interviewee GMNC5, CFCL - 2011, Hall and Soskice, 2001). This meant that the evolution from public leverage towards strategic partnering in my HFC PPP typology was swifter and more pronounced in the UK whose LME status also meant HFC PPPs were deployed in proportionally greater numbers than Germany (but ultimately coinciding with proportionally less private HFC actor involvement post-1998).

6.1.3 Findings from Comparative Analysis of Spatial Indicators

In this section, I explore the comparative results of the second of my extended indicators: the spatial aspect of TIS events (cf. Duncan, 1989, Massey and Jess, 1995, Coenen and Truffer, 2012, Binz et al., 2014). In order to answer Research Question 2, I want to assess what impact the geography of both TIS events and actors' locations had on the socio-technical processes underpinning HFC innovation and diffusion in each country. These processes are highlighted in the discussion below in terms of barriers to and enablers of innovation and diffusion in both the UK and German HFC TISs (cf. Negro et al., 2007). As described in Chapter 3, additional geographical data based on spatial coordinates and regional locations permitted further spatial indicators to emerge via analysis, e.g. regional location quotients and degrees of actor clustering. These indicators, consolidated with my longitudinal spatial coding for TIS events (Louis, 1982, Onwuegbuzie and Teddlie, 2003), suggest how and why the distinctly uneven spatial distribution patterns of events and actors emerged. Ultimately, this comparative analysis makes it clear that spatial *and* temporal (or *spatio-temporal*) dimensions of change were impacting upon the socio-technical processes at work.

Both countries revealed uneven geographical patterns of HFC innovation and diffusion in the snapshots of actor locations made for 2012 (Figure 28 and Figure 50). Thanks to the TIS narratives, this geographic unevenness can be linked to varying access to resources over time. Access to resources has been shown in the TIS narratives to depend on relative degrees of networked power for HFC actors. These uneven actor distributions are also linked to context-specific structures of spatial governance: Germany is a federal state compared to the UK's partly devolved situation which largely took shape from 1999. In both countries, new entrant regions emerged to undertake HFC work from 2000 – around the peak of global HFC activity during hype C - but these later entrants become active at a slower rate than the leading established regions (Figure 29 and Figure 30 for the UK and Figure 51 and Figure 52 for Germany). This suggests that, with what little early HFC comparative advantage there was in Period 1, certain regions in the UK and Germany witnessed much greater levels of activity than others (in some regions there was no activity at all throughout). This then suggests that the socio-technical processes of path creation, path dependence and cumulative causation highlighted in the TIS event data help to create, and in turn are further impacted by, the skewed geographical distributions of actors and events in a mutually reinforcing way (cf. Garud et al., 2010, Simmie, 2012, Morgan, 2013, Matos-Castaño et al., 2014). This insight into the evolution of the UK HFC TIS is not reported elsewhere.

Further evidence for a spatial component to the socio-technical processes at work in both countries (cf. Coenen et al., 2012) came from narrative descriptions of the regionally-based PPPs and regional breakdowns for entrepreneurial activity (F1) and knowledge development (F2). The TIS narrative in Chapter 5 revealed that the first 1st regionally-led PPPs were in Bavaria in the late 1980s and 1990s. There was public leverage through: a) the encouragement of international HFC firms to locate in high-tech clusters, b) a competence network offering support was set up, c) Länder-level grants and subsidies were offered and d) some JVs were entered into. This organizational approach to state support for HFCs then diffused from 2000 onwards to other German regions where it also encompassed strategic partnering: e.g. North Rhine-Westphalia, Hesse, Baden-Württemberg and Hamburg (Figure 53). While Bavaria was a leading 'first mover' high-tech Land with a thriving economy, North Rhine-Westphalia's support for HFCs was about economic regeneration of a former region whose economy had been based on coal and steel and so a strategic partnering PPP made most sense. Having had relatively little HFC activity in Period

1, ‘hoped for’ clusters – i.e. entirely new ones - were then sought in this region (cf. Mans et al., 2008). In the UK, regionally-led HFC PPP activity first arose in the North-East and in Wales from 2001. Both of these first movers in the UK have hydrogen infrastructure including pipelines. They also have key actors including active universities and automotive supply chains in the area, but later on they nevertheless appear to underperform as regions with their ‘hoped for’ HFC clusters (Hodson and Marvin, 2005a, Hodson and Marvin, 2005b). Instead, outside the South-East region, the West Midlands and East Midlands had seemingly done better by 2012 (at least in terms of the numbers of actors and TIS events).[86]

This evidence suggests that one of the key socio-technical process for HFCs in these case studies - path creation (Garud and Karnøe, 2001, Garud et al., 2010) – has a spatial component. In Germany, early innovation led to greater diffusion later on, but only in certain places. An HFC technological path, like Daimler’s innovatory use of metal hydrides for hydrogen storage in Period 1, for example, created its own path dependence for HFC actor activity in and around the historic core of the German car industry in Stuttgart in Baden-Württemberg during Period 2. This technical approach to HFC mobility was challenged by BMW’s development of hydrogen internal combustion engines thanks to its links to state-backed research at the state-funded DLR research centre in Stuttgart and its skilled workforce based in Munich. In fact, across the transport sector, actors in all historic German transport core areas, which also includes Volkswagen in Wolfsburg in Lower Saxony, had all established a degree of comparative advantage through working with HFCs in Period 1. The paths that were subsequently created draw on pre-existing regional high-tech clusters and supply chains (cf. Tanner, 2014, Tanner, 2016). By contrast, in the UK in Period 1, HFC activity terminated after end of hype cycle B (around 1982/3) for economic reasons. The unit costs of Shell and Lucas’ HFC DAF 44 prototype vehicle were said to be too high. Simultaneously there was the energy policy lock out for HFCs and a weakening car industry. HFC mobility activity in the historic core of UK vehicle manufacturing in the West Midlands, and supported by Shell’s electrochemists in the North-West, ended (only to restart in Period 2 via a number of smaller firms in PPPs and private JVs). Leading up to 2012, none of these new UK entrants to the HFC transport sector were able to dominate technological path creation in the ways that Daimler and BMW have.

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[86] This may well be to do with the pre-existing automotive and aerospace skillsets of employees in these regions.

Ultimately, in terms of research question 2, this comparative analysis of spatial indicators suggests geographical *and* temporal, or *spatio-temporal,* factors were impacting the socio-technical processes at work in both the UK and Germany. Resilient HFC technological pathways were being created in certain sectors at certain times and in certain places. This suggests that time *and* place matter to the socio-technical processes at work in these two empirical case studies where uneven spatial development of HFCs was revealed during and between a number of hype cycles. This point, and those emerging from Sections 6.1.1 and 6.1.2, are discussed in the next section where I answer research question 2.

6.2 Warranted Assertions Based on Case Study Comparisons

In this section, I give warranted assertions based on the comparative findings about socio-technical change with HFCs in these two case studies. This analysis allows me to return to and answer Research Question 2 and to take forward these warranted assertions into Chapter 7's methodological and policy discussions (cf. Smith, 1997).

As is shown above in Figure 54 and Figure 55, the UK and Germany were clearly on different socio-technical pathways with HFCs by 2012 (given the more rapid rate of increasing TIS events in Period 2 in Germany). Understanding why this should be the case, comes down to answering Research Question 2 about which socio-technical processes are most important in these HFC TISs. I use the language of 'barriers' and 'enablers' below to describe such processes but recognise that these same processes can be favourable or unfavourable at any point depending upon the contextual circumstances (cf. Negro et al., 2008). Ultimately, therefore, I identify the socio-technical processes and the circumstances that contribute to the greatest resilience in the national HFC TISs which the empirical records show began to strengthen in both countries in Period 2 (cf. Walker et al., 2004, Fiksel, 2006). This analysis answers Research Question 2 which provides the basis for answering Research Questions 3 and 4 in Chapter 7.

The TSIS approach highlighted temporal shifts in the context of a number of socio-technical processes. The external shocks to the national TISs in Period 1 both enabled and ended HFC activity. Reactions to the 1956 Suez Crisis, for example, boosted HFC activity in the UK in hype A but energy policy after the 1973 Oil Crisis revealed HFC activity's relatively poor resilience in Period 1. The same pattern was witnessed in Germany except it was delayed to generating some activity at the start of hype B in 1974, but was similarly over by 1983 when oil prices began dropping consistently. By contrast, in Period 2, neither the global blow-out in hydrogen hype in 2006 nor the 2008 global financial crisis were able to stop the upward rise in TIS event numbers (and increases in their functional diversity) in both countries up to the end of 2012.

The reason why activity in Period 2 was more resilient than in Period 1 appears from the TSIS perspective to be down to whether or not cumulative causation between functions was picking up (cf. Suurs and Hekkert, 2012), something proponents of the TSIS approach suggest is increasingly possible with the UK and Germany but, without triangulating with qualitative data, cannot be absolutely confirmed (cf. Coenen et al., 2012). There was also a temporal context to the governance of TIS activity: more functionally diverse HFC activity in Period 2 was dependent upon actors securing access to resources from an increasingly sophisticated multi-level system of governance which evolved significantly from Period 1. Examples of this changing institutional environment where actors must plan more reflexively include Germany's pro-active pursuit of a greener industrial policy, the 'energy transformation' or *Energiewende*, and the UK's devolution (cf. Voß et al., 2006).

However, when trying to identify the most important socio-technical processes at work in these two case studies, further contextual explanatory factors emerged from my extended indicators: organisational funding and geographical location.

Firstly, in terms of TIS event funding, there was greater reliance on PPPs in the UK which had evolved from near CME status early in Period 1 to being an advanced LME in Period 2 (cf. Hall and Soskice, 2001). This discrepency, shown in the particularly marked rise of PPPs post 1998 (Figure 24). Much more private HFC activity was witnessed in Germany which remained a CME throughout.

Secondly, within and between the temporal shifts in HFC activity in both countries, the TIS narratives revealed the importance of networked power amongst private and PPP actors, in particular. The project-level narratives in Chapters 4 and 5 revealed that the TIS event source material, when examined in detail, typically showed that HFC technological pathways were highly contested between actors and the individuals within them. The TSIS approach adopted the enactors and selectors heuristic (via Garud and Ahlstrom, 1997) to describe such contestations between actors with different levels of financial and political leverage over time (Suurs, 2009). However, the ways such differences in how power relations between HFC actors play out on the ground over time were shown to be country-specific in Chapters 4 and 5. These differences included the relative degrees of lock out for HFCs in the UK and Germany from their national energy policies, for example, as well as socio-technical activities linked to private HFC activity and PPPs: e.g. trust building, knowledge sharing, legitimacy building, devising road maps, appointing political champions, de-risking efforts, etc. All of these are effective ways for the state to be involved in promoting innovation and diffusion of HFC technologies, but the empirical evidence suggests that the UK and Germany's current status as an LME and a CME respectively, ensures different socio-economic pressures shaping RD&D investment at different times.

Thirdly, my organizational indicators suggested that path creation and path dependence were crucial socio-technical processes which were shaped by the first two points outlined here (Garud et al., 2010, cf. Morgan, 2013). When examined in more detail, it became clear from the TIS narratives in Chapters 4 and 5 that HFC actors in the UK and Germany were consistently struggling to break three types of path dependence identified by Grabher (1993) - functional, cognitive and political (see Section 1.4.6) – and that the state can play a significant role in breaking down the path dependence of the incumbent energy regime which is based on hydrocarbons (cf. Morgan, 2013).

In sum, the TSIS indicators in combination with my extended indicators revealed that HFC innovation does not happen anywhere. The empirical evidence of Chapters 4 and 5 revealed that time, place and networked power - all impacted upon known socio-technical processes at work with HFC innovation and diffusion in these two cases. This conclusion is important because understanding uneven temporal *and* spatial development has always been central to Innovation Studies (see, inter alia, Freeman, 1974, Freeman, 1987, Fagerberg et al., 2007). The uneven nature of processes like cumulative causation and path creation, evidenced in the case studies, necessarily affects thinking about methods and policy which I examine next in Chapter 7.

Chapter 7: Findings, Implications, Reflections & Contribution

7.0 Introduction

In this chapter, I assess all warranted assertions from Chapters 4, 5 and 6. I show how these assertions have contributed to distinct empirical, theoretical, methodological and policy findings. This assessment centres on the processes and dimensions that were shown in Chapter 6 to be important in the socio-technical evolution of hydrogen fuel cell (HFC) innovation in both countries, e.g. cumulative causation, system resilience, path dependence, path creation, networked power relations, and geographical proximity. This activity lets me answer Research Questions 3 and 4 (from Text Box 3 in Chapter 1):

3) Are there research suggestions that would add and enrich existing theoretical and methodological approaches in Innovation Studies?

4) What are the appropriate policy options that follow on from this analysis?

This analytical activity also allows me to consider the implications of this assessment when I describe my contribution to knowledge, reflections and suggested lines of further research.

To recap this research journey, Chapter 1 began by stating that HFCs are a disruptive technology with the potential to help policymakers wishing to adapt to climate change through decarbonizing national, regional and local energy systems (Hardman et al., 2013). In bringing about sustainable change with HFCs, some researchers suggest that innovation and diffusion can happen anywhere (e.g. Hekkert et al., 2007a), but others disagree (e.g. Coenen et al., 2012). In Chapter 2, I made a theoretical contribution to this debate with a critique of the Innovation Studies' literature. The literature includes three strands of theorizing: Innovation Systems (IS), Systems Innovation (SI)/Technological Transitions (TT) and the Sociology of Expectations (SOE). My specific focus was the Technologically-specific Innovation Systems (TSIS) heuristic where I identified four thematic knowledge gaps: a) micro-macro conceptions of actors' agency and structure, b) system delineation, c) system indicators, and d) policy guidance. I then suggested methodological adjustments for the TSIS heuristic involving adding further coding to events for their ownership – whether public, private or public-private – given the rapid rise in strategic partnering public-private partnerships (PPPs) from the late-1990s onwards (Figure 27). This activity adds weight to an assessment that, in some sectors, certain HFC technologies in both countries are beginning to transition from state-protected niches to state-supported market entries (cf. Kemp et al., 1998b).[87] Secondly, events were also additionally coded for their spatial context – their geographical dimension – because time *and* place matter to HFC innovation and diffusion (cf. Coenen et al., 2012). In Chapter 3, I advanced a neopragmatic research design informed by the TSIS approach. This framework added confidence to my analysis of a range of data sources in later chapters by advancing warranted assertions covering the nature of the socio-technical processes at work with HFCs in the UK (Chapter 4), in Germany (Chapter 5) and comparatively (Chapter 6) and helped to answer Research Questions 1 and 2. This analysis offers new empirical, methodological and policy insights based on my gathering of evidence. My analysis indicates that HFC innovation and diffusion in the UK and Germany does *not* arise anywhere in time and space (cf. Coenen and Truffer, 2012, Coenen et al., 2012, Binz et al., 2014). My assessment of such findings is therefore framed in terms of the socio-technical processes which have led to periods of either national HFC system weakness or resilience at particular times and in particular places (cf. Walker et al., 2004, Fiksel, 2006).

In terms of the structure of this chapter, Section 7.1 involves a theoretical discussion of the findings from the critical literature review. Section 7.2 brings together all warranted assertions from Chapters 4, 5 and 6 recapping the empirical findings made via the case studies from the UK and Germany. In Section 7.3, there is a methodological discussion of the impact of the theoretical findings, i.e. in the context of *how* the findings were arrived at. I complete Research Activity 4 (Text Box 4 and Figure 4 in Chapter 1) which is an assessment of how effectively the methods involved with the TSIS heuristic captured the nature of HFC innovation and diffusion in the two case studies. This theoretical and methodological assessment also involves gauging the relative utility of my extended indicators when used alongside the TSIS heuristic with these two case studies. In Section 7.4, I examine the impact of the findings from the theoretical critique in Sections 7.1 and methodological analysis in 7.2 in terms of HFC-specific policy development which involves completing Research Activity 5 (Text Box 4 and Figure 4 in Chapter 1). Then, having answered my four research questions, I provide reflections in Section 7.5. I summarise my contribution to knowledge in Section 7.6 and, finally, make suggestions for future research in Section 7.7.

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[87] Mazzucato (2013) indicates there is a long-standing discursive battle over the nature of innovation processes in which the state, amongst others, is cast by neoliberal economists as simply wealth extractors or distributors rather than capable of dynamic involvement in PPPs.

7.1 Theoretical Findings: HFC Innovation & Diffusion in the UK & Germany

In Chapter 2, I used the critical literature review of all Innovations Studies' heuristics to establish what the gaps are in the knowledge base regarding HFC innovation and diffusion activity. My critique of approaches to HFC innovation and diffusion is divided into four interlinked and emergent themes involving the Innovation Systems (IS), Systems Innovation (SI)/Technological Transitions (TT) and the Sociology of Expectations strands of theorizing: a) micro-macro conceptions of actors' agency and structure, b) system delineation, c) system indicators, and d) policy guidance. Specifically in terms of the TIS/TSIS heuristics, I described theoretical concerns which include: a) the reliance on aggregating micro-level data to the meso- and macro-levels, b) the system itself being regarded as the causal agent of change, c) the lack of a regional 'container' for analysis, and d) the lack of predictive powers.

In summary, the critical literature review was of key importance to every chapter of this thesis through: a) refining my research questions (described in Chapter 1), b) assessing the scope for enhancing the methodological approaches of the TSIS heuristic to overcome these knowledge gaps (Chapter 3), c) contextualizing the case study presentations (Chapters 4 and 5), 5) completing comparative analysis of socio-technical change with HFC innovation and diffusion within and between the UK and Germany (Chapters 6 and 7).

I look at findings in the four thematic areas in turn below.

7.1.1 Conceptions of Actors' Agency and Structure

I examined conceptions of actors' agency and structure because they relate to Research Questions 1 and 2:

1) 'How, when and where has innovation and diffusion of Hydrogen Fuel Cell (HFC) technologies taken place in the UK and Germany?'

2) 'Which socio-technical factors have had the most influence on the nature and pace of HFC innovation and diffusion in these cases and why?'

The literature review revealed three leading areas of concern: networked power relations, the aggregation of micro-level data to the meso- and/or macro-levels and the nature of causality.

In terms of networked power relations, it is clear that individuals and actors cannot act alone: networks are key to agency. When attempting to explain actors' uneven access to resources, the literature review showed that IS approaches based on

Granovetter (1973) are relatively poorly developed regarding theorizing network power relations (Shove and Walker, 2007, Weber, 2007, Avelino and Rotmans, 2009, Lawhon and Murphy, 2012, Truffer and Coenen, 2012). This deficit suggests that structural change - the struggles faced by actors pushing emerging innovations out of niches and up against existing regimes - may not be well addressed (Geels, 2011). With HFCs, for example, Suurs et al. (2009, 9652) suggest that: "[T]he TIS approach could benefit from a more sophisticated actor concept." I concluded that TIS/TSIS HFC case studies risk underplaying the co-evolution of actors and emerging technological regimes with their institutional landscape. There is also the risk of under-conceptualizing the role of new technologies in social transformations studies by downplaying the impact of non-market users and the broader political context conditions (Truffer and Coenen, 2012).

A second key problem for the TSIS approach in terms of answering my research questions was shown in the critical literature review to be its reliance on aggregating micro-level data to the meso- and macro-levels. Specific micro-level understandings of the strategic behaviour of individuals (and/or groups of individuals) in projects may not necessarily forthcoming (cf. Bruun and Hukkinen, 2003). I concluded that this inevitable analytical deficit with a neofunctional heuristic like the TSIS can de-emphasize the importance of power struggles between actors seeking to achieve their strategic ends. Similarly, in terms of structure, universal ease of access to resources by actors, the so-called 'global technological opportunity set' proposed with the TIS heuristic (Carlsson, 1997, Carlsson et al., 2002), is unrealistic – the resources actors seek to control are typically spatially embedded and exhibit path dependence (Coenen et al., 2012).

Another theoretical concern for TIS/TSIS approaches is causality. Kern (2012), points out that while TIS narratives may imply causality between events on an Event History Analysis (EHA) timeline, any correlation between them - however derived - does not necessarily mean causation exists. Coenen et al. (2012) suggest there is a risk of a logical fallacy of *post hoc ergo propter hoc,* or 'after this, because of this', producing false positives because of a tendency to use time as an independent variable. The EHA approach privileges time over space risking: "[O]veremphasizing 'universal' (abstract) mechanisms as causal explanations for innovation at the expense of (real) embedded actor strategies and institutional structures" (Coenen et al., 2012, 970).

On power relations, data aggregation and causality, I therefore felt some caution was required with the TSIS approach's analyses of agency and structure when answering my research questions.

7.1.2 System Delineation

In the literature review, IS heuristics were critiqued for their delineation, i.e. where the analytical boundaries are drawn in case studies. With the descriptive delineation of IS heuristics, the socially-constructed territorial borders used in the TSIS heuristic are only ever loosely defined. Coenen and Díaz López (2010, 1150) suggest that, without isolating the system from its environmental context: “It is important to consistently consider the boundaries of the innovation system in order to avoid an explosion of possible factors and drivers for innovation.” However, boundaries are crossed by heterogeneous actors embedded in networks who make links with each other between and across hierarchical levels of activity (Hodson et al., 2010). ‘Glocal’ knowledge flows for innovation activities therefore arise involving global knowledge networks of multinational companies (MNCs) and localized learning embedded in local nodes or clusters. As Binz et al. (2014, 139) state: “Scrutinizing these interconnected relational dynamics has been ignored so far by TIS research, but [has] become one of the hallmarks in the so-called relational turn in economic geography.” This theoretical deficit TIS/TSIS approaches was therefore another area of caution when answering my research questions.

7.1.3 System Performance

On system performance, the literature review showed that Innovation Studies heuristics have also been critiqued for offering a range of models but no testable theories with predictive powers (Fagerberg, 2003). With the TSIS heuristic, overcoming this deficit involves efforts to improve methodological consistency, increase the transferability of case study results and, ideally, move towards theoretical formalisation. Markard and Truffer (2008c) feel that influential external actors and institutions linked to rival technologies nevertheless offer useful dimensions when understanding a technology’s system performance: "[T]he systems approach runs the risk to miss influential processes because the review of the environment is less systematic … novel technologies or products that emerge in competing innovation systems and thus affect the innovation under study may be neglected in the analysis." (Markard and Truffer, 2008c, 610). Similar to the critique in 7.1.1, TSIS analyses aggregate micro-level data to the meso and macro levels (unlike the EHA used by Van de Ven, Poole and colleagues in the Minnesota Studies), thus potentially blurring analyses of individuals’ and actors’ activities within a socio-technical system.

7.1.4 Policy Guidance

In general, uncertainties exist in Innovation Studies' approaches to the governance of transitions including whether or not wicked and super-wicked problems are 'solvable' at all in policy terms. The policy theme in the Innovation Studies literature directly impacts upon Research Question 4 which is shaped by answers to RQs 1, 2 and 3 (Text Box 3 in Chapter 1):

4) 'What are policy options that follow on from answering RQs 1, 2 & 3?'

My specific critique of TSIS policy guidance based on Innovation Studies' theorising involves the recognition that, once the gaps and limitations in the theoretical approaches are demarcated, uncertainties in applying these heuristics still need to be worked through (cf. Fagerberg, 2003). The empirical evidence suggests that a cautious, nuanced approach to the agency of networked actors is required in order to avoid heavy-handed, top-down policy prescriptions at all levels (Giddens, 1979, Smith et al., 2005, Hendriks, 2009, Voß et al., 2009).

The critical literature review made it clear that policymakers need to decide how, when and where to deploy resources to encourage the growth of a healthy HFC innovation system. Theorizing about sustainability transitions involving technologies such as HFCs has moved away from suggesting that state actors can single-handedly effect an entire transition. States still retain very important roles (Mazzucato, 2013, Morgan, 2013). In terms of transitions, the state can:

> "[P]erform various roles from facilitating to directing, depending on the stage of the transition. Key roles early on in transitions ... [are] to mould the agenda for change, build shared long-term visions across society and to create opportunities for learning about the substance and process of change." (Genus and Coles, 2008, 1439)

In this context, the literature review highlighted how the user-friendliness of TIS/TSIS policies and the expectations of their users have been critiqued in the past (Sharif, 2006, Truffer and Coenen, 2012). Bergek et al. (2008) responded with the suggestion that healthy feedback between TIS/TSIS system functions is often impeded by blocking mechanisms (elaborated in Figure 56 below). These socio-technical mechanisms include uncertainties of needs among potential customers, inadequate knowledge of relations between investments and benefits, lack of capability and poor articulation of demand, lack of standards, few relevant university programmes for skills and a weak advocacy coalition. Remedying such concerns in policy terms involves increasing user capability, supporting users to increase and diffuse knowledge, supporting experiments with new applications, developing standards, altering research and education and supporting an advocacy coalition (Bergek et al., 2008).

It was similarly suggested that to achieve a more sophisticated policy analysis, IS proponents need to go beyond a narrow concern with innovation systems (Metcalfe and Ramlogan, 2008). Systemic tools are needed for a number of Innovation Studies heuristics that permit the selection of a policy mix across the whole HFC innovation cycle (cf. Coenen and Díaz López, 2010). In terms of system delineation, an HFC policy encourages the clustering of hi-tech enterprises has been pursued in developed nations for over thirty years. However, the study by Mans et al. (2008, 1384) offers a cautionary note in an analysis of self-declared HFC clusters within an NSI framework in the Netherlands: “Just labelling a cluster is not expected to be enough … [C]luster policies … [need] to include incentives for the cluster partners to actually function as a cluster … Stimulating cooperation can be done by anticipating on initiatives arising in the market, and subsequently facilitating these initiatives by assuming the role of broker in the exchange of knowledge.”

7.1.5 Summary

When compared to heuristics based on the Rational Choice approach, Innovation Studies’ approaches have had relative success in offering improved understandings of the social processes of innovation (Fagerberg and Verspagen, 2009, Markard et al., 2012). Nevertheless, in terms of conceptions of agency and structure, epistemic differences between these heuristics mean that networks and power are conceived of differently amongst different Innovation Studies heuristics (especially regarding how actors seek access to unevenly distributed resources). Advocates of the TIS/TSISs heuristics, in particular, are at risk of losing out on micro-level insights into the socio-technical processes shaping technological transition pathways given their aggregation of micro-level data at the meso- and macro-levels (cf. Bruun and Hukkinen, 2003). Similarly, in terms of systems delineation, *ex ante* boundary setting has been identified as problematic (Coenen and Díaz López, 2010, Markard and Truffer, 2008c, Weber, 2007). When it comes to practical questions, like gauging both the local influence and the global reach of multinational companies (MNCs) on a national HFC TIS, for example, where analytical ‘containers’ may seem artificial, further theoretical elaboration may be required if more meaningful guidance is to be offered to policy makers regarding HFC-specific policies. Indicators of system performance are shown to be problematic given the shortcomings of some indicators and the seeming impossibility of finding definitive ones that can be agreed on. Also, SI/TT and SOE advocates with their social constructivist assumptions suggest that a solely quantitative approach to indicators of system performance may be erroneous. Only measures of technological expectations, they say, can give a meaningful insight into system performance (Alkemade and Suurs, 2012). As suggested above, epistemic differences involve rival methodologies and produce apparently irreconcilable uncertainties about what is gained and lost with different approaches. Finally, and linked to all of these areas of critique, the quality of policy guidance stemming from Innovation Studies' heuristics has so far been uneven in the countries where it has been tried, i.e. the Netherlands and Sweden. It remains relatively early days for policies based on the TSIS heuristic, but early Transition Management (TM) efforts, for example, in the Netherlands generally did not go as expected (Kern and Smith, 2008, Kern and Howlett, 2009, Hendriks, 2009, Voß et al., 2009).

My theoretical concerns about the TSIS heuristic, evidenced in the empirical findings in Section 7.2 below, justified the four methodological suggestions that I made and which I review in Section 7.3).

7.2 Empirical Findings: HFC Innovation & Diffusion in the UK & Germany

In terms of summarising the empirical findings from the evolution of the HFC TISs in the UK and Germany (Chapters 4, 5 and 6), I found evidence in both countries for: 1) cumulative causation, 2) co-evolution, 3) asymmetric power relations in actor networks, and 4) the uneven influence of space and place.

When seen through the theoretical lens of the TSIS heuristic, I was able to produce a longitudinal picture of structural, functional and technological co-evolutionary change in both countries. From the TSIS perspective, institutional governance of the TIS was largely shaped by regime-level legislative responses – whether supranational, national and/or regional - to external, landscape-level events (cf. Geels, 2010). Throughout each national TIS event narrative, there were coincident periods of global hype – A to D - indicating the specific impact of external global events on both of these national TISs (these hype periods are shown for the UK in Figure 10 in Chapter 4 and for Germany in Figure 32 in Chapter 5). UK public and private actors organized themselves into increasingly powerful and sophisticated private JVs and PPPs in strategic attempts to gain resources and lower unit costs as niche application were brought to market (cf. Soecipto et al., 2015). Over time, HFC RD&D branched along certain pathways and not others depending upon the structural barriers and enablers encountered by actors (cf. Foxon et al., 2013). I found the beginnings of sustained positive feedback based on cumulative causation between HFC TIS system functions in both countries in Period 2.[88] As both public and private activity increased in both national TISs from around 1995, HFC activity in all three sectors continued to gather strength up to 2012 in spite of the 'blowout' of hydrogen hype around 2006 and the global financial crisis in 2009. Compared to Period 1 when HFC activity was sparse and periodically faltered, the number and variety of TIS events appeared to be contributing significantly to overall national HFC TIS resilience (cf. Walker et al., 2004, Fiksel, 2006) and looked like the beginnings of transitional change in the HFC sectors of each country. Both countries appeared to show similar 'motors of sustainable change' beginning to appear in Period 2 (as shown for the UK in Figures 19, 21, 22 and 23 and for Germany in Figures 40, 42, 43, 44 and 45). Comparative empirical evidence of such a shift has not been reported elsewhere.

However, my use of the TSIS heuristic with these two case studies had been shown with the earlier EPSRC DoSH study to have relatively limited explanatory power. I therefore modified the TSIS approach with the use of extended indicators in the hope of providing further insights with the datasets. My extended indicator for organisational funding helped show that, in terms of agency and actor networks, PPP activity was significant in Period 2 in both national HFC TISs. I found that PPPs ran a close second to corporate-only activity and were significantly associated with the knowledge development and entrepreneurial activity functions of the TSIS approach. I also found that private and PPP HFC activity was distinctly unevenly distributed in time *and* space in both countries. I separately triangulated the 2012 snapshots of where UK and German HFC actors were located with the longitudinal records by region of knowledge development activity (F2) and entrepreneurial activity (F1) starting in the 1950s. From this, Figures 29 and 51 suggested that path dependence was in evidence. In whatever region HFC knowledge development activity was first established in Period 1, that region appeared to be advantageous in terms of greater activity in Period 2. In the UK, this was the case for the leading region, the South-East, and in Germany, for Baden-Württemberg.

Sectoral analysis largely focused on HFC transport activity because of the volume of events. In the UK, HFC transport actors in Period 1 did not build on their historic comparative advantages in Period 2 with the work of Shell, Lucas and Bacon. Transport sector activity ended after the end of hype cycle A (i.e. post-1983) for economic, technical and political reasons: unit costs were too high, there was no

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[88] There remain concerns about ascribing causality with Innovation Systems' (IS) heuristics. Consolidating temporal and spatial data is one way to reduce uncertainty (Kern, 2012, Coenen et al, 2012).

dominant design, there was policy lock out and the motor vehicle industry had become significantly weakened compared to two decades earlier. The rise in knowledge development post-2002 was stronger in the transport sectors of both countries compared to defence and aerospace, and stationary power. German HFC transport actors in Period 2 built on their historic comparative advantages in working with HFCs in Period 1. The rapid rise in knowledge development post-2002 was stronger in the transport sector than in defence and aerospace (and stationary power) and there were many new entrants although Germany's HFC transport activity was dominated in 2012 by just two domestic firms, Daimler and BMW, and one foreign one, GM (cf. Ehret and Dignum, 2012). In the UK, HFC transport innovative activity around the historic core of Birmingham restarted in Period 2 via PPPs linked to local vehicle parts firms and universities. However, all such enterprises were SMEs lacking the deep pockets needed for sustained RD&D of Daimler, BMW or GM.

Overall, the uneven timing of the socio-technical processes underpinning HFC innovation and diffusion in both countries appeared to be closely linked to the shifting institutional context where, in response to external events, ever-increasing top-down and bottom-up regulation was appearing, and whether or not certain social cumulative causation was leading to greater system resilience.

In the next section, I look at how I arrived at these insights and what the implications are in terms of methods.

7.3 Methodological Findings: TIS/TSIS Approaches to HFC Innovation

In order to answer Research Question 3 about adding and enriching methodological approaches to Innovation Studies, I firstly recall three thematic areas of theoretical critique of Innovation Studies heuristics from Chapter 2. In Section 2.4, I described theoretical concerns about the TIS/TSIS heuristics which include: i) the reliance on aggregating micro-level data to the meso- and macro-levels, ii) the system itself being regarded as the causal agent of change, iii) the lack of a regional 'container' for analysis, and iv) the lack of predictive powers. The methodological points raised in each of the three sub-sections below – Sections 7.1.1 to 7.1.3 - are then assessed alongside similar examinations of my extended indicators in Sections 7.1.4 and 7.1.5. In Section 7.1.6, I give my warranted assertions about these methodological approaches.

This methodological assessment starts with a reminder of how the TIS/TSIS heuristics were critiqued in terms of conceptions of agency and structure. In each thematic area of theoretical critique from Chapter 2, I draw on the empirical record to offer insights and make suggestions.

7.3.1 Critiques of Conceptions of Agency and Structure

In this section, I draw on critiques of conceptions of agency and structure of Innovation Studies heuristics from Section 2.3.1. These critiques help me to assess which methodological improvements could be made to the TIS/TSIS heuristics. Looking at the empirical evidence from the UK and Germany, it is worth noting that socio-technical processes linked to agency and structure involved a number of actor motivations including: 1) financial risk reduction, 2) the need for recombination/sharing of knowledge, and 3) coordinating RD&D, infrastructure and planned manufacturing. There was plenty of evidence in both case studies that these strategic ends were being facilitated by trust building and that trust was established in public and private networks.

In Section 2.3.1, Innovation Studies literature was cited which highlights how neofunctional approaches to innovation, specifically the TIS and TSIS heuristics, aggregate micro-level event data at meso- and/or macro levels. My concern whilst undertaking the Supergen XIV DoSH study was that this neofunctional approach risked not emphasizing the importance of the contestation of individuals/groups over technological choices at and between key branching points. Analysis of the precise mechanics of how such strategic approaches co-evolved with the development of HFC technologies must include analysis at the project and/or individual levels. Aggregating data on such outcomes to the firm, sectoral and national levels, as described above, risks losing significant insights into the socio-technical processes that, over time, are playing out on the ground. The incorporation of the approach of Garud and Ahlstrom (1997) - enactors and selectors - to the TSIS model (Suurs, 2009) was an improvement in this area of concern as it offers an evolutionary approach to contestation drawn from management studies and psychology. However, the aggregation of micro-level data to the firm, sectoral and/or national levels still has the potential to de-emphasize the asymmetries of power that exist within and between networks (cf. Avelino and Rotmans, 2009, Geels, 2011). Power relations were shown in the TIS narratives in both countries to be powerful determinants of whether innovation and diffusion occurs or not. In Chapter 2, I suggested that this data aggregation means that key epistemological questions remain unanswered. For example, Fagerberg (2003, 152) asks: “What is the relationship between individual cognition and collective cognition?” and “How do firms ‘think’?” I specifically included the project-level narratives in the text boxes in

Chapters 4 and 5 because they suggest the significant influence that individuals and competing project-level groups can have on HFC socio-technical pathways.[89]

Similarly, the empirical evidence from both case studies showed that, whether it is expressed from the top-down, from the bottom-up or from a mixture of the two, agency was only achieved by actors who were embedded in networks, who had resource interdependency and who pursued particular strategies (which may or may not prove successful). The ensuing contestations over access to resources were shown in the TIS narrative source material from both countries to have been won and lost thanks in large part to the relative size and structure of these rival networks (Markard and Truffer, 2008a). The empirical evidence from the UK and Germany suggested that actors in networks operating predominantly at different levels of governance – whether supranational, national or regional - differed in terms of their relative agency (cf. Coenen et al., 2012).

Certainly, the emerging technological pathways towards a range of marketable HFC applications were heavily contested right up to the end of 2012. Evidence for this was highlighted in the project-level narrative text boxes in Chapters 4 and 5. Some of these project-level narratives centred on a particular technological branching point where a full understanding of the socio-technical processes at work was only revealed by unpacking the activity of competing research managers and their teams at the micro-level as Van de Ven et al. (1999) do with their research. There is thus a trade-off when using the TSIS methodology between gains in meso- and macro-level analysis versus losses in understandings of the socio-technical processes at work at the micro-level. A solution to this micro-macro problem appears unlikely (cf. Merton, 1948/1968, Hellström, 2004) because the TSIS heuristics' meso- and macro-levels of analysis are dictated by its neofunctional ontology (cf. Geels, 2010). For this reason above all others, I will be unlikely in the future to pursue my suggested lines of future research solely with the TSIS approach as put forward by (Hekkert et al., 2007a, Suurs and Hekkert, 2012) (as I also describe below in Section 7.6).

In terms of agency and structure, another area of critique highlighted in Section 2.3.1 was the way that neofunctional approaches suggest that the social system itself is the causal agent of change. The TIS event narrative methodology therefore suggests causation between events - the occurrence of event Y implies the occurrence of an earlier event X - but this is not formal causation (Kern, 2012). This situation regarding causality suggests to some researchers that the TIS/TSIS

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[89] The use of qualitative interviewee results in the TIS narratives is another way to avoid losing the micro-level insights of HFC actors.

heuristics risk “overemphasizing ‘universal’ (abstract) mechanisms as causal explanations for innovation at the expense of (real) embedded actor strategies and institutional structures” (Coenen et al., 2012, 970). When the empirical HFC evidence for the UK and Germany was examined at the project and regional levels, the contexts regarding organisational funding and spatial activity emerged more strongly in all three sectors, but particularly in the HFC transport sector which was growing most rapidly in both countries post 1999. As Coenen et al. (2012) suggest, this implies that the key socio-technical processes at work are not universal and abstract but rather grounded in real, place-dependent actor activity which is linked to institutional structures.

In the next section, I examine the evidence for critiques of system delineation in my pursuit of methodological improvements to the TIS/TSIS heuristics.

7.3.2 Critiques of System Delineation

In this section, I return to Chapter 2’s critique of systems’ approaches to innovation in terms of their delineation, i.e. where their analytical boundaries lie, and examine what the case studies reveal about potential methodological improvements to the TIS/TSIS heuristics.

As Section 2.3.2 showed, debate in the literature suggests that users of the TSIS heuristic may struggle in a way noted with sectoral systems of innovation (SSIs) by Coenen and Díaz López (2010, 1151): “*Ex-ante* boundary setting of the system may … miss out on important factors and actors driving innovation”. Similarly, divisions in the TSIS heuristic’s nested hierarchy between the global, national and sectoral ‘containers’ of HFC activity are overlapping and socially-constructed, i.e. arbitrary. This was supported by the case studies where empirical evidence in the TIS narratives in Chapter 4 and 5 suggests that the agency of multinational companies (MNCs) involved with HFCs, for example, is all pervasive, operating from the global to the local scales. This was the case for Australian-based MNC, CFCL, and the Canadian MNC, Ballard Power Systems, who were shown to be able to operate in, and make strategic trade-offs between, the national HFC TISs of the UK and Germany. In Section 2.3.2, MNCs were shown to create global-local, or ‘glocal’, flows of knowledge about HFCs between regionally-embedded operations as they gained access to local resources. This project-level knowledge inevitably moved across arbitrary TSIS system boundaries (cf. Healy and Morgan, 2012, Heidenreich, 2012a, Heidenreich, 2012b). As Coenen and Díaz López (2010, 1151) suggest, such multinational agency makes it difficult to be sure that TSIS descriptions of structural activity within sectoral and national containers covers the full range of “factors and actors driving innovation". Also, the TIS/TSIS heuristics may overlook the fact that: "these local resources are produced in much wider economic, business, political and organizational networks, hierarchies and markets" (Coenen et al., 2012, 970).

In the Supergen XIV DoSH study and in this thesis, the technology level of analysis was used with the TSIS approach in the UK and German case studies. While this followed an evolving technological boundary in the TSIS over time, structural elements of TIS structures - actors, institutions and networks - highlighted resources, competencies and synergies provided by actors operating in very specific locales/regions. The empirical evidence of the socio-technical processes at work – centred on localized learning embedded in local nodes/clusters moving alongside information flowing in via global knowledge networks (employing relational 'glocal' linkage) - in both the UK and Germany (as described below in Sections 7.1.5 and 7.1.6), bears this out.

In sum, when answering research question 3, it is worth recalling that, in any study, the research questions and ontology determine the level of analysis (Geels, 2010). The empirical evidence in the two HFC case studies presented here suggests that the TSIS approach could usefully include a regional level of analysis given that *where* TIS events took place mattered. Ideally, this regional level of analysis would be integrated into the TSIS heuristics' nested hierarchy of analytical levels (given that, as suggested in 7.1.1, a truly micro-level resolution of the micro-macro problem is unlikely). I attempted to achieve this in both case studies by focusing on the supranational, national *and* regional levels of TIS event activity. It also seemed in Section 2.3.2 that some kind of supranational relational framework to operationalize the networking/'glocal' linkages between multinational actors who have embedded operations in regional sites would also be potentially useful.

In the next section, I examine the evidence for critiques of system performance with the TIS/TSIS heuristics.

7.3.3 Critiques of System Performance

In this brief section, I again return to Chapter 2's critique of system performance and focus on which indicators are used to gauge change in Innovation Studies' heuristics in order to answer research question 3.

In the Innovation Studies literature, as noted in Section 2.3.3, one critique of innovation systems heuristics is that they are not testable theories with predictive powers (Fagerberg, 2003). TIS/TSIS researchers have progressively sought agreement on methods in terms of which system indicators are the best to use. A result of this process is the coding frame for generic renewables shown in Table 7 in

Chapter 3. As case study evidence builds, TSIS proponents hope that theoretical formalization can occur and predictive powers will emerge. The results and analysis presented in Chapters 4 to 6 suggest that there may be room for methodological improvement. While the TSIS heuristic provides a good tool for highlighting changes in functional activity over time, more agreement might yet be needed on quantitative and qualitative system indicators given that the extended contextual indicators that I have put forward, which are based on organisational funding and geographic location (see below), add further useful insights into conceptions of agency and structure (Section 7.1.1) and system performance.

In the next two sections, I examine my organisational and spatial indicators in terms of the critiques of Innovation Studies methodologies in Chapter 2.

7.3.4 Extended Indicators - Organisational

In this section, I refer back to Section 2.4.1 which suggests organisational funding as a new indicator and Section 3.3.1.3 which described how this indicators was added to the research design. This means I answer Research Question 3 via methodological insights related to the use of my organisational indicators concerning TIS event funding. The DoSH study suggested that no universal ease of access to resources existed (cf. Metcalfe and Ramlogan, 2008). I therefore produced organisational funding indicators for each TIS event which were based in part on public and/or private ownership and my own HFC PPP typology (Table 4 in Chapter 2). Explanations for this uneven access to resources were not obvious via the TIS/TSIS heuristics. In general, Section 2.4.1 confirmed the need with neofunctional heuristics to better elaborate contestations of emerging innovations against existing regimes (cf. Geels, 2011). As suggested in Section 7.1.1 above, the incorporation of the enactors and selectors approach to the TSIS heuristic still risks underemphasizing the role of power relations in HFC networks. My HFC data and analysis presented in Chapters 4 to 6 suggested that non-market users and broad political conditions were more significant in UK and Germany than TIS/TSIS heuristics suggest (cf. Truffer and Coenen, 2012, Breukers et al., 2014). The strategic response to uneven resource access meant that actors achieved agency via contestations of claims within and between HFC actor networks (Markard and Truffer, 2008a). My suggestion for answering research questions 1 and 2 was therefore to better foreground the micro-level contestations of HFC actors' in private and public-private networked efforts (cf. Van de Ven et al., 1999). The evidence suggested that the most effective HFC activity occurred when agency at all three levels of governance was aligned. My organisational indicators also showed that PPPs, especially the use of strategic partnering in conjunction with state procurement, were as significant as corporate-only activity in producing change in the UK HFC TIS (see Sections 4.4.2 and 5.4.2). This coordinated state activity is part of efforts to pro-actively support HFC technologies in niches. Simultaneously, these states are supporting HFCs' ability to form part of a broader energy transition through challenging existing product regimes (Kemp et al., 1998b, Kemp et al., 2007b, Kemp et al., 2010). I conclude from this that *organisational* coding about TIS event funding offered a valuable indicator of agency that I was able to use to supplement the functional picture revealed by the TSIS indicators.

In the next section, I make a similar examination for my extended spatial indicators in terms of the critiques of Innovation Studies methodologies in Chapter 2.

7.3.5 Extended Indicators - Spatial

In this section, I examine the methodological implications of adding my spatial indicators to the analysis of both case studies. As stated in Chapter 1, this extra coding was undertaken on the basis of the EPSRC Supergen XIV DoSH study.

The evidence and analysis in Chapters 4 to 6 revealed increasingly uneven national and regional rates of HFC innovation and diffusion. For example, the dominant three regions for knowledge development (F2) in each case study stayed dominant in both Period 1 and Period 2. My analysis revealed distinct clustering of HFC activity and actors by 2012. The TIS narratives revealed this clustering to be based on limited resource availability, the desire for knowledge exchange and path creation/path dependence. The interviews revealed that small- and medium-sized enterprises (SMEs) near larger MNCs benefit from knowledge spillovers. Both HFC firm types were exploiting new ideas and niche markets for innovation by 2012 (cf. (Audretsch and Feldman, 1996). Much of the comparative case study differences described in Chapter 6 come down to different spatially-specific contexts, i.e. the varying national (and regional) approaches to capital. Germany's status as a coordinated market economy (CME) versus the UK's liberal market economy (LME) stance arguably dampens the socio-technical processes producing and reinforcing highly uneven patterns of HFC innovation and diffusion. Also, the varying degrees of federal/devolved powers also meant that spatial governance of HFCs was uneven in both case studies. Such examples of the institutional factors driving uneven development do not appear to be undesirable, however, given the promotion of HFC clustering policies in both countries.

In sum, the evidence revealed by the extended spatial indicators strongly suggests the need to foreground the impact of spatially-specific path creation and path dependence on the socio-technical processes at work in these two HFC case studies. Such a methodological improvement is based on a key observation by Coenen et al. (2012, 970): "Don't obscure simple, place-specific causal relationships behind a more general systems analysis [because] … Without explicitly elaborating why actors in particular TISs choose to pursue their activities in particular regional and national contexts, it is very difficult to isolate individual success factors". Ultimately, the critiques of the TSIS approach in combination with the case study evidence suggest a regional level of analysis is needed in which an improved methodological framework for better understanding the embedded nature of local resources can be advanced.

7.3.6 Methodological Analysis: Summary

This brief section combines and summarises the assessments made in the previous sections in order to answer research question 3, i.e. are there research suggestions that would add and enrich existing theoretical and methodological approaches in Innovation Studies? The answer will then feed into Sections 7.3 on policy, reflections in 7.4 and my contribution to knowledge in 7.5.

The empirical record of HFC activity in the UK and Germany reveals much about the nature of agency for HFC actors, i.e. what can and cannot be achieved at certain times and in certain contexts. In Period 1, hypes A and B were not particularly resilient (except in defence) and activity faded. The reverse was true for Period 2. Poor resilience in Period 1 was due in large part to negative shifts in the broad institutional selection environment for HFCs. As Metcalfe and Ramlogan (2008, 440) suggest: "If politics and economic power combine to suppress enterprise then little can be expected of innovative experimentation." The TIS narratives in both countries revealed an inability by some HFC actors to break the three types of path dependence identified by Grabher (1993). In Period 2, by contrast, the UK and German states accepted responsibility for overcoming the path dependence HFC actors face (cf. Morgan, 2013). Increasing numbers of networked actors in private JVs and PPPs began to overcome a range of structural barriers. By 2012, at least, there was a picture of rising HFC activity that appeared far more resilient than anything previously witnessed. The methodological implication of this analytical picture, broken down throughout Section 7.1, is that the results of coding for organisational and spatial indicators benefitted the TSIS analysis in these two cases.

With this methodological conclusion in mind, I now examine the appropriate policy options that follow on from answering the first three research questions.

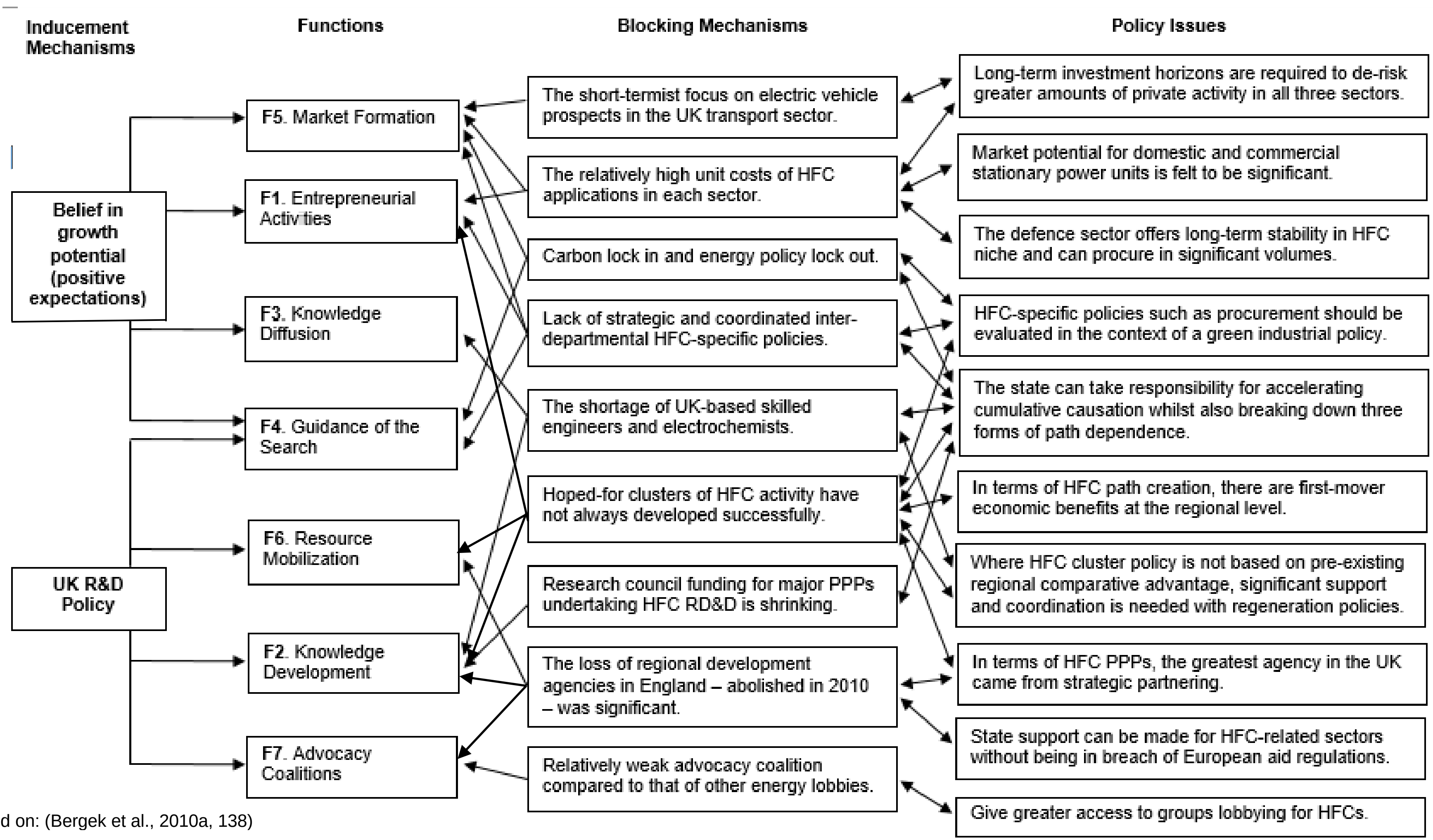
7.4 UK HFC Policy Analysis

I use this section to answer research question 4, i.e. 'What are the appropriate policy options that follow on from answering my previous research questions?' In the discussion below, I make explicit reference to the TSIS approach's analysis of barriers and enablers for both case studies.

In general, it is worth noting from Section 2.3.4 that systems theory has been critiqued for its rational approach to social policy (Fløysand and Jakobsen, 2011). Proponents assume that social policy problems are solvable when, in fact, they may be intractable, i.e. 'wicked' or 'super-wicked' (cf. Rittel and Webber, 1973, Levin et al., 2012). Also, whilst it is clear that state actors cannot single-handedly effect an entire transition, the evidence of HFCs in the UK and Germany suggests the state retains a powerful role. The evidence suggests that when three types of path dependence can be overcome, including carbon lock-in (Unruh, 2000, Unruh, 2002), then state-led management of radical innovations is needed (Hillman et al., 2011). In this context, highlighted in Section 2.3.4, the kind of collectivist policy learning witnessed in both TIS narratives appeared effective (Grin and Loeber, 2006). The response of proponents of the TIS/TSIS heuristics to the critique that policies were not user-friendly (Sharif, 2006, Truffer and Coenen, 2012) was to highlight how healthy feedback between system functions was often impeded by 'blocking mechanisms' (Bergek et al., 2008). Negro et al. (2007) similarly suggest ways of policy learning via innovation failures highlighted by TIS analyses. However, caution is still required as the TSIS heuristic is not a formal testable theory. It still has no claims to predictive powers.

Figure 56 presents TSIS policy analysis for the UK HFC TIS made on the basis of the evidence of barriers ('blocking mechanisms') evidenced in Chapters 4 and 6 and via the methodological conclusions made above in Section 7.1.6. Two inducement mechanisms are shown for the UK HFC TIS - expectations and R&D policy – for 2012. These inducement mechanisms are shown to impact certain of the seven functions which are, in turn, associated with particular blocking mechanisms. Each blocking mechanism is similarly linked to specific policy points that are distinctive to the UK HFC TIS. For example, Figure 56 shows that the market formation function (F5) was associated in the UK TIS event data with at least four blocking mechanisms:

1) The short-termist focus on electric vehicle prospects in the transport sector,



based on: (Bergek et al., 2010a, 138)

Figure 56: Inducement and Blocking Mechanisms, Functions and Policy Issues for the UK HFC TIS in 2012

2) The relatively high unit costs of HFC applications in each sector,
3) Carbon lock in and energy policy lock out, and
4) The lack of strategic and coordinated inter-departmental HFC-specific policies.

The policy guidance that stems from these four points, shown on the right-hand side of Figure 56, suggests that the state can address the short-termism of the financial markets by undertaking long-term forecasting exercises and extending its own political horizons and the financial horizons of others to de-risk greater amounts of private activity in all three sectors (Interviewee GFIN1, NOW GmbH – 2011). In this sense, the central state can take responsibility for accelerating cumulative causation with HFCs whilst also breaking down three forms of path dependence (cf. Grabher, 1993, Morgan, 2013). This has occurred in the UK to some extent, but not with the same degree of long-term coordination, political buy-in and financial commitment as in Germany (Williamson, 2010). As shown in Figure 56, another factor linked to the rollout of major public-private programmes like the Callux CHP trials in Germany has been the perceived high market demand for domestic and commercial stationary power units (FCB, 2012). The perception that swift uptake of domestic HFC CHP units in high volumes could rapidly cut unit costs in Germany before other European nations has led UK HFC CHP manufacturers and other multinationals to invest there since the mid 2000s. The defence sector similarly offers the potential to procure HFC niche applications in significant volumes and has provided the greatest long-term stability in terms of RD&D of all the three sectors of interest in both countries. On this point, HFC-specific policies such as public procurement of HFC CHP units and vehicles should be evaluated by central and regional government in the broader institutional context of a green industrial policy, as indicated in Figure 56 (cf. Rodrik, 2013). Such a policy would help to address the means of the UK meeting its climate change commitments whilst also achieving sustainable economic growth in niche sectors where the country’s corporate and university RD&D is world-class. A green industrial policy would also help with the present lack of strategic and coordinated inter-departmental approaches to HFC-specific policies in the UK (Interviewee UKPOL2, Energy and Climate Change Committee – 2011).

Other policy suggestions that emerge from Figure 56 include first mover benefits for HFC actors at the regional level. This suggestion comes from the evidence for regional path creation/path dependence in both countries revealed in Figures 29 and 51 where successful HFC clusters were shown to have become established thanks to the presence of regional comparative advantages in the form of place-specific human and physical resources going back many decades (cf. Mans et al., 2008). From this suggestion, I concluded that another point relating to cluster policy is that where such comparative advantages do not exist and a new cluster is suggested, it will need local and central state support, ideally via resources released with regeneration and skills policies (specifically targeted at engineering and science skills). Figure 56 highlights that an existing policy approach, strategic partnering HFC PPPs, offer the greatest agency to actors, particularly when in England the regional development agencies were abolished in 2010. This assessment is based on the evidence of my extended indicator on organisational funding shown in Sections 4.5.2 and 5.5.2. As Figure 56 suggests, nominating 'areas of technological interest' has been a useful way for the UK and Germany to avoid breaching EU competition rules on supporting individual firms with state aid (Interviewee GHAM1, HySolutions - 2011). Finally, another policy suggestion for the UK is to involve HFC lobby groups in energy policy debates more proportionately as compared with lobbyists from the oil and gas companies. Both the UK and German HFC lobby groups, although active, lacked many TIS events allocated to them as shown in Figure 22 in Chapter 4 and Figure 44 in Chapter 5.

The TIS/TSIS heuristics, however deployed in case studies like these two in this thesis, should not be considered simple, functional toolkits to be used without problems in a techno-economically deterministic manner. On the basis of the evidence in Chapters 4 to 6 and the methodological discussion above, I would also argue that some caution is required by policymakers with the TSIS approach until:

1) a regional level of analysis is developed,
2) there is a more overt methodological recognition that HFC actor agency was the greatest via private JVs and state-led PPPs, and
3) there is a more overt methodological recognition that no universal ease of access to HFC resources exists in time and space.

To answer research question 4, it is worth noting that a number of points emerged from the evidence of the TIS narratives and the interviews in both the UK and Germany. Building on the outline guidance in Figure 6, there is a clear need to think long-term and to be reflexive given that transitional change takes many decades. The policy learning that took place in both HFC TISs came from actors examining success *and* failure (see the discussions of the failures of Energy Conversion Ltd in Text Box 8 and ZeTek in Text Box 11 in Chapter 4 and the blowout of hydrogen hype in Germany in Section 5.3). State instruments de-risked and stabilised long-term RD&D and reinforced positive feedback. If the central and regional states take political leadership, as they have done more effectively in Germany than in the UK with HFCs, then strategic policy objectives can be better coordinated with actors on multiple levels. By pursuing roadmaps, taxation levels, subsidy measures, match-funding, state procurement, funding of networking/knowledge exchange, the UK and German states have both been able to contribute to the resilience of a range of HFC niches. There were organisational and spatial dimensions to this activity: HFC policies appeared effective when coordinated with regional high-tech cluster policies as has been the case in Germany (cf. Tanner, 2014). At the micro-level where innovation and diffusion physically takes pace, such policies can help to optimise trust through increased proximity of networks in clusters if targeted carefully (Mans et al., 2008).

Having answered my four research questions, I offer my reflections on the production of the entire thesis in the next section.

7.5 Reflections

In this section, I outline the strengths and limitations of this research work. In describing where academically I feel this work situates, I discuss the reasons for doing certain things but not others, describe what I would do differently in terms of the selection of methods, and I indicate how these points link to potentially valuable lines of research in the future.

The key strengths of this research are, firstly, my critique of theoretical approaches in Innovation Studies particularly the TSIS heuristic (Chapter 2), and, secondly, the significant empirical case study evidence of HFC activity in the UK and in Germany. As outlined in Section 7.1, I found new evidence in both countries for socio-technical processes linked to: 1) cumulative causation, 2) co-evolution, 3) asymmetric power relations in actor networks, and 4) the uneven influence of space and place. When offering socio-technical understandings of how TIS events unfolded, additional indicators provided new empirical evidence for: 1) the increased emphasis on the need to understand the organisational nature of actors especially in terms of networked agency and power with public-private partnerships, and 2) placing greater emphasis on the place-specific contextualisation of structure and institutions. Ultimately, with this evidence in hand, I am now more confident that my socio-technical understandings of HFC TIS evolution in these two countries, which is based around factors 1) to 4), were making particularly important contributions to system resilience in Period 2 (and the general absence of it in Period 1).

In terms of limitations, I feel that this thesis could have benefitted from not being constrained by the datasets originating from the Supergen XIV DoSH study. Whilst that study brought the initial insights and helped me to develop my research questions, much added time has been spent ensuring that this thesis is successfully fitted with that pre-existing data. In emergent areas of analysis, such as the organisational and spatial indicators, it would have been useful to have more qualitative interview data to work from in which participants responded to more direct questions about these specific thematic areas.

In terms of situating this work, it should be considered a neopragmatic comparative HFC case study that is on the inter-disciplinary borders of Innovation Studies and Economic

Geography. Methodologically, this thesis neopragmatic methodology, which I described in Chapter 3, allows a full range of qualitative and quantitative data associated with the TSIS approach *and* the extended indicators to be drawn together into warranted conclusions at the end of Chapter 6's comparative results. My hope is that the case studies will be drawn on for their depth and detail as HFC TIS studies, but that they will also spark methodological and policy debate that this chapter shows follows on from the empirical evidence.

If I was starting the thesis again, methodologically I would focus more of my attention on acquiring new quantitative and qualitative material to measure the relative power relations at the *project- and regional-levels* within and between HFC actor networks (and rival technology networks) in ways seen in micro-level analyses such as Van de Ven et al. (1999). I would pursue these levels of analysis via Social Network Analysis because the micro-level dynamics of power well illustrate how patterns of innovation and diffusion really play out *over time* and *in specific places*.

In the next section, I summarize my contribution to knowledge before concluding with suggested lines of future research based on these reflections.

7.6 Contribution to Knowledge

This thesis makes three significant contributions to analyses of HFC innovation and diffusion: theoretical, empirical, methodological and in terms of policy.

7.6.1 Theoretical

In the critical literature review in Chapter 2, four thematic areas involving knowledge gaps were identified with the three strands of Innovation Studies thinking: 1) conceptions of actors' agency and structure, 2) system delineation, 3) system indicators, and 4) policy guidance. Specifically in terms of the TIS/TSIS heuristics, I explored theoretical concerns which include: 1) the reliance on aggregating micro-level data to the meso- and macro-levels, 2) the system itself being regarded as the causal agent of change, 3) the lack of a regional 'container' for analysis, and 4) the lack of predictive powers.

Whilst I specifically did not seek to develop a contribution based upon a new theoretical approach to innovation, these theoretical concerns impacted upon my methods (Chapter 3), the resulting data collected (Chapters 4 and 5) and the analysis (Chapters 6 and 7) as I outline below in the next three sub sections.

7.6.2 Empirical

In the empirical material from the UK and Germany, I found new information on the RD&D of hydrogen fuel cells in the UK and Germany. This data involves new evidence for sustained positive feedback between HFC TIS system functions in Period 2 (cf. Hekkert et al., 2007a, Suurs and Hekkert, 2012). This evidence looks like the beginnings of transitional change in this particular clean technology sector in these countries. When seen through the theoretical lens of the TSIS heuristic, I was able to show how, when and where HFC technologies have co-evolved with their institutional environment. Over time, HFC RD&D branched along certain pathways and not others depending upon the structural barriers and enablers encountered by actors (cf. Foxon et al., 2013).

However, to better understand *why* events unfolded in the ways they did between the 1950s and 2012, I went beyond the TSIS methodology and used organisational and spatio-temporal indictors to reveal how much funding type – public, private and public-private – as well as space and place matter to analyses of HFC innovation and diffusion (cf. Hacking and Eames, 2012). PPP activity was significant in both Periods 1 and 2 in both national HFC TISs. In Period 2, HFC PPP activity ran a close second to corporate-only activity and was significantly associated with the knowledge development and entrepreneurial activity functions of the TSIS approach.

I also found that private and PPP HFC activity was distinctly unevenly distributed in time *and* space in both countries. Early regional comparative advantage in Period 1 arose in particular places and persisted in Period 2 via path creation. This evidence, amongst others, allowed me to conclude that place matters to the TSIS analysis: there was no universal ease of access to HFC resources by actors in either country as TIS theory, for example, suggests (Carlsson, 1997, Carlsson et al., 2002). Similarly, I found that notions of causality used with the TIS/TSIS heuristics could be strengthened by place-specific contextual information (cf. Coenen and Díaz López, 2010, Coenen et al., 2012, Binz et al., 2014).

In this context, I demonstrated with the empirical evidence the existence of a location effect in national innovation programmes. I also pusued a sensitivity to issues related to boundary crossing activities between project, and organisation, local, national and global activities. This activity also highlighted the pattern of research development, ownership and funding through the analysis of private and public investment decisions.

These processes were shown to impact upon the comparative warranted assertions made in Section 6.2 and are linked to the methodological and policy contributions outlined below.

7.6.3 Methodological

To achieve these empirical contributions, I firstly critiqued Innovation Studies heuristics in Chapter 2 in terms of knowledge gaps in four areas of thematic concern: 1) conceptions of agency and structure, 2) system delineation, 3) system performance and 4) policy guidance. In terms of agency and structure, the Innovation Studies literature critiqued in Section 2.3.1

suggests that, in general, innovative activity needs to involve broad regime membership in terms of networks (Smith et al., 2005). Analysis of the TSIS heuristic suggests it needs an operationalization of networked power at different levels/scales (cf. Archibugi and Michie, 1997, Bunnell and Coe, 2001, Coenen et al., 2012, Coenen and Díaz López, 2010). The HFC-specific literature outlined in Section 2.3.1.1 bears this out. To improve on such deficits, I described in Section 3.3.1.3 how the national HFC TIS events were also coded for the organizational funding status of HFC projects. This meant that the financial status of HFC projects – public, private, public-private – and their relative networked power was then triangulated with other sources to strengthen conceptions about agency and structure linked to power relations. Also, in terms of agency and structure, my TIS event narratives for the UK and Germany provided project-level text boxes in several places which expand the normal aggregated narrative event data seen with TSIS analyses. These expanded narrative descriptions covered episodes which, *in hindsight*, were important branching points in HFC socio-technical pathways and which helped detail the nature of micro-level contestations between HFC actors and individuals which are subject to power relations (cf. Giddens, 1979).

Regarding system delineation, systems approaches to innovation were critiqued in Section 2.3.2 for the arbitrariness of where analytical boundaries are drawn with case studies (Weber, 2007). As described in Section 2.4.4, to try to avoid such concerns, I included a regional level of analysis with the TSIS approach, something not seen in other TSIS studies. I also discussed the impact of global *and* local academic-industry links which cross TSIS boundaries in Section 4.4.2 and 5.4.2. Shown to be both geographical *and* relational – i.e. ‘global-local’ or ‘glocal’ – this actor linkage in both countries was suggested from the material in the interviews to be underpinning the institutional embeddedness of clustering activity within regions (cf. Braczyk et al., 1998, Heidenreich, 2004, Heidenreich, 2012a).

Innovation Studies heuristics were critiqued in Section 2.3.3 in terms of systems performance for offering a range of models but no testable theories with predictive powers (Fagerberg, 2003).[90] In order to improve system performance of this evolving body of research, I made efforts to improve methodological consistency with two new indicators: organizational funding and geographical location, as described in Sections 2.4.1 and 2.4.2.

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[90] Fagerberg (2003, 143) suggests: “some cross-fertilization with the more formal evolutionary theories [is required]”.

7.6.4 Policy

I make a contribution to knowledge by offering policy insights based upon the empirical evidence. In terms of policy guidance, Innovation Studies heuristics were critiqued in Section 2.3.4 for a lack of user friendliness, i.e. not making it clearer to policymakers how, when and where best to deploy resources to encourage the growth of a healthy HFC innovation system. The two national TIS narratives showed that state actors can and have taken responsibility for encouraging HFC growth and development. This growth can come as part of a green industrial policy involving HFC innovation and diffusion in a range of sectors – as discussed in Section 7.3 – and which draw on a wide range of policy levers. Apart from legislation, roadmaps and tax incentives, these case studies reveal the powerful impact of PPP activity, from straightforward public leverage to more advanced forms of strategic partnering. PPPs in combination with state procurement were shown to offer HFCs actors the greatest levels of agency and in certain cases, appear set to permit certain applications to begin to move out from their sectoral niches and into the broader marketplace.

In the next section, I conclude this thesis with a short description of some suggested lines of future research.

7.7 Suggested Lines of Future Research

The results of this study demonstrate the persistence of regional innovation clustering with HFCs, although it is not clear whether the clusters are an indication of regional strength, an emerging system or even early signs of a transition. There are therefore two lines of future empirical research into HFC innovation and diffusion that I would like to pursue which have theoretical, methodological and policy considerations and which involve interdisciplinary insights from Innovation Studies and Economic Geography.

Firstly, I would like to see further national and regional comparisons of HFC innovation and diffusion which pursue a more realist approach to power and place in their event history narratives (cf. Flyvbjerg, 1998). In spite of the successful incorporation of the enactors and selectors heuristic into the TSIS approach, a better understanding is needed of the uneven spatio-temporal outcomes on the ground regarding contestations over innovation and diffusion (Breukers et al., 2014). As suggested in Section 2.3.1, one way to do this is to use a relational approach, Social Network Analysis (SNA), to gauge the relative networked agency of HFC actors (particularly strategic partnering PPPs) (cf. Wieczorek et al., 2013). With an SNA framework in place, I would want to further pursue how socio-spatial processes, such as the ‘stickiness’ of knowledge (Binz et al, 2014) and actors’ ability to mobilize key resources (Binz et al., 2016), impact on socio-technical processes. An SNA framework would also permit the pursuit of an improved understanding of the interconnected dynamics of how MNCs and SMEs interact in emerging HFC clusters (cf. Heidenreich, 2012a, Heidenreich, 2012b). The focus of such a study could be examining how effectively localized HFC learning processes embedded in local nodes/clusters make new knowledge available locally and to global HFC actors over the course of hype cycles.

Secondly, given that the TSIS heuristic's neofunctionalist ontology only permits meso- and macro-level analyses, I would suggest further exploring HFC innovation and diffusion via a relational ontological framework. This would offer a project level of analysis (cf. Van de Ven et al., 2000), which could also be aggregated to the regional (meso) level. In this way, I would want to pursue interdisciplinary insights from the Sociology of Expectations' heuristics and Relational Economic Geography (cf. Bathelt and Glückler, 2003, Murdoch, 2006, Fløysand and Jakobsen, 2011). I would use such a relational framework to pursue the nature of power and place in HFC event narratives as suggested above.

Overall, this thesis reveals scope for further interdisciplinary research work between Innovation Studies and Economic Geography over the provision of insights into HFC infrastructure (Murphy, 2015).

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Appendix A: Anonymised Lists of Interviewees

UK (37)	
Individual (Code Name)	**Actors**
UKFIN1	Carbon Trust [Greater London]
UKFIN2	Carbon Trust [Greater London]
UKFIN3	Conduit Ventures Ltd [Greater London]
UKFIN4	Technology Strategy Board (TSB) [Greater London]
UKFIN5	EPSRC [Reading, SE]
UKLOB1	Synnogy Consultants (Lobbyists for UKHFCA) [SE]
UKLOB2	Friends of the Earth [Greater London]
UKLON1	London Development Agency [Greater London]
UKLON2	London Hydrogen Partnership [Greater London]
UKLON3	Imperial College [Greater London]
UKMED	Fuel Cell Today [Greater London]
UKMID1	UKHFCA Member [EM]
UKMID2	Advantage West Midlands (RDA) [WM]
UKMID4	University of Birmingham [WM]
UKMID5	Valeswood ETD Ltd [HFC stack manufacturer, WM]
UKMNC1	Low Carbon Technologies Division, Johnson Matthey [Reading, SE]
Individual (Code Name)	**Actors**
UKMNC2	AFC Energy Ltd [SE]
UKMNC3	ITM Power Ltd [YH]
UKMNC4	Ricardo UK Ltd [SE]
UKNEE1	Newcastle University [NE]
UKNEE2	Newcastle University [NE]
UKPOL1	Department of Energy and Climate Change (DECC) [Greater London]
UKPOL2	Energy and Climate Change (ECC) Select Committee Member [Gt. London]

UKSCO1	Scottish Enterprise [Edinburgh, SCO]
UKSCO2	St Andrews University [SCO]
UKSCO3	University of the Highlands and Islands [SCO]
UKSCO4	Scottish Hydrogen and Fuel Cell Association [Glasgow, SCO]
UKSCO5	St Andrews University [SCO]
UKSCO6	*Peterhead Port Authority* [SCO]
UKSCO7	Comhairle nan Eilean Siar (Isle of Lewis Council), Stornoway, Isle of Harris
UKSCO8	Comhairle Nan Eilean Siar (Isle of Lewis Council), Stornoway, Isle of Harris
UKSCO9	Lews Castle College, Isle of Lewis, Outer Hebrides [SCO]
UKSCO10	Strathclyde University [Glasgow, SCO]
UKWAL1	*Glamorgan University [Pontypridd, WAL]*
UKWAL2	Business Development, Welsh Assembly Government [Cardiff, WAL]
UKWAL3	Neath Port Talbot County Borough Council (CBC) [Port Talbot, WAL]
UKWAL4	Welsh Automotive Forum [Cardiff, WAL]

GERMANY (10)	
Individual (Code Name)	**Actors**
GBW1	Energie Baden-Württemberg AG (EnBW) [Karlsruhe, BW]
GFIN1	Die Nationale Organisation Wasserstoff- und Brennstoffzellentechnologie (*NOW*) GmbH (National Organisation for H_2 & Fuel Cell Technology) [Berlin]
GHAM1	hySOLUTIONS GmbH [Hamburg]
GHAM2	Vattenfall Europe Innovation GmbH [Hamburg]
GLOB1	Deutscher Wasserstoff- und Brennstoffzellen-Verband e.V. (DWV) (German Hydrogen Association) [Berlin]
GMNC2	Environmental Sciences (H_2), Ford of Europe [Aachen, NRW]
GMNC3	Public Affairs, Ford of Europe [Aachen, NRW]
GMNC4	Infrastructure Development, Mercedes-Benz Cars R&D [Stuttgart, BW]
GMNC5	Business Development, Ceramic Fuel Cells Ltd (CFCL) [Heinsberg, NRW]

GNRW1	EnergieRegion.NRW (Fuel Cell & H_2 Network NRW) [Düsseldorf, NRW]

BELGIUM (2)	
Individual (Code Name)	**Actors**
EUFIN1	Fuel Cells & Hydrogen Joint Undertaking, European Commission [Brussels]
EUFIN2	Fuel Cells & Hydrogen Joint Undertaking, European Commission [Brussels]

Appendix B: Topic Guide

Supergen XIV 'Delivery of Sustainable Hydrogen'
WP 4.2 - H-Delivery - Topic Guide for Participants
Date: Oct 11
Author: N Hacking

Note: The interview questions are all designed to reveal individuals' perceptions about the strengths and weaknesses of the national/regional innovation systems of the UK with respect to hydrogen. As such there are no wrong answers.

Topics

I am interested in who or what you feel determines the direction of hydrogen research and development in Europe. This can include the management of expectations.

I would like to know what you feel about knowledge creation and its protection.

I will ask you about the networks you are in terms of learning, knowledge diffusion and the support you draw from them.

I am keen to know what you feel about the appraisal of hydrogen in terms of environmental, social and economic sustainability.

I'll ask about the importance of mobilising resources in terms of research funding.

I am also interested in how you regard facilitating the formation of new markets.

I will ask you about the importance of having an advocacy coalition for hydrogen and also how you regard the role of the investigator/entrepreneur in terms of making things happen.

I'll ask what you think the barriers to innovation are and how to overcome them.

Lastly, we'll talk about the role of public and private research funding with respect to boosting national/regional innovation systems (and hydrogen's role therein).

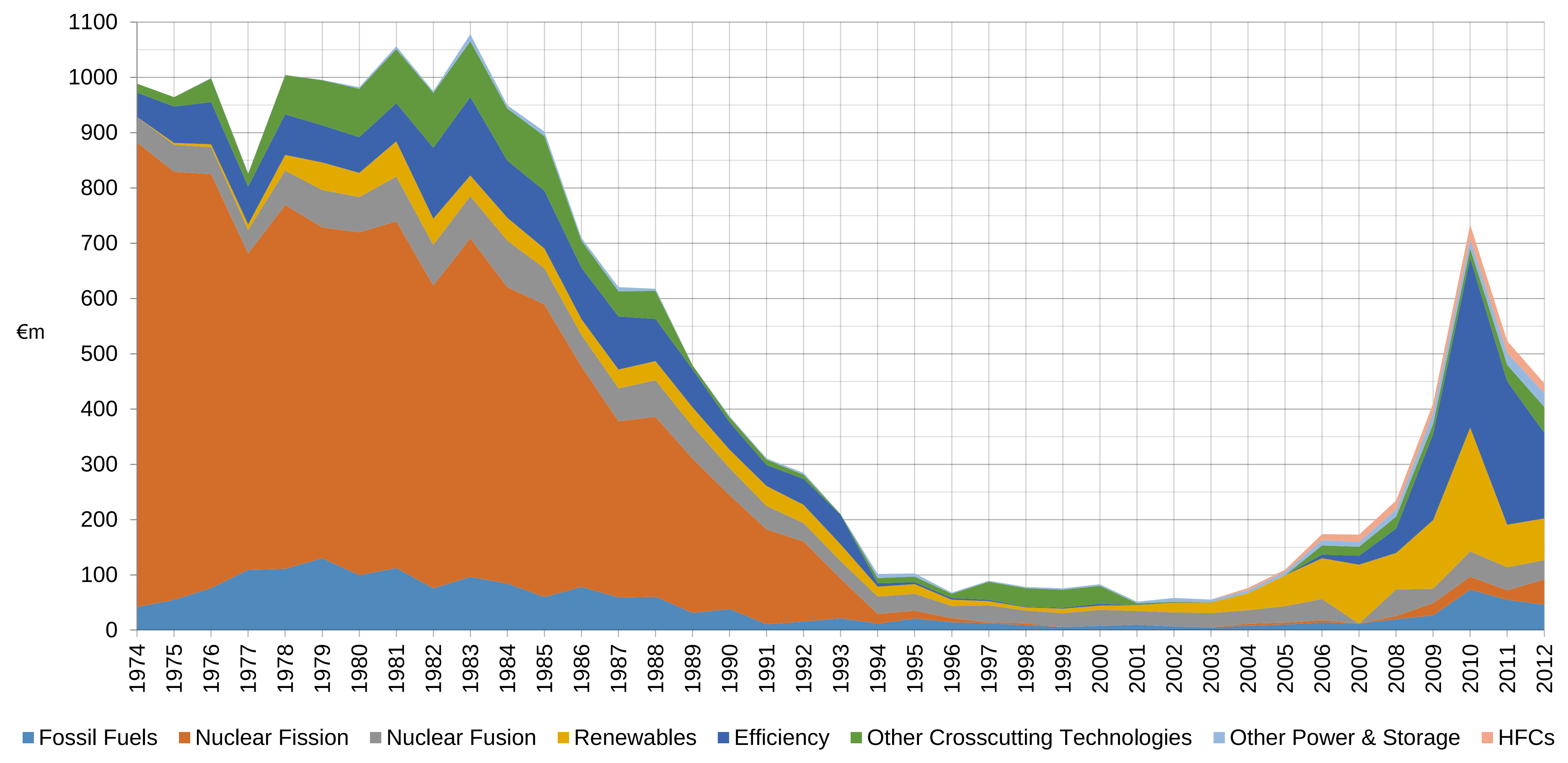
Appendix C: UK – All HFC TIS Events by TSIS Function, 1954-2012

	1954	**1955**	**1956**	**1957**	**1958**	**1959**	**1960**	**1961**	**1962**	**1963**	**1964**	**1965**	**1966**	**1967**	**1968**	**1969**	**1970**	**1971**	**1972**	**1973**
F1 Entrepreneurial activities	0	0	0	4	1	1	1	0	1	1	0	1	0	0	0	1	1	1	0	1
F2 Knowledge development	2	0	1	0	4	7	4	5	8	11	4	9	7	5	5	4	4	6	1	3
F3 Knowledge diffusion	0	0	0	0	0	1	0	3	0	1	0	0	0	0	0	0	0	0	0	0
F4 Guidance of the search	3	0	1	0	0	1	0	0	1	0	0	2	0	1	-2	2	0	0	2	2
F5 Market formation	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F6 Resource mobilization	-1	1	-1	1	-2	2	1	2	2	0	-1	0	-2	0	-2	0	0	0	0	1
F7 Advocacy coalitions	-2	0	-1	0	-1	0	0	0	0	0	0	0	0	0	0	0	-1	-1	-1	0
total	*2*	*1*	*1*	*5*	*2*	*12*	*6*	*10*	*12*	*13*	*3*	*12*	*5*	*6*	*1*	*7*	*4*	*6*	*2*	*7*
cumulative total	*4*	*5*	*6*	*11*	*13*	*25*	*31*	*41*	*53*	*66*	*69*	*81*	*86*	*92*	*93*	*100*	*104*	*110*	*112*	*119*

	1974	**1975**	**1976**	**1977**	**1978**	**1979**	**1980**	**1981**	**1982**	**1983**	**1984**	**1985**	**1986**	**1987**	**1988**	**1989**	**1990**	**1991**	**1992**	**1993**
F1 Entrepreneurial activities	0	0	2	1	1	1	0	1	0	1	1	0	2	1	0	0	1	0	1	0
F2 Knowledge development	2	6	3	2	4	5	1	5	2	4	1	3	6	0	1	2	6	2	4	6
F3 Knowledge diffusion	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
F4 Guidance of the search	-1	1	0	0	0	1	0	0	0	0	0	0	1	1	0	1	0	0	3	0
F5 Market formation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F6 Resource mobilization	1	-1	0	0	0	-1	1	-1	-1	0	0	0	1	0	1	0	0	0	0	0
F7 Advocacy coalitions	4	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
total	*6*	*7*	*5*	*4*	*5*	*6*	*2*	*5*	*1*	*5*	*2*	*3*	*11*	*2*	*2*	*3*	*7*	*2*	*8*	*6*
cumulative total	*125*	*132*	*137*	*141*	*146*	*152*	*154*	*159*	*160*	*165*	*167*	*170*	*181*	*183*	*185*	*188*	*195*	*197*	*205*	*211*

	1994	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
F1 Entrepreneurial activities	0	0	0	1	1	0	1	0	0	2	1	1	4	6	9	5	15	15	15
F2 Knowledge development	3	10	5	5	4	3	6	8	20	23	21	14	8	19	24	14	25	27	27
F3 Knowledge diffusion	0	0	0	0	0	6	0	0	1	5	2	-1	3	1	1	3	3	4	4
F4 Guidance of the search	1	0	0	0	1	5	2	2	11	5	5	3	5	2	6	3	8	6	7
F5 Market formation	0	0	0	0	0	0	0	1	0	0	3	0	1	3	5	1	2	2	5
F6 Resource mobilization	0	0	2	0	1	2	2	1	1	1	2	0	6	3	3	6	4	9	10
F7 Advocacy coalitions	0	0	0	0	1	0	1	0	-1	1	0	1	0	0	0	9	6	0	0
total	*4*	*10*	*7*	*6*	*8*	*16*	*12*	*12*	*32*	*37*	*34*	*18*	*27*	*34*	*48*	*41*	*63*	*63*	*68*
cumulative total	*215*	*225*	*232*	*238*	*246*	*262*	*274*	*286*	*318*	*355*	*389*	*407*	*434*	*468*	*516*	*557*	*620*	*683*	*751*

Appendix D: UK - Energy RD&D Spend 1974-2012 (€m 2014 prices)



source: International Energy Agency (2015a)

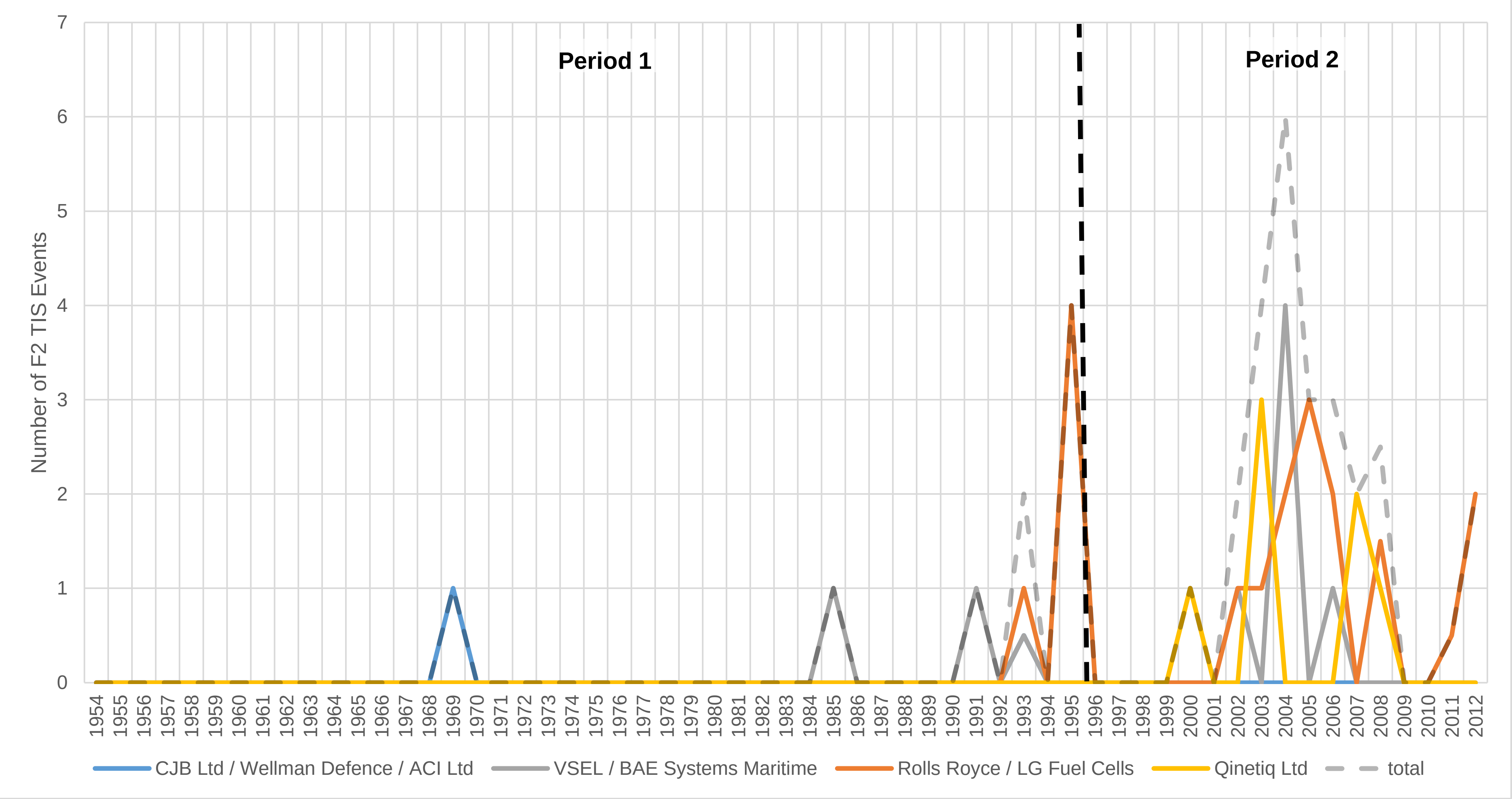
Appendix E: UK – Knowledge Development (F2) TIS Events by Actor for Defence and Aerospace, 1954-2012

	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973
CJB Dev's Ltd / Wellman Defence / ACI Ltd	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Rolls Royce / LG Fuel Cells	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VSEL / BAE Systems Maritime	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Qinetiq Ltd	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
annual total	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*1*	*0*	*0*	*0*	*0*
cumulative total	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*1*	*1*	*1*	*1*	*1*

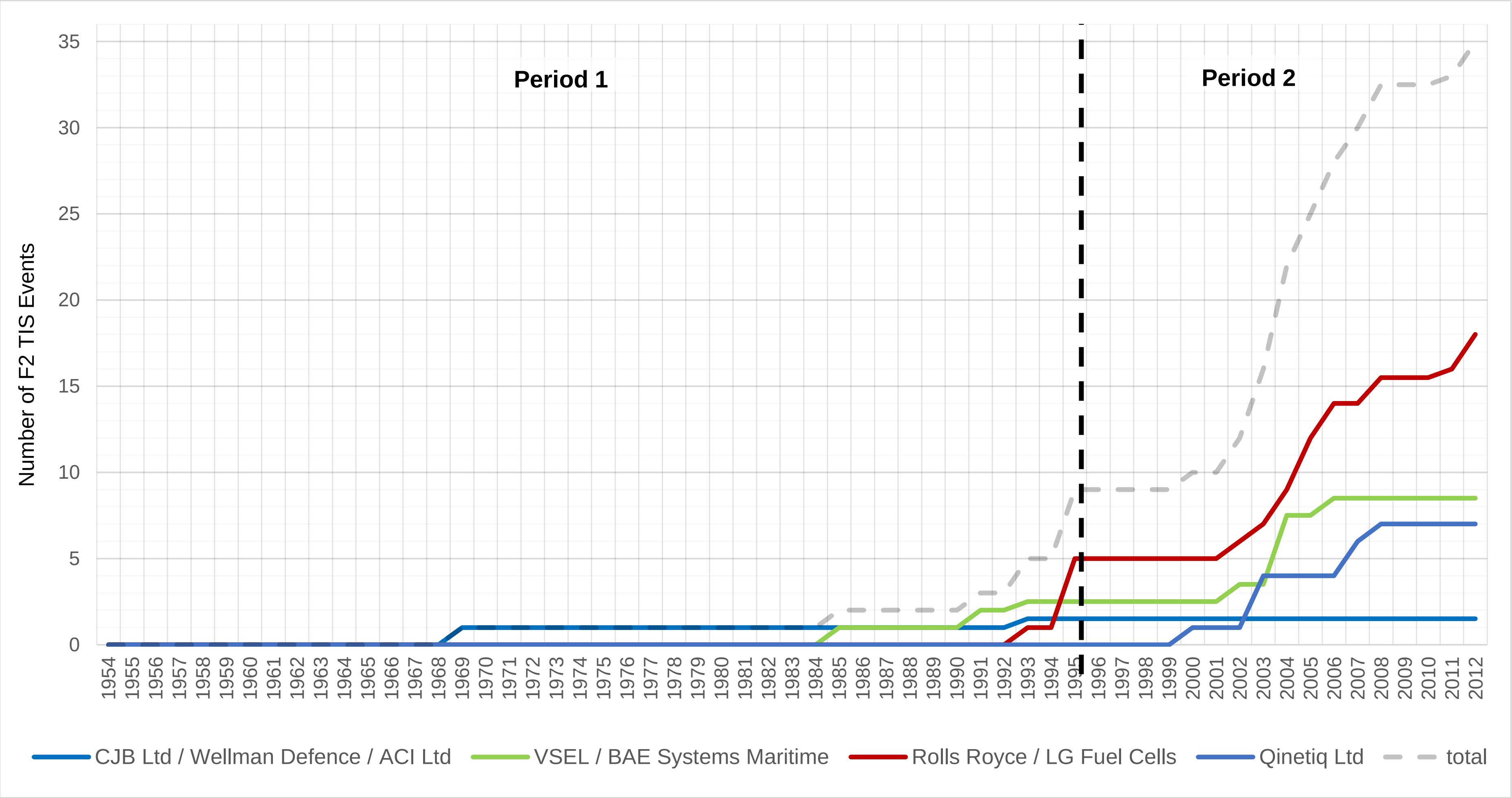
	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993
CJB Dev's Ltd / Wellman Defence / ACI Ltd	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Rolls Royce / LG Fuel Cells	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
VSEL / BAE Systems Maritime	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1
Qinetiq Ltd	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
annual total	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*1*	*0*	*0*	*0*	*0*	*0*	*1*	*0*	*2*
cumulative total	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*2*	*2*	*2*	*2*	*2*	*2*	*3*	*3*	*5*

	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
CJB Dev's Ltd / Wellman Defence / ACI Ltd	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rolls Royce / LG Fuel Cells	0	0	0	0	0	0	0	0	1	1	2	3	2	0	2	0	0	1	2
VSEL / BAE Systems Maritime	0	0	0	0	0	0	0	0	1	0	4	0	1	0	0	0	0	0	0
Qinetiq Ltd	0	0	0	0	0	0	1	0	0	3	0	0	0	2	1	0	0	0	0
annual total	*0*	*4*	*0*	*0*	*0*	*0*	*1*	*0*	*2*	*4*	*6*	*3*	*3*	*2*	*3*	*0*	*0*	*1*	*2*
cumulative total	*5*	*9*	*9*	*9*	*9*	*9*	*10*	*10*	*12*	*16*	*22*	*25*	*28*	*30*	*33*	*33*	*33*	*33*	*35*

Appendix F: UK – Annual Totals of TIS Events (F2) by Actor for Defence and Aerospace Sector, 1954-2012



Appendix G: UK – Cumulative Totals of TIS Events (F2) by Actor for Defence and Aerospace Sector, 1954-2012



Appendix H: UK – Nuclear Submarine Production

TIS Period	Class	HMS	Ensign	Type	Ordered	Laid Down	Launched	Commissioned	Decommissioned	Electrolyser Supplier
1	*Valiant*	Valiant	S102	Hunter-killer	31/8/1960	22/1/1962	3/12/1963	1966	1994	CJB Developments Ltd
		Warspite	S103		12/12/1962	10/12/1963	25/09/1965	1967	1991	CJB Developments Ltd
	Resolution	Resolution	S22	Ballistic missile	May 1963	26/2/1964	15/9/1966	1967	1994	CJB Developments Ltd
		Repulse	S23		May 1963	12/3/1965	4/11/1967	1967	1996	CJB Developments Ltd
		Renown	S26		May 1963		25/2/1967	1967	1996	CJB Developments Ltd
		Revenge	S27		May 1963	19/05/1965	15/03/1968	1969	1992	CJB Developments Ltd
	Churchill	Churchill	S46	Hunter-killer	21/10/1965	30/06/1967	20/12/1968	1970	1991	CJB Developments Ltd
		Conqueror	S48		09/08/1966		28/08/1969	1971	1990	CJB Developments Ltd
		Courageous	S50		01/03/1967		07/03/1970	1971	1992	CJB Developments Ltd
	Swiftsure	Swiftsure	S126	Hunter-killer			07/09/1971	1973	1992	CJB Developments Ltd
		Sovereign	S108		16/03/1969		17/02/1973	1974	2006	CJB Developments Ltd
		Superb	S109		20/05/1970		30/11/1974	1976	2008	CJB Developments Ltd
		Sceptre	S104		01/11/1971		20/11/1976	1978	2010	CJB Developments Ltd/ RN Special Contracts
		Spartan	S105		07/02/1976		07/05/1978	1979	2006	CJB Developments Ltd/ RN Special Contracts
		Splendid	S106		26/05/1976		05/10/1979	1981	2004	CJB Developments Ltd/ RN Special Contracts
	Trafalgar	Trafalgar	S107	Hunter-killer	07/04/1977		01/07/1981	1983	2009	CJB Developments Ltd/ RN Special Contracts
		Turbulent	S87		28/07/1978		01/12/1982	1984	2012	CJB Developments Ltd/ RN Special Contracts
		Tireless	S88		05/07/1979		17/03/1984	1985	2014	CJB Developments Ltd/ RN Special Contracts
		Torbay	S90		26/06/1981		08/03/1985	1987	-	CJB Developments Ltd/ RN Special Contracts
		Trenchant	S91		22/03/1983		03/11/1986	1989	-	CJB Developments Ltd/ RN Special Contracts
		Talent	S92		10/09/1984		15/04/1988	1990	-	CJB Developments Ltd/ RN Special Contracts
		Triumph	S93		03/01/1986		16/02/1991	1991	-	CJB Developments Ltd/ RN Special Contracts
	Vanguard	Vanguard	S28	Ballistic missile	30/05/1986		04/03/1992	1993	-	CJB Developments Ltd/ RN Special Contracts
		Victorious	S29		06/10/1987		29/09/1993	1995	-	CJB Developments Ltd/ RN Special Contracts
		Vigilant	S30		1990		31/03/1996	1996	-	CJB Developments Ltd/ RN Special Contracts
		Vengeance	S31		1992		19/09/1998	1999	-	CJB Developments Ltd/ RN Special Contracts
2	*Astute*	Astute	S119	Hunter-killer	17/03/1997		08/06/2007	2010	-	Wellman Defence Ltd
		Ambush	S120		17/03/1997		06/01/2011	2013	-	Wellman Defence Ltd
		Artful	S121		17/03/1997		2014	-	-	Wellman Defence Ltd
		Audacious	S122		2009		-	-	-	Wellman Defence Ltd
		Anson	S123		2011		-	-	-	Corac Group/ACI

Appendix I: UK – HFC TIS Events (F2) by Actor for Transport Sector, 1954-2012 (Part 1)

	event	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973
Air Products	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Birmingham University	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BOC (Linde)	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
British Petroleum (BP)	annual	0	0	0	1	1	1	0	1	0	1	0	1	1	0	0	0	0	0	0	0
	cumulative	0	0	0	1	2	3	3	4	4	5	5	6	7	7	7	7	7	7	7	7
Delta Motorsport	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Honda	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Intelligent Energy	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ITM Power	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Johnson Matthey (transport)	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lotus Engineering	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lucas Industries	annual	0	0	0	0	0	0	0	0	0	0	0	2	0	1	0	0	0	1	1	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	2	2	3	3	3	3	4	5	5
Microcab	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Morgan Cars	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Qinetiq (vehicles)	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Riversimple	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Shell	annual	0	0	0	0	0	0	1	0	1	1	0	1	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	1	1	2	3	3	4	4	4	4	4	4	4	4	4
Suzuki	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Unigate	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
totals	annual	0	0	0	1	1	1	1	1	1	2	0	4	1	1	0	0	0	1	1	0
	cumulative	0	0	0	1	2	3	4	5	6	8	8	12	13	14	14	14	14	15	16	16

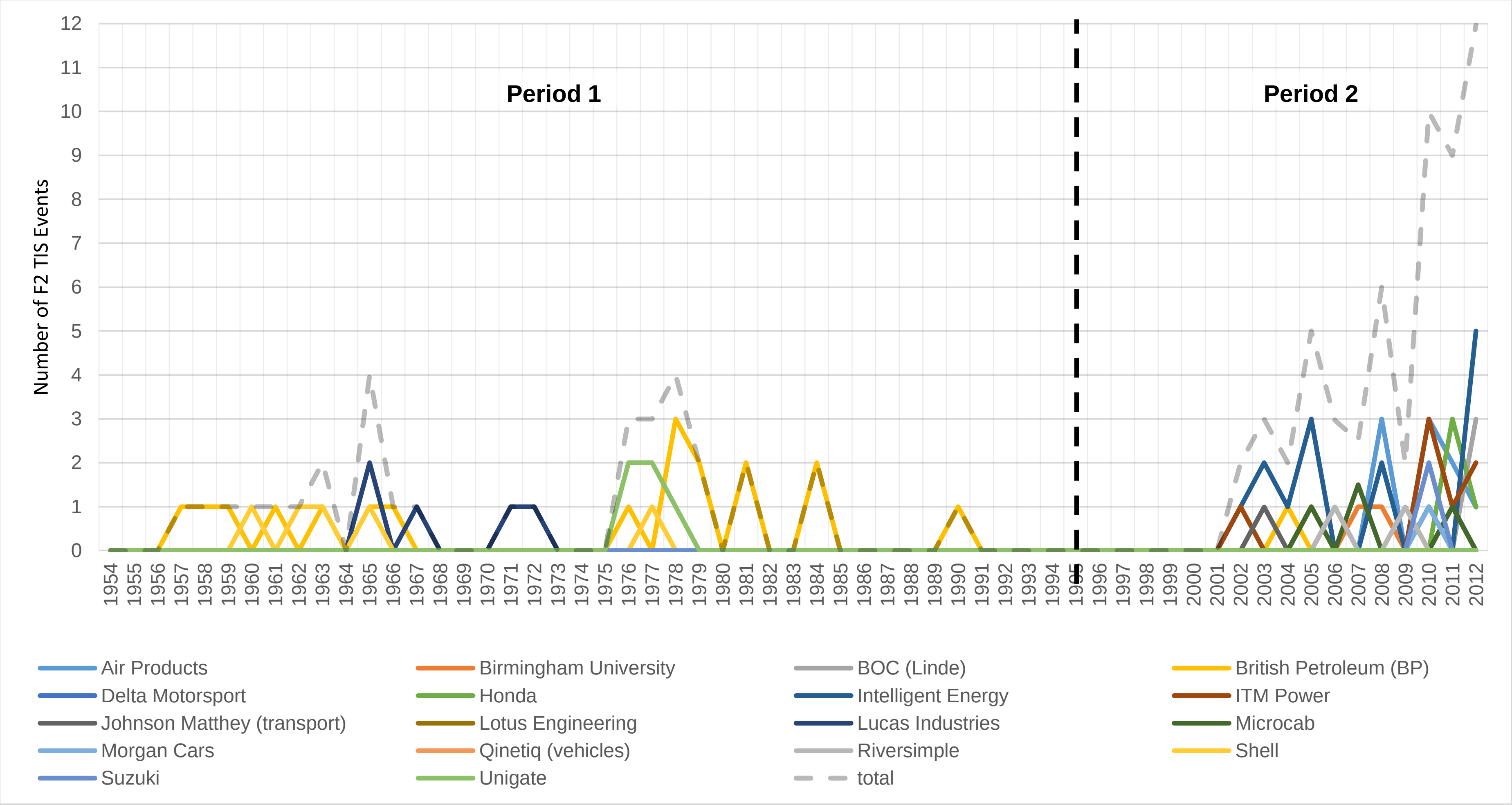
Appendix I: UK – HFC TIS Events (F2) by Actor for Transport Sector, 1954-2012 (Part 2)

	event	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993
Air Products	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Birmingham University	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BOC (Linde)	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
British Petroleum (BP)	annual	0	0	1	0	3	2	0	2	0	0	2	0	0	0	0	0	1	0	0	0
	cumulative	7	7	8	8	11	13	13	15	15	15	17	17	17	17	17	17	18	18	18	18
Delta Motorsport	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Honda	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Intelligent Energy	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ITM Power	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Johnson Matthey (transport)	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lotus Engineering	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lucas Industries	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Microcab	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Morgan Cars	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Qinetiq (vehicles)	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Riversimple	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Shell	annual	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	4	4	4	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Suzuki	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Unigate	annual	0	0	2	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	0	0	2	4	5	5	5	5	5	5	5	5	5	0	0	2	4	5	5	5
totals	annual	0	0	3	3	4	2	0	2	0	0	2	0	0	0	0	0	1	0	0	0
	cumulative	16	16	19	22	26	28	28	30	30	30	32	32	32	32	32	32	33	33	33	33

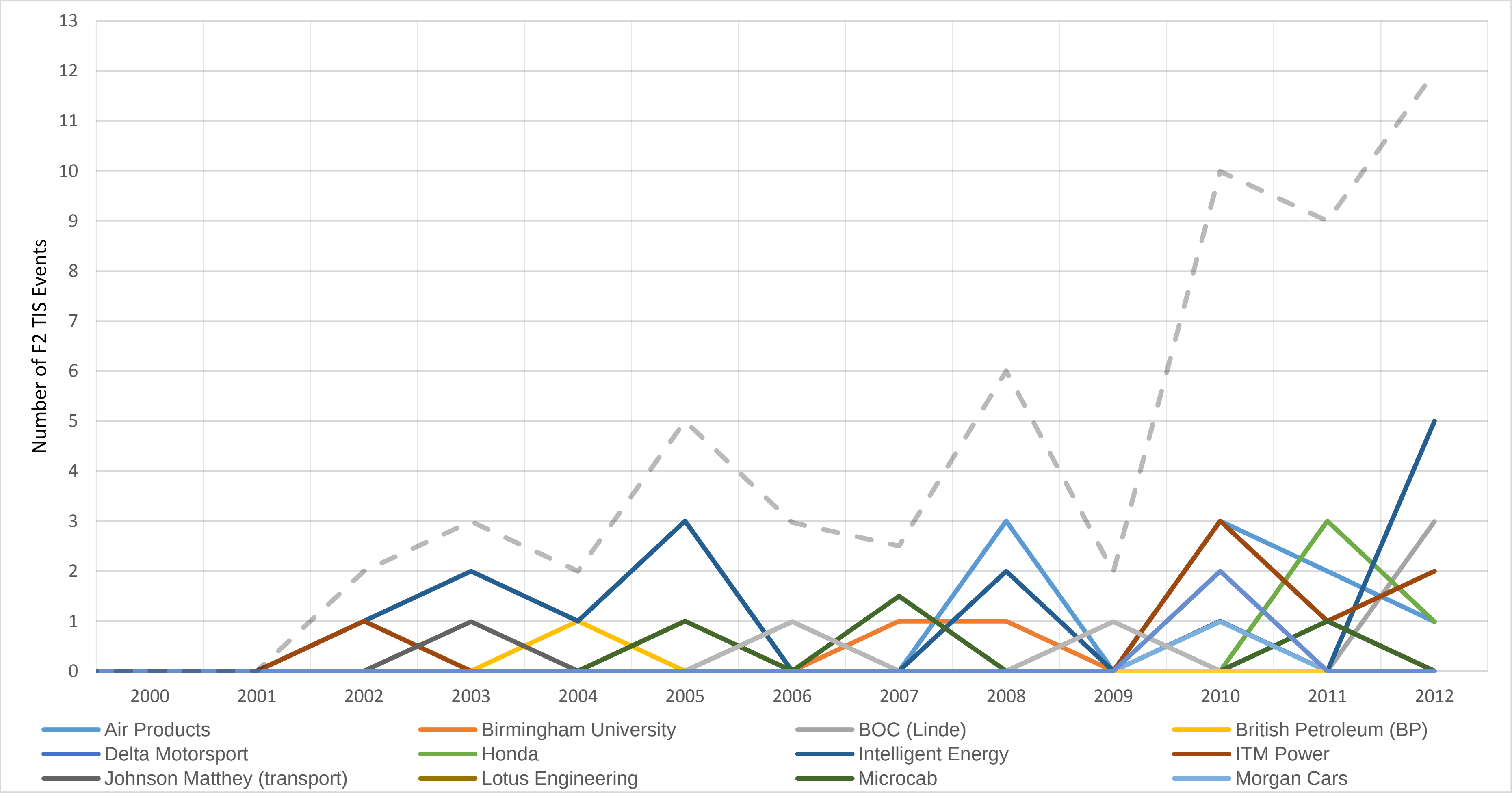
Appendix I: UK – HFC TIS Events (F2) by Actor for Transport Sector, 1954-2012 (part 3)

	event	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Air Products	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	3	2	1
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	6	8	9
Birmingham University	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	2	2	2	2
BOC (Linde)	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
British Petroleum (BP)	annual	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
	cumulative	18	18	18	18	18	18	18	18	18	18	19	19	19	19	19	19	19	19	19
Delta Motorsport	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Honda	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	1
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	4
Intelligent Energy	annual	0	0	0	0	0	0	0	0	1	2	1	3	0	0	2	0	1	0	5
	cumulative	0	0	0	0	0	0	0	0	1	3	4	7	7	7	9	9	10	10	15
ITM Power	annual	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	3	1	2
	cumulative	0	0	0	0	0	0	0	0	1	1	1	2	2	2	2	2	5	6	8
Johnson Matthey (transport)	annual	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1
Lotus Engineering	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Lucas Industries	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Microcab	annual	0	0	0	0	0	0	0	0	0	0	0	1	0	2	0	0	0	1	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	1	1	3	3	3	3	4	4
Morgan Cars	annual	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	2	2	2
Qinetiq (vehicles)	annual	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	2	2	2	2
Riversimple	annual	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	2	2	2	2
Shell	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Suzuki	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0
	cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2
Unigate	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	cumulative	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
totals	annual	0	0	0	0	0	0	0	0	2	3	2	5	3	3	6	2	10	9	12
	cumulative	33	33	33	33	33	33	33	33	35	38	40	45	48	50	56	58	68	77	89

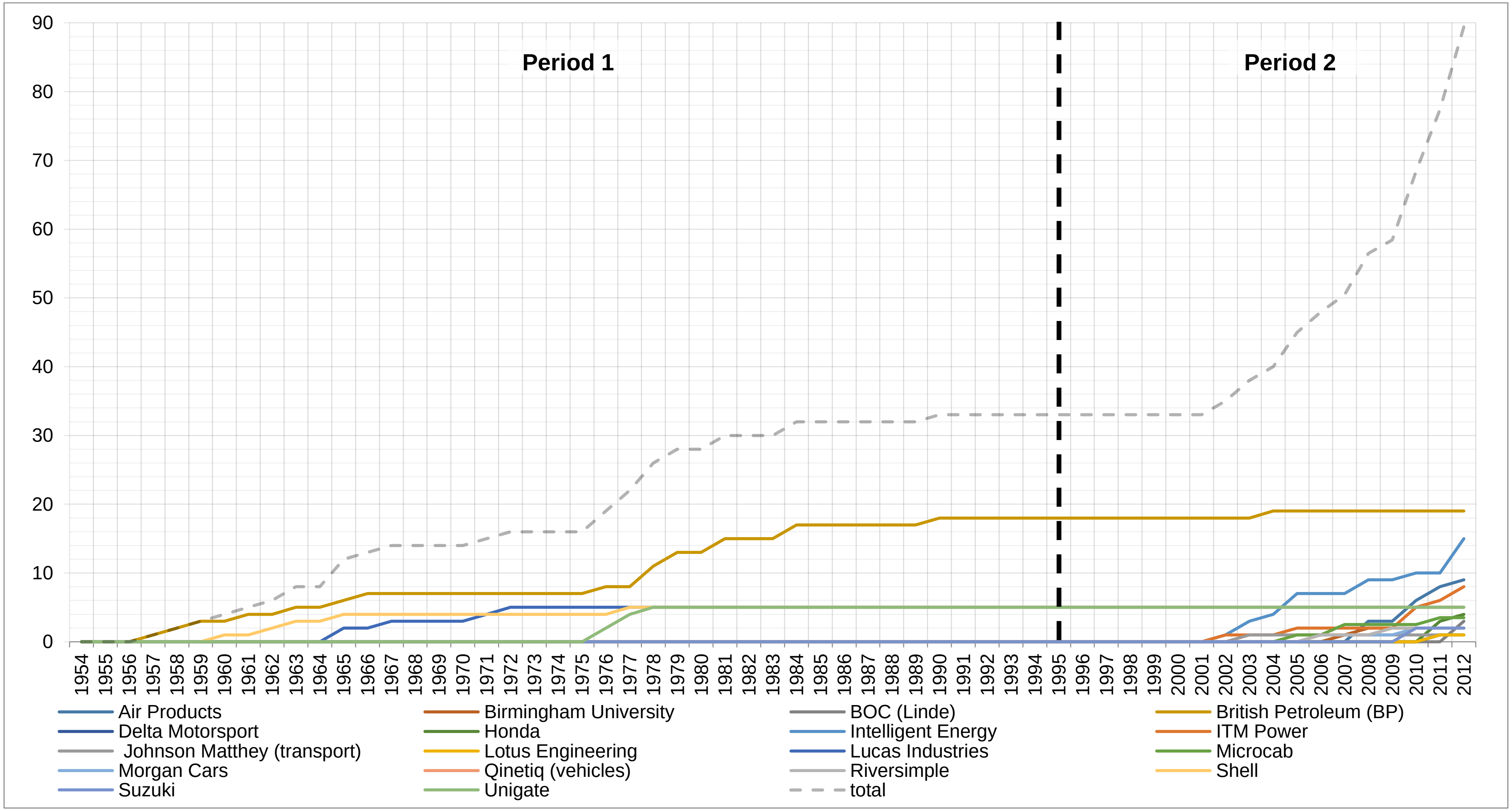
Appendix J: UK – Annual Knowledge Development Activity (F2) by Actor in the Transport Sector, 1954-2012



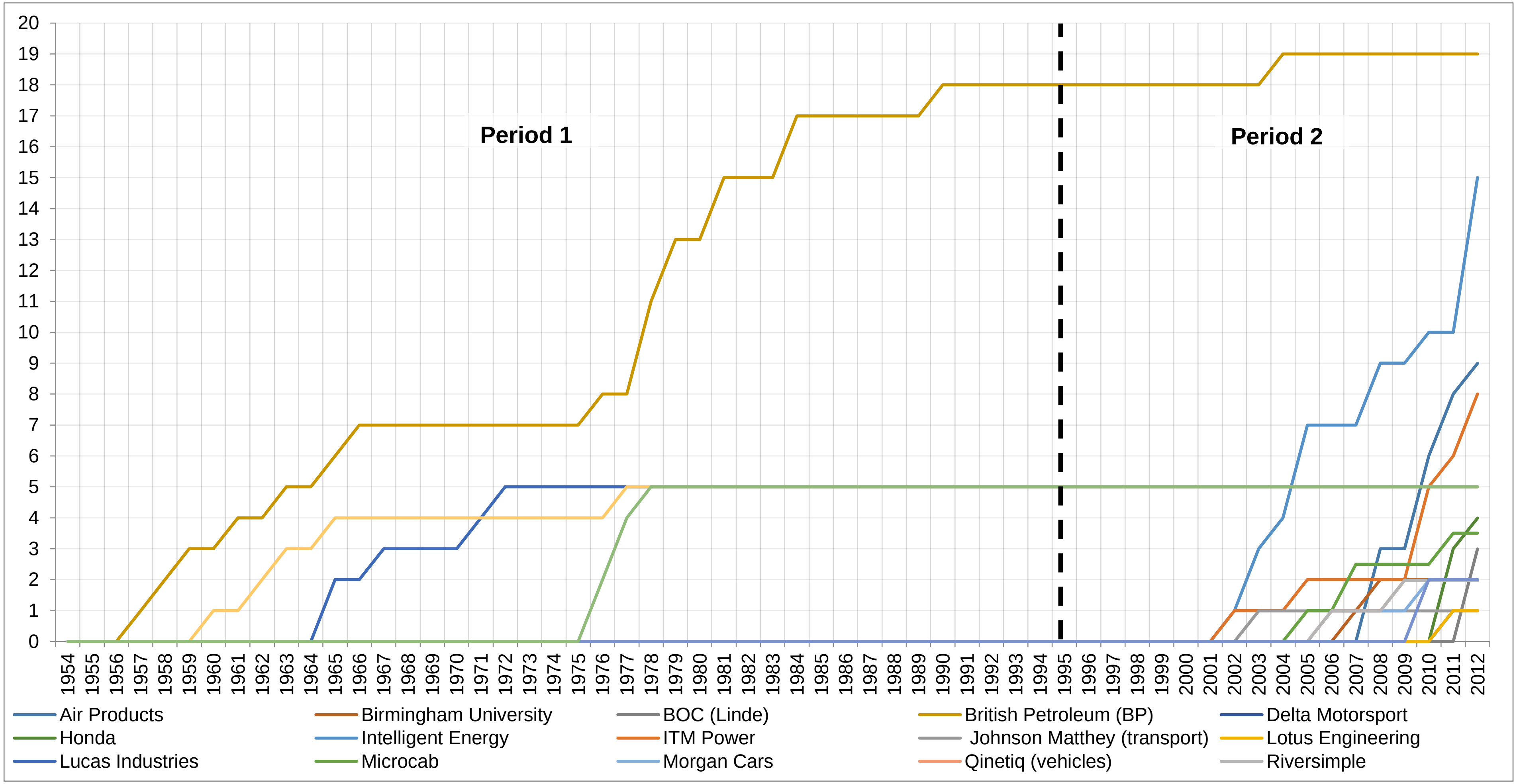
Appendix K: UK – Annual Knowledge Development Activity (F2) by Actor in the Transport Sector, 2000-2012



Appendix L: UK – Cumulative Knowledge Development (F2) by Actor in the Transport Sector, 1954-2012 (with total)



Appendix M: UK – Cumulative Knowledge Development (F2) by Actor in the Transport Sector, 1954-2012 (no total)



Appendix N: UK –TIS Events by Organisational Funding Type, 1954-2012

	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973
Public only (inc. academia)	1	-1	-1	0	0	0	0	2	0	1	1	0	0	1	0	1	0	2	1	3
Public & Private (no partnership)	4	0	0	6	1	6	1	0	4	6	0	5	4	3	0	1	1	1	1	0
Private (only)	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
PPPs	-3	0	1	-1	-1	6	3	8	7	6	3	6	6	5	3	5	3	3	0	3
annual total	*2*	*-1*	*0*	*5*	*0*	*12*	*5*	*10*	*11*	*13*	*4*	*11*	*10*	*9*	*3*	*7*	*4*	*6*	*2*	*6*
cumulative total	*2*	*1*	*1*	*6*	*6*	*18*	*23*	*33*	*44*	*57*	*61*	*72*	*82*	*91*	*94*	*101*	*105*	*111*	*113*	*119*

	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993
Public only (inc. academia)	2	1	-1	2	1	-1	1	1	0	0	0	0	1	0	0	0	0	0	-1	1
Public & Private (no partnership)	3	5	1	0	1	2	0	2	0	2	1	1	5	0	0	1	6	0	3	3
Private (only)	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PPPs	0	0	5	2	3	4	0	2	1	3	1	2	3	1	1	0	1	2	3	2
annual total	*5*	*7*	*5*	*4*	*5*	*5*	*1*	*5*	*1*	*5*	*2*	*3*	*9*	*1*	*1*	*1*	*7*	*2*	*5*	*6*
cumulative total	*124*	*131*	*136*	*140*	*145*	*150*	*151*	*156*	*157*	*162*	*164*	*167*	*176*	*177*	*178*	*179*	*186*	*188*	*193*	*199*

	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Public only (inc. academia)	0	1	1	1	2	8	1	3	10	2	3	1	0	3	6	3	2	7	4
Public & Private (no partnership)	3	8	4	4	4	5	7	5	12	22	18	15	17	18	23	20	37	31	25
Private (only)	0	0	0	0	0	0	1	0	2	0	0	0	0	0	1	6	3	1	1
PPPs	1	1	2	1	2	3	1	3	3	11	13	6	6	12	19	11	19	23	38
annual total	*4*	*10*	*7*	*6*	*8*	*16*	*10*	*11*	*27*	*35*	*34*	*22*	*23*	*33*	*49*	*40*	*61*	*62*	*68*
cumulative total	*203*	*213*	*220*	*226*	*234*	*250*	*260*	*271*	*298*	*333*	*367*	*389*	*412*	*445*	*494*	*534*	*595*	*657*	*725*

Appendix O: UK – HFC Public-Private Partnership (PPP) Types, 1954-2012

	1954	**1955**	**1956**	**1957**	**1958**	**1959**	**1960**	**1961**	**1962**	**1963**	**1964**	**1965**	**1966**	**1967**	**1968**	**1969**	**1970**	**1971**	**1972**	**1973**
Public Leverage	0	0	2	0	0	5	1	5	3	3	2	1	1	0	1	3	1	2	0	1
Contracting-Out	0	0	1	0	2	1	1	0	2	4	1	4	4	4	2	2	2	3	0	1
Public JV	0	0	0	0	0	0	0	3	0	0	0	1	1	1	0	0	0	-2	0	0
Strategic Partnering	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
annual total	*0*	*0*	*3*	*0*	*2*	*6*	*2*	*8*	*7*	*7*	*3*	*6*	*6*	*5*	*3*	*5*	*3*	*3*	*0*	*2*
cumulative total	*0*	*0*	*3*	*3*	*5*	*11*	*13*	*21*	*28*	*35*	*38*	*44*	*50*	*55*	*58*	*63*	*66*	*69*	*69*	*71*

	1974	**1975**	**1976**	**1977**	**1978**	**1979**	**1980**	**1981**	**1982**	**1983**	**1984**	**1985**	**1986**	**1987**	**1988**	**1989**	**1990**	**1991**	**1992**	**1993**
Public Leverage	0	0	1	1	1	1	0	0	0	2	0	1	0	0	0	0	0	0	0	0
Contracting-Out	0	0	4	1	2	3	0	2	1	1	1	1	3	1	1	0	1	2	3	2
Public JV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Strategic Partnering	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
annual total	*0*	*0*	*5*	*2*	*3*	*4*	*0*	*2*	*1*	*3*	*1*	*2*	*3*	*1*	*1*	*0*	*1*	*2*	*3*	*2*
cumulative total	*71*	*71*	*76*	*78*	*81*	*85*	*85*	*87*	*88*	*91*	*92*	*94*	*97*	*98*	*99*	*99*	*100*	*102*	*105*	*107*

	1994	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
Public Leverage	0	0	1	0	1	0	0	0	1	0	2	1	0	0	1	0	2	0	0
Contracting-Out	0	1	1	1	1	0	0	0	0	0	0	0	0	1	0	0	0	1	1
Public JV	0	0	0	0	0	0	0	0	0	0	3	0	1	7	6	4	2	4	2
Strategic Partnering	1	0	0	0	0	3	1	2	2	11	8	1	5	5	12	7	16	18	35
annual total	*1*	*1*	*2*	*1*	*2*	*3*	*1*	*2*	*3*	*11*	*13*	*2*	*6*	*13*	*19*	*11*	*20*	*23*	*38*
cumulative total	*108*	*109*	*111*	*112*	*114*	*117*	*118*	*120*	*123*	*134*	*147*	*149*	*155*	*168*	*187*	*198*	*218*	*241*	*279*

Appendix P: UK - 2012 List of Research Bodies Working on HFCs by Region

HE Institution / Research Institute	Region	Location	Postcode	Latitude	Longitude	Easting	Northing
Brunel University (School of Engineering and Design)	LON	Middlesex	UB8 3PH	51.532847	-0.472855	506024	182654
Imperial College	LON	London	SW7 2AZ	51.486523	-3.183159	317945	177061
Institute for Sustainability	LON	London	N1 6AH	51.489066	-3.179811	318176	177343
University College London	LON	London	NW1 2BU	51.572576	-1.315923	447506	186189
Diamond light source / Rutherford Appleton Lab	SE	Oxfordshire	OX11 0QX	55.933325	-3.213896	324260	671806
Oxford Brookes University	SE	Oxford	OX3 0BP	58.585698	-3.534681	310874	967431
Oxford University	SE	Oxford	OX1 2JD	51.500505	-0.178219	526549	179525
Southampton University	SE	Southampton	SO17 1BJ	51.528777	-0.087806	532742	182829
University of Reading	SE	Berkshire	RG6 6UR	53.470682	-2.239506	384199	397132
University of Surrey (Advanced Technology Institute)	SE	Guildford	GU2 7XH	54.98032	-1.615713	424693	565147
Science and Technology Facilities Council	SW	Swindon	SN2 1SZ	51.75438	-1.2232	453717	206473
Cardiff University (Low Carbon Research Institute - LCRI)	WAL	Cardiff	CF10 3NB	51.757639	-1.262886	450974	206807
Cardiff University (School of Chemistry)	WAL	Cardiff	CF10 3AT	57.148372	-2.10116	393978	806392
University of Glamorgan (Sustainable Environment Research Centre - SERC)	WAL	Cardiff	CF37 1DL	51.566838	-1.785952	414933	185351
University of Keele (School of Chemistry)	WM	Newcastle-under-Lyme	ST5 5BG	53.003952	-2.274598	381670	345217
University of Birmingham (The Centre for Hydrogen & Fuel Cell Research, School of Chemical Engineering, College of Engineering & Physical Sciences)	WM	Birmingham	B15 2TT	56.451153	-5.440741	188057	734086
Loughborough University (Centre for Renewable Energy Systems Technology - CREST)	EM	Loughborough	LE11 3TU	52.764873	-1.229474	452089	318864
University of Nottingham (Solar Hydrogen Centre, Department of Architecture and Built Environment)	EM	Nottingham	NG7 2RD	50.934189	-1.395685	442562	115145
University of Cambridge	E	Cambridge	CB2 3RA	51.524866	-0.137012	529340	182306
Manchester Metropolitan University (Division of Chemistry & Environmental Science)	NW	Manchester	M15 6BH	57.165311	-2.10448	393780	808278
Newcastle University (Sir Joseph Swan Centre for energy research, Catalysis for Energy)	NE	Newcastle	NE1 7RU	57.165311	-2.10448	393780	808278
Edinburgh Napier University (School of Engineering & the Built Environment)	SCO	Edinburgh	EH10 5DT	52.448972	-1.93086	404796	283448
Environmental Research Institute (ERI)	SCO	Thurso, Caithness	KW14 7EE	52.2034336	0.1325789	545830.9943	258277.0063
Robert Gordon University (School of Engineering)	SCO	Aberdeen	AB10 1FR	56.457209	-2.978476	339795	729880
Scottish Association for Marine Science (SAMS)	SCO	Dunstaffnage, Argyll	PA37 1QA	55.92245	-3.172445	326829	670551
University of Aberdeen (Department of Chemistry, School of Natural and Computing Sciences)	SCO	Aberdeen	AB24 3UE	51.588738	-3.325775	308249	188598
University of Aberdeen (School of Engineering)	SCO	Aberdeen	AB24 3UE	55.871751	-4.28836	256916	666655
University of Dundee (Division of Civil Engineering)	SCO	Dundee	DD1 4HN	52.94125	-1.18648	454768	338516
University of Edinburgh (Institute for Energy Systems - IES, School of Engineering)	SCO	Edinburgh	EH9 3JL	51.440563	-0.947108	473277	171811

University of Glasgow (School of Chemistry)	SCO	Glasgow	G12 8QQ	56.33986	-2.810697	349981	716684
University of St Andrews (School of Chemistry)	SCO	St Andrews, Fife	KY16 9ST	55.86151	-4.246702	259485	665430
University of Strathclyde (Department of Electronic & Electrical Engineering)	SCO	Glasgow	G1 1XW	51.242572	-0.587946	498663	150213
University of the Highlands and Islands (Hebridean Hydrogen Lab)	SCO	Stornoway, Isle Of Lewis	HS2 0XR	58.213	-6.396517	141875	933342
University of Ulster (Faculty of Art, Design & the Built Environment)	NI	Shore Road	BT37 0QB	54.68836	-5.882807	336574	383982

Appendix Q: UK - 2012 List of Corporate HFC Actors by Region

Company	Region	Location	Postcode	Latitude	Longitude	Northing	Easting	Est. Employees
Balton CP Ltd (consultancy)	E	Watford, Herts	WD25 8HG	51.666433	-0.365253	513155	197671	2
Bronkhorst UK Ltd	E	Newmarket, Suffolk	CB8 7TG	52.259537	0.395845	563613	265078	2
CMR Fuel Cells Ltd / CMR Fuel Cells (UK) Ltd	E	Cambridge	CB21 5XE	52.185999	0.191403	549909	256458	2
Element Energy (consultancy)	E	Cambridge, Cambridgeshire	CB1 2JD	52.194551	0.133002	545889	257290	2
Fuel Cell Today Ltd	E	Royston, Hertfordshire	SG8 5HE	52.05409	-0.034739	534848	241345	5
Leading Light Software Services Ltd	E	Cambridge, Cambridgeshire	CB2 1PH	52.194077	0.131853	545812	257235	7
Lotus Engineering Ltd	E	Norwich	NR14 8EZ	52.561638	1.180018	615642	300729	60
MC 498 Ltd	E	High Wycombe	HP10 0AP	51.597592	-0.68301	491318	189571	51
Nissan Motor (GB) Ltd	E	Rickmansworth, Hertfordshire	WD3 9YS	51.625819	-0.505897	503521	192946	30
Nissan Technical Centre Europe (NTCE)	E	Cranfield, Bedfordshire	MK43 0DB	52.065815	-0.637888	493470	241702	20
Omnagen Ltd	E	Hatfield, Hertfordshire	AL10 9JS	51.771551	-0.233621	521975	209573	3
Revolve Technologies Ltd	E	Brentwood, Essex	CM13 1XA	51.639693	0.35535	563082	196059	2
UK Hydrogen and Fuel Cell Association	E	Colchester	CO6 3BW	51.912722	0.845628	595817	227625	2
Wardown Engineering Limited	E	Dunstable	LU5 5BA	51.899163	-0.523285	501702	223321	4
CENEX (Centre of Excellence for Low Carbon and Fuel Cell Technologies)	EM	Loughborough, Leicestershire	LE11 3TU	52.764873	-1.229474	452089	318864	20
Intelligent Energy Holdings PLC	EM	Loughborough, Leicestershire	LE11 3GB	52.759798	-1.246946	450916	318287	2
Intelligent Energy Ltd	EM	Loughborough, Leicestershire	LE11 3GB	52.759798	-1.246946	450916	318287	200
Rolls-Royce Fuel Cell Systems (RRFCS) Ltd	EM	Derby, Derbyshire	DE24 8BJ	52.91504	-1.466139	435996	335424	80
Alstom UK (HQ)	LON	London	WC1V 7AA	51.515731	-0.125307	530178	181311	33
AMEC (Global HQ)	LON	London	EC1V 9RU	51.524143	-0.094819	532269	182301	9
Arcola Energy Ltd	LON	London	E8 3DL	51.546962	-0.074756	533594	184875	5
Carbon Trust (consultancy/funding)	LON	London	SE1 9NT	51.506832	-0.10534	531589	180357	10
Coller IP Management	LON	London	W1G 0TT	51.515667	-0.143874	528890	181271	2
Conduit Ventures Ltd	LON	London	EC1N 8LS	51.521324	-0.109034	531291	181962	3
Horizon Fuel Cell UK LTD	LON	London	E8 3DL	51.546962	-0.074756	533594	184875	2
HyTwo UK Ltd	LON	London	EC2V 7QP	51.516047	-0.096324	532188	181398	3
IdaTech Ltd	LON	London	EC2V 7QP	51.516047	-0.096324	532188	181398	8

IdaTech UK Ltd	LON	London	EC2V 7QP	51.516047	-0.096324	532188	181398	1
Investec Group Investments (UK) Ltd	LON	London	EC2V 7QP	51.516047	-0.096324	532188	181398	5
IP Group PLC	LON	London	EC3V 3ND	51.513208	-0.087118	532835	181099	5
Johnson Matthey PLC	LON	London	SW1Y 5BQ	51.507879	-0.129664	529898	180430	1
MC Fuel Cell Investments II Ltd	LON	London	WC1V 6BA	51.518471	-0.1161	530809	181632	2
MC Fuel Cell Investments Ltd	LON	London	WC1V 6BA	51.518471	-0.1161	530809	181632	2
PSA Parts Ltd	LON	London	SW19 2PX	51.413076	-0.176836	526887	169805	6
Rolls Royce Plc (UK HQ)	LON	London	SW1E 6AT	51.498091	-0.135641	529511	179331	16
Shell Chemicals Limited	LON	London	SE1 7NA	51.503655	-0.115774	530874	179985	13
Surrey Nanosystems Limited	LON	London	EC3V 3ND	51.513208	-0.087118	532835	181099	11
Waste2tricity Ltd	LON	London	EC1V 9EE	51.526844	-0.087263	532785	182615	10
Water Fuel Cell Limited	LON	London	E6 3HS	51.52747	0.047685	542144	182938	2
Whitefox Technologies	LON	London	E1 7NJ	51.518136	-0.075035	533659	181669	12
AMEC (Power and Process Europe)	NE	Darlington	DL1 4JN	54.517926	-1.507126	432004	513737	54
Hydrogen & Fuel Cell Cooperative Ltd	NE	Sedgefield	TS21 3FD	54.670301	-1.45134	435483	530719	4
Johnson Matthey Catalysts (UK)	NE	Cleveland	TS23 1LB	54.613903	-1.261819	447772	524555	40
Nissan Motor Manufacturing (UK) Limited	NE	Sunderland	SR5 3NS	54.920629	-1.466865	434270	558567	20
Proton Power Systems Plc.	NE	Newcastle upon Tyne	NE99 1SB	54.967722	-1.615787	424696	563745	50
Acal Energy Ltd	NW	Runcorn, Cheshire	WA7 4QX	53.324683	-2.732898	351281	381113	20
Cabot Plastics Ltd	NW	Dukinfield, Cheshire	SK16 4RU	53.46626	-2.101321	393371	396618	17
Ceramic Fuel (Powder) Ltd.	NW	Bromborough, Wirral	CH62 3QB	53.33054	-2.971284	335412	381954	5
Ineos Chlor	NW	Runcorn, Cheshire	WA7 4JE	53.325776	-2.694466	353842	381209	25
Technical Fibre Products - James Cropper PLC	NW	Kendal	LA9 6PZ	54.356053	-2.761573	350603	495881	25
Vickers Shipbuilding and Engineering Ltd (VSEL)	NW	Barrow-in-Furness	LA14 1AB	54.123181	-3.234639	319406	470407	20
Axeon Ltd	SCO	Dundee, Scotland	DD2 4UH	56.476266	-3.055221	335098	732071	50
Caledonian Marine Assets Ltd (CMAL)	SCO	Port Glasgow	PA14 5EQ	55.934888	-4.687407	232227	674577	5
Denchi Power Ltd (formerly ABSL Power Solutions Ltd)	SCO	Thurso	KW14 7XW	58.596506	-3.549471	310042	968654	7
Energy Technology Centre (ETC)	SCO	East Kilbride, Lanarkshire	G75 0QF	55.764352	-4.176999	263507	654480	1
Enertrag Ltd	SCO	Castle Brae, Dunfermline	KY11 8QF	56.046567	-3.414026	312016	684646	13
Fuel Cells (Scotland) Ltd	SCO	Rosewell	EH24 9DT	55.845272	-3.141085	328647	661929	25

Hydrogen Office Ltd	SCO	Methil, Fife	KY8 3RS	56.188474	-3.001272	337955	699990	3
IE-CHP, Intelligent Energy-Combined Heat & Power (UK & Eire) Ltd	SCO	Bellshill, Lanarkshire	ML4 3BF	55.833938	-4.034957	272645	661952	14
iPower Energy Ltd	SCO	Stirling, Stirlingshire	FK9 4DU	56.154285	-3.940331	279572	697429	3
Linnet Technology	SCO	Stirling, Stirlingshire	FK9 5QD	56.137303	-3.885658	282916	695445	8
Logan Energy Ltd	SCO	Edinburgh, East Lothian	EH2 2AZ	55.950205	-3.207115	324716	673677	6
M Power World Ltd	SCO	Tranent, East Lothian	EH33 1EH	55.95535	-2.86438	346126	673929	2
PURE Energy Centre Ltd	SCO	Shetland	ZE2 9DS	60.764962	-0.843611	463106	1209660	10
Sasol Technology UK Ltd	SCO	St Andrews, Fife	KY16 9SR	56.339626	-2.809333	350065	716657	4
Scottish and Southern Energy Plc (SSE)	SCO	Perth	PH1 3AQ	56.417342	-3.464173	309769	725975	20
Scottish Hydrogen and Fuel Cell Association Ltd, The (SHFCA)	SCO	East Kilbride	G75 0QF	55.754386	-4.16267	264371	653343	2
Scottish Power Renewables	SCO	Glasgow	G44 4BE	55.812417	-4.270335	257827	660016	10
Spruce Fuel Cells LLP	SCO	Kirkintilloch	G66 3PA	55.935758	-4.128642	267127	673458	8
3M United Kingdom PLC	SE	Bracknell	RG12 8HT	51.416455	-0.778331	485052	169312	40
ABSL Power Solutions Ltd (formerly part of AEA Technology Group)	SE	Culham, Oxfordshire	OX14 3ED	51.652096	-1.270273	450581	195064	25
AFC Energy	SE	Cranleigh, Surrey	GU6 8TB	51.120053	-0.5321	502833	136665	31
Air Products PLC	SE	Hersham, Surrey	KT12 4RZ	51.367657	-0.398584	511577	164394	85
bac2 Ltd	SE	Romsey	SO51 9AQ	50.980835	-1.462487	437830	120296	25
BOC Industrial Gases UK	SE	Guildford, Surrey	GU2 7XY	51.238291	-0.614235	496837	149702	30
British Gas (BG Group PLC)	SE	Reading, Berkshire	RG6 1PT	51.460459	-0.932788	474240	174038	57
Cella Energy Ltd	SE	Didcot, Oxfordshire	OX11 0QX	51.572576	-1.315923	447506	186189	31
Ceramic Fuel Cells (Europe) Ltd (Bluegen sales)	SE	Wallingford, Oxfordshire	OX10 8BA	51.606439	-1.113094	461517	190106	1
Ceres Power Ltd	SE	Horsham, West Sussex	RH13 5PX	51.071298	-0.31494	518155	131569	31
Coller IP Management	SE	Wallingford, Oxfordshire	OX10 9RB	51.598622	-1.140533	459627	189214	5
Denchi Power Ltd (formerly ABSL Power Solutions Ltd)	SE	Abingdon, Oxfordshire	OX14 4RQ	51.624024	-1.296009	448831	191924	10
Diverse Energy	SE	Slinfold, West Sussex	RH13 0SZ	51.067724	-0.416935	511018	131013	31
Eco Island Partnership CIC	SE	Cowes, Isle of Wight	PO31 8EB	50.759203	-1.32053	448022	95732	5
Fuel Cell Systems Ltd	SE	Hungerford, Berkshire	RG17 0YU	51.419912	-1.517569	433643	169099	4
h2gogo Industries Limited	SE	Harrow, Middlesex	HA1 3AW	51.552225	-0.302583	517784	185069	5
h2gogo Ltd	SE	Harrow, Middlesex	HA1 3AW	51.552225	-0.302583	517784	185069	15
Ilika plc (University of Southampton spin out; largest shareholder is IP Group)	SE	Southampton	SO16 7NS	50.960954	-1.424926	440484	118105	4

Johnson Matthey Fuel Cells Ltd (R&D)	SE	Reading, Berkshire	RG4 9NH	51.460725	-0.974799	471321	174026	70
Morgan Crucible / Morgan Advanced Materials PLC	SE	Windsor	SL4 1LP	51.48136	-0.605858	496908	176744	50
RE Hydrogen Ltd	SE	Cranleigh, Surrey	GU6 8TB	51.120053	-0.5321	502833	136665	5
Ricardo PLC	SE	Shoreham-by-Sea	BN43 5FG	50.841302	-0.290386	520468	106034	10
Ricardo-AEA Ltd	SE	Harwell, Oxfordshire	OX11 0QR	51.577514	-1.307003	448119	186744	10
UPS Systems Plc - Fuel Cell Systems	SE	Hungerford, Berkshire	RG17 0YU	51.419912	-1.517569	433643	169099	31
Velocys Technologies Ltd	SE	Oxford	OX14 4SA	51.623549	-1.29021	449233	191875	30
Auriga Energy Ltd	SW	Bristol	BS5 0HE	51.462086	-2.567488	360672	173832	8
CeramTec UK Ltd	SW	Colyton, Devon	EX24 6JP	50.74033	-3.073404	324355	93963	30
Johnson Matthey Fuel Cells (Production)	SW	Swindon, Wiltshire	SN5 8AT	51.547659	-1.856345	410058	183206	70
Kiwa Ltd (trading as GASTEC at CRE)	SW	Cheltenham, Gloucestershire	GL52 7RZ	51.954296	-2.121939	391717	228430	10
MMI Engineering (consultancy)	SW	Bristol	BS30 8FJ	51.457737	-2.475981	367026	173303	6
Sigma-Aldrich Company Limited	SW	Gillingham, Dorset	SP8 4XT	51.032003	-2.275521	380776	125885	4
Fuel Cell Sensors Ltd	WAL	Barry, Vale of Glamorgan	CF62 8DH	51.407298	-3.271275	311674	168353	4
Lion Laboratories Ltd	WAL	Barry, Vale of Glamorgan	CF63 2BE	51.415051	-3.235008	314211	169172	40
Riversimple Ltd	WAL	Llandrindod Wells	LD1 6DF	52.25361	-3.376454	306137	262608	20
UNIFRAX Emission Control Europe Ltd	WAL	Holywell, Clywd	CH8 7HJ	53.283904	-3.201848	319970	377000	8
Adelan	WM	Birmingham	B15 3RN	52.464293	-1.935458	404482	285152	2
Air Liquide UK Ltd	WM	Coleshill, Birmingham	B46 1JY	52.515848	-1.706914	419986	290925	80
Alstom Power (Alternative Energy Concepts Group/Future Technologies organisation)	WM	Rugby, Warwickshire	CV21 2NH	52.379979	-1.26707	449987	276024	30
Amalyst	WM	Birmingham	B7 4BB	52.488656	-1.887221	407755	287866	8
Calor Gas UK	WM	Warwick	CV34 6RL	52.276425	-1.547932	430941	264349	5
E.On (UK) Plc	WM	Coventry, West Midlands	CV4 8LG	52.388622	-1.586886	428212	276813	12
Microcab Industries Ltd	WM	Coventry, West Midlands	CV1 2HG	52.403911	-1.504136	433832	278549	50
Teer Coatings Ltd	WM	Droitwich	WR9 9AS	52.279848	-2.161835	389056	264646	6
TRW Conekt	WM	Solihull	B90 4GW	52.394361	-1.816379	412592	277387	10
Valeswood Fuel Cells Ltd	WM	Moseley, Birmingham	B13 8LB	52.449648	-1.896325	407143	283526	11
ITM Power (Research) Ltd	YH	Sheffield, South Yorkshire	S4 7QQ	53.398186	-1.443226	437119	389184	1
ITM Power (Trading) Ltd	YH	Sheffield, South Yorkshire	S4 7QQ	53.398186	-1.443226	437119	389184	1
ITM Power PLC	YH	Sheffield, South Yorkshire	S4 7QQ	53.398186	-1.443226	437119	389184	62

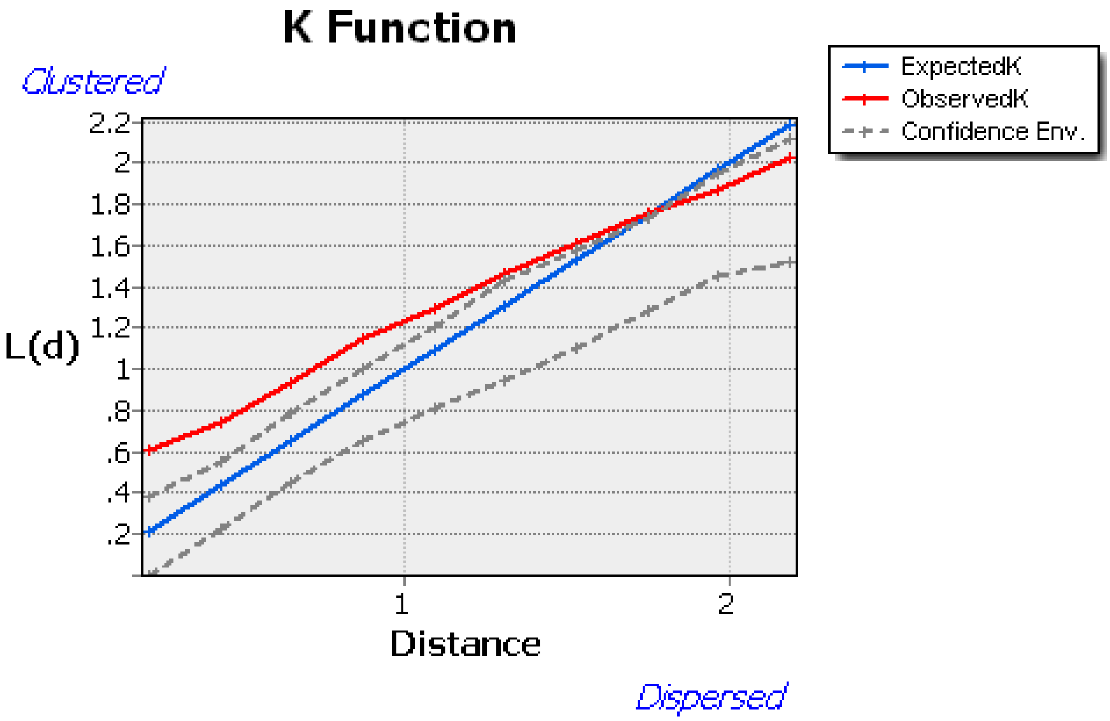
Rex Procter and Partners	YH	Leeds, West Yorkshire	LS2 9AE	53.807748	-1.549945	429735	434700	25
Victrex Manufacturing Ltd	YH	Rotherham	S61 4QH	53.440555	-1.363501	442378	393942	5

Appendix R: UK – Employee Location Quotients for Regional HFC Corporate Activity

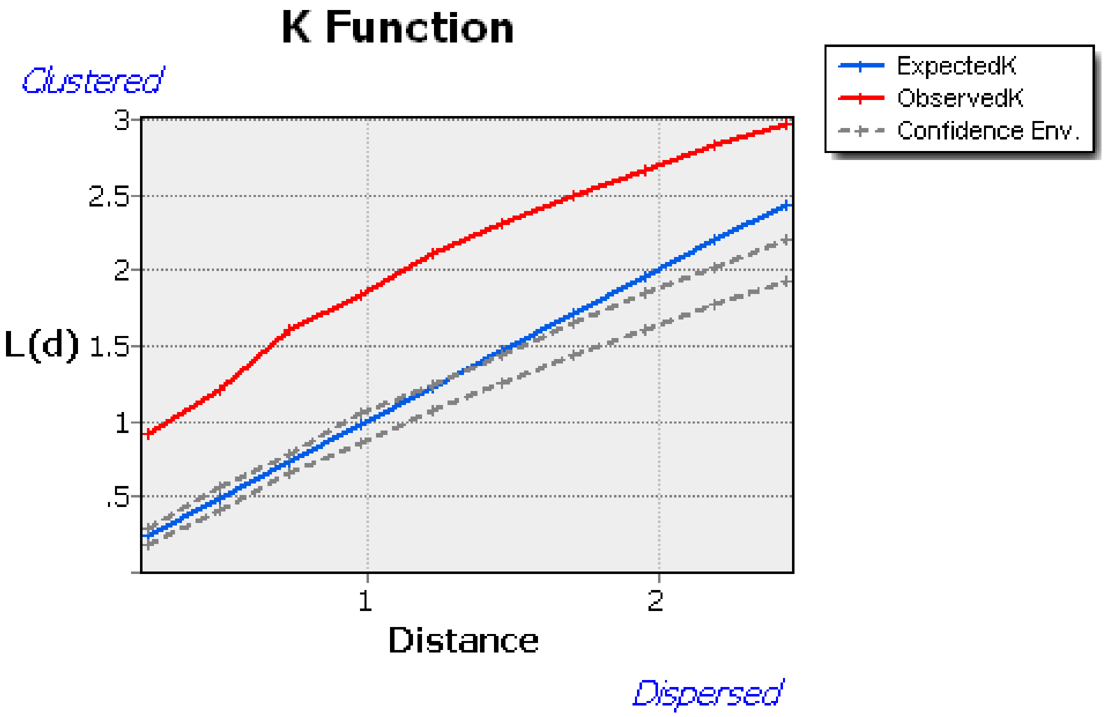
Region	Code	Total HFC Employee (estimate only)	Total All Employment (2012)	Employee Location Quotients (LQs)	Rank Order
East	E	211	2865000	1.01	6
East Midlands	EM	302	2102000	1.97	3
Greater London	LON	160	3854000	0.57	9
North East	NE	168	1140000	2.02	2
Northern Ireland	NI	2	477210	0.06	12
North West	NW	112	3096000	0.50	11
Scotland	SCO	191	2481000	1.06	5
South East	SE	641	4189000	2.10	1
South West	SW	128	2502000	0.70	8
Wales	WAL	72	1331000	0.74	7
West Midlands	WM	214	2423000	1.21	4
Yorkshire and Humberside	YH	94	2408000	0.54	10
total	-	2103	28868210	1.00	-

Appendix S: UK - Clustering Analysis (Ripley's K) of Actors in 2012

a) higher education bodies and research institutes:

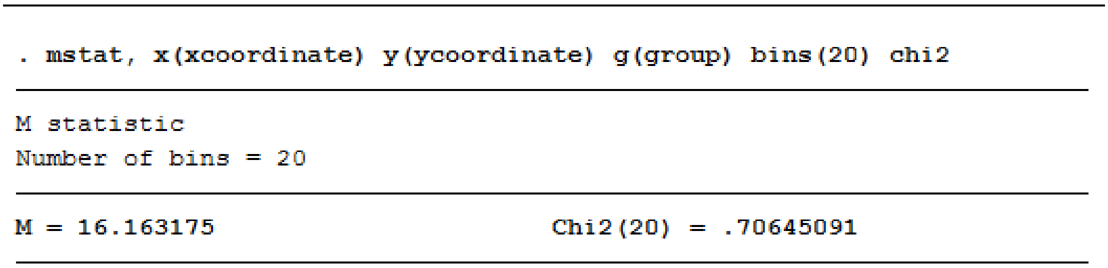


b) corporate HFC actors:



Appendix T: UK – Interpoint Distribution Analysis (*M*) of Actors in 2012

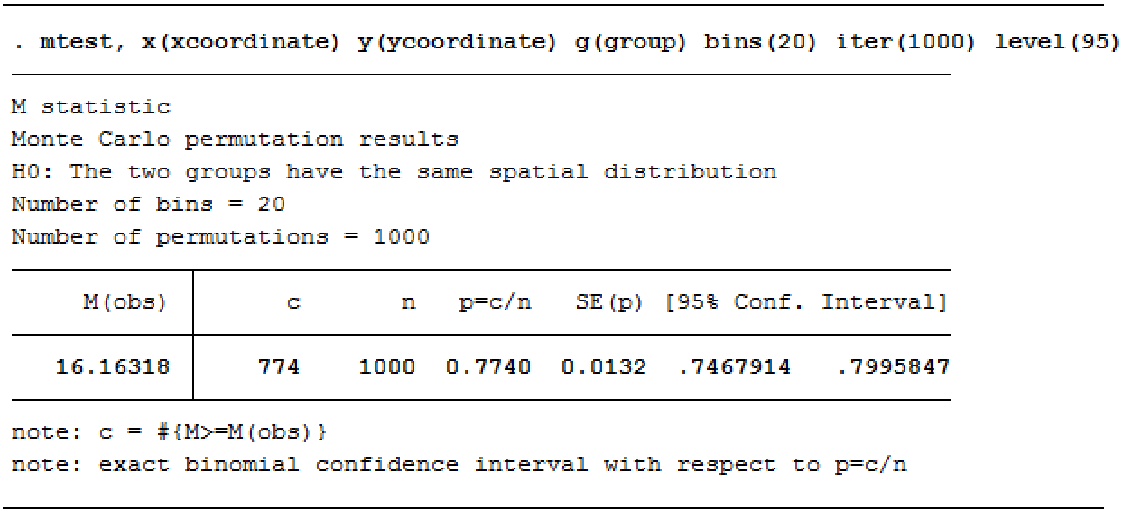
a) results for both groups via *mstat* (chi^2) and *mtest* (Monte Carlo) in StataMP14:



```
. mstat, x(xcoordinate) y(ycoordinate) g(group) bins(20) chi2

M statistic
Number of bins = 20

M = 16.163175                         Chi2(20) = .70645091
```



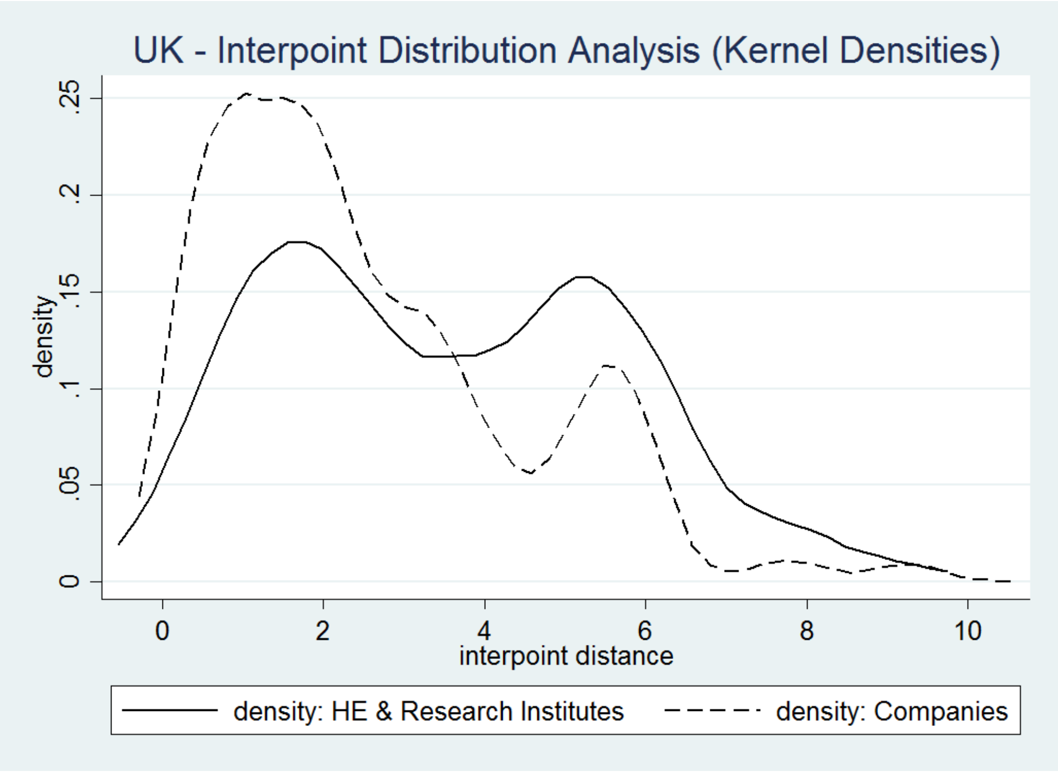
```
. mtest, x(xcoordinate) y(ycoordinate) g(group) bins(20) iter(1000) level(95)

M statistic
Monte Carlo permutation results
H0: The two groups have the same spatial distribution
Number of bins = 20
Number of permutations = 1000

     M(obs) |        c        n    p=c/n    SE(p)  [95% Conf. Interval]
 -----------+------------------------------------------------------------
   16.16318 |      774     1000   0.7740   0.0132   .7467914    .7995847

note: c = #{M>=M(obs)}
note: exact binomial confidence interval with respect to p=c/n
```

b) kernel density results in *mtest* for both groups of HFC actors:



Appendix U: UK – Regional Diffusion of HFC Knowledge Development Activity (F2), 1954-2012 (Part 1)

Nation / Region	code	total type	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973
Northern Ireland	NI	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Scotland	SCO	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
North East	NE	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
North West	NW	annual	0	0	0	0	0	2	2	0	5	6	0	4	1	2	1	1	3	1	0	0
		cumulative	0	0	0	0	0	2	4	4	9	15	15	18	19	21	22	22	25	25	25	25
York & Humber	YH	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
West Midlands	WM	annual	0	0	0	0	0	0	0	0	0	0	0	2	0	2	0	0	0	1	1	0
		cumulative	0	0	0	0	0	0	0	0	0	0	0	2	2	4	4	4	4	5	6	6
East Midlands	EM	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
East	E	annual	1	0	0	0	0	2	0	0	1	0	0	0	1	-1	0	0	0	0	0	0
		cumulative	1	1	1	1	1	3	3	3	4	4	4	4	5	4	4	4	4	4	4	4
Greater London	LON	annual	0	0	0	0	0	2	1	3	1	3	1	0	2	1	2	0	0	3	0	3
		cumulative	0	0	0	0	0	2	3	6	7	10	11	11	13	14	16	16	16	18	18	21
South East	SE	annual	0	0	0	2	1	1	1	2	0	3	3	4	5	2	2	3	2	2	0	1
		cumulative	0	0	0	2	3	4	5	7	7	10	12	16	20	22	24	27	28	30	30	31
South West	SW	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wales	WAL	annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
grand totals		annual	1	0	0	2	2	7	4	5	7	11	4	9	8	6	5	3	4	6	1	3
		cumulative	1	1	1	3	5	12	16	21	27	38	42	51	59	65	70	73	77	83	84	87

Appendix U: UK – Regional Diffusion of HFC Knowledge Development Activity (F2), 1954-2012 (Part 2)

Nation / Region	code	total type	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993
Northern Ireland	**NI**	**annual**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Scotland	**SCO**	**annual**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
North East	**NE**	**annual**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
		cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
North West	**NW**	**annual**	1	4	0	2	0	0	0	1	0	0	0	1	4	0	0	2	2	1	0	1
		cumulative	26	30	30	32	32	32	32	33	33	33	33	34	38	38	38	40	42	43	43	43
York & Humber	**YH**	**annual**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
West Midlands	**WM**	**annual**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		cumulative	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
East Midlands	**EM**	**annual**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
		cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
East	**E**	**annual**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
		cumulative	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	5
Greater London	**LON**	**annual**	0	2	2	2	2	3	3	0	2	3	0	2	3	0	1	0	0	1	1	1
		cumulative	21	23	24	26	28	30	33	33	34	37	37	39	41	41	42	42	42	42	43	43
South East	**SE**	**annual**	2	0	2	-2	3	3	0	3	1	1	1	1	1	0	1	0	4	1	3	1
		cumulative	32	32	34	32	34	37	37	39	40	41	42	42	43	43	43	43	47	48	51	52
South West	**SW**	**annual**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
		cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Wales	**WAL**	**annual**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
		cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
grand totals		**annual**	3	6	3	2	4	5	3	4	2	4	1	3	7	0	1	2	6	2	4	6
		cumulative	89	95	98	100	104	109	112	115	117	121	122	125	132	132	133	135	141	143	147	153

Appendix U: UK – Regional Diffusion of HFC Knowledge Development Activity (F2), 1954-2012 (Part 3)

Nation / Region	**code**		**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
Northern Ireland	**NI**	**annual**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
		cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	2
Scotland	**SCO**	**annual**	0	0	0	0	0	0	0	1	0	1	1	0	0	3	1	4	1	3	1
		cumulative	0	0	0	0	0	0	0	1	1	2	3	3	3	6	7	11	12	15	16
North East	**NE**	**annual**	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1	2	0	0	0
		cumulative	1	1	1	1	1	1	1	1	1	1	2	3	3	4	5	7	7	7	7
North West	**NW**	**annual**	2	0	0	0	1	0	0	1	3	3	0	0	0	3	2	3	5	3	0
		cumulative	45	45	45	45	46	46	46	47	49	52	52	52	52	55	57	60	65	68	68
York & Humber	**YH**	**annual**	0	0	0	0	0	0	0	0	3	4	0	1	1	0	1	2	6	3	3
		cumulative	0	0	0	0	0	0	0	0	3	7	7	8	9	9	10	12	18	21	24
West Midlands	**WM**	**annual**	0	1	0	0	0	0	1	0	0	1	1	1	2	3	0	5	1	3	0
		cumulative	6	7	7	7	7	7	8	8	8	9	10	11	13	16	16	21	22	25	25
East Midlands	**EM**	**annual**	0	6	0	1	1	0	0	2	2	4	3	6	2	0	5	0	3	2	7
		cumulative	1	7	7	8	9	9	9	11	13	17	20	26	28	28	33	33	35	37	44
East	**E**	**annual**	0	0	0	0	0	0	0	0	3	0	0	0	0	0	1	1	0	1	0
		cumulative	5	5	5	5	5	5	5	5	8	8	8	8	8	8	9	10	10	11	11
Greater London	**LON**	**annual**	0	1	2	0	1	0	0	1	3	1	0	1	0	1	0	2	0	2	3
		cumulative	43	44	46	46	47	47	47	48	51	52	52	53	53	54	54	56	56	58	60
South East	**SE**	**annual**	1	2	2	4	2	3	5	3	8	13	11	4	1	7	6	6	7	5	6
		cumulative	53	54	56	60	61	64	69	72	80	94	105	109	110	117	123	129	135	140	146
South West	**SW**	**annual**	0	1	1	0	0	0	0	0	0	2	1	0	0	0	3	1	0	4	5
		cumulative	1	2	3	3	3	3	3	3	3	5	6	6	6	6	9	10	10	14	18
Wales	**WAL**	**annual**	0	0	0	0	0	0	0	0	0	1	0	0	1	0	1	1	0	0	0
		cumulative	1	1	1	1	1	1	1	1	1	2	2	2	3	3	4	5	5	5	5
grand totals		**annual**	*3*	*10*	*5*	*5*	*4*	*3*	*6*	*8*	*20*	*30*	*18*	*14*	*7*	*18*	*21*	*27*	*23*	*25*	*26*
		cumulative	*156*	*166*	*171*	*176*	*180*	*183*	*189*	*197*	*217*	*247*	*266*	*280*	*287*	*305*	*326*	*352*	*376*	*401*	*427*

Appendix V: UK – Entrepreneurial Activity TIS Events (F1) by Region, 1999-2012

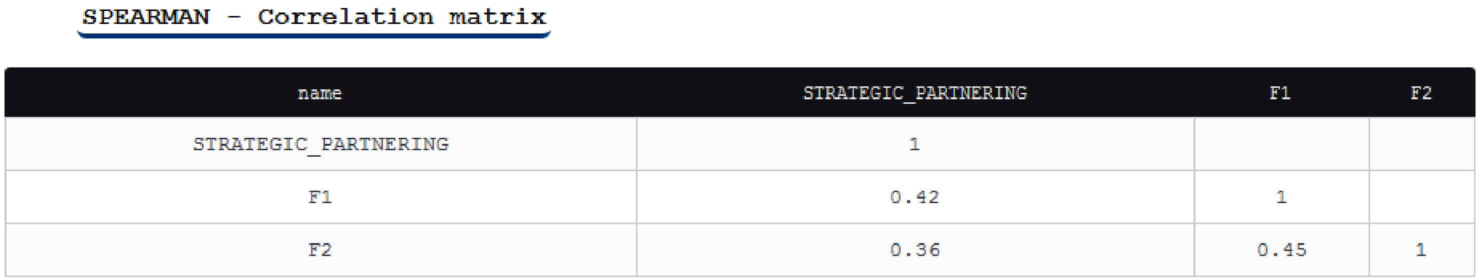
Nation/Region	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**total**	**share**
Northern Ireland	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
East	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Wales	0	0	0	0	0	0	0	0	0	2	0	0	0	0	2	3%
North East	0	0	0	0	0	0	0	0	1	1	0	0	0	0	2	3%
Greater London	0	0	0	0	0	1	0	0	0	0	0	0	1	2	4	6%
Scotland	0	0	0	0	1	0	0	1	0	0	0	3	1	0	6	8%
South West	0	0	0	0	0	0	0	0	0	0	0	0	3	4	7	11%
East Midlands	0	0	0	0	0	0	0	0	0	1	0	2	1	0	4	7%
North West	0	0	0	0	0	0	0	0	0	0	0	2	3	2	7	9%
West Midlands	0	0	0	0	1	0	1	1	2	2	1	0	1	1	10	13%
Yorkshire & Humberside	0	0	0	0	0	0	0	0	0	1	1	2	2	2	8	11%
South East	0	1	0	0	0	0	0	2	3	1	3	4	1	3	18	27%
annual total	0	1	0	0	2	1	1	4	6	8	5	13	13	14	68	100%
cumulative total	0	1	1	1	3	4	5	9	15	23	28	41	54	68	-	-

Appendix W: UK – Strategic Partnering PPP Activity for All TIS Events by Region, 1999-2012

Nation/Region	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**total**	**share**
Northern Ireland	0	0	0	0	0	0	0	0	0	0	0	**0**	0	0	0	0%
East	0	0	0	0	1	0	0	0	0	0	4	**0**	0	-1	4	2%
Wales	0	0	1	0	1	2	0	0	0	1	6	2	0	1	14	8%
North East	0	1	1	2	0	4	0	0	3	0	2	0	0	-1	12	7%
Greater London	0	0	0	0	4	1	0	0	0	0	3	2	-1	13	22	13%
Scotland	0	0	0	0	5	1	0	2	0	1	9	4	2	2	26	14%
South West	3	0	0	0	6	0	0	0	0	0	0	3	10	12	34	19%
East Midlands	0	0	0	0	3	1	1	0	0	2	0	0	1	0	8	4%
North West	0	0	0	0	4	0	0	0	0	0	3	1	3	3	14	7%
West Midlands	0	0	0	0	0	1	0	2	1	4	7	0	7	0	22	12%
Yorkshire & mberside	0	0	0	0	0	0	0	0	1	0	3	0	0	0	4	3%
South East	0	0	0	0	3	0	0	0	1	2	3	2	2	9	22	12%
annual total	3	1	2	2	27	10	1	4	6	10	40	14	24	38	182	100%
cumulative total	3	4	6	8	35	45	46	50	56	66	106	120	144	182	-	-

Appendix X: UK – Correlation Matrix for Strategic Partnering PPP and Functional Activity, 1999-2012

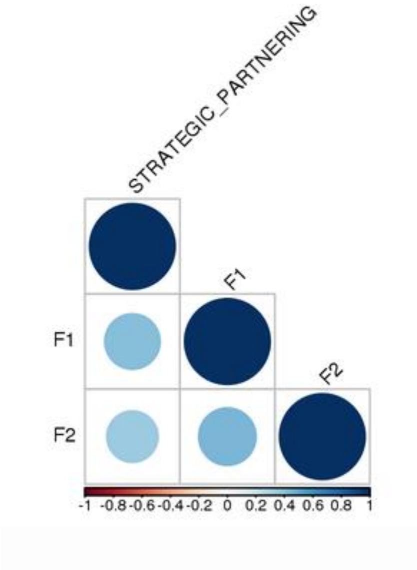
i) tabulated analysis in R (online via www.sthda.com) (1999-2012 data in Appendices AY, BB and BA compared):



SPEARMAN - Correlation matrix

name	STRATEGIC_PARTNERING	F1	F2
STRATEGIC_PARTNERING	1		
F1	0.42	1	
F2	0.36	0.45	1

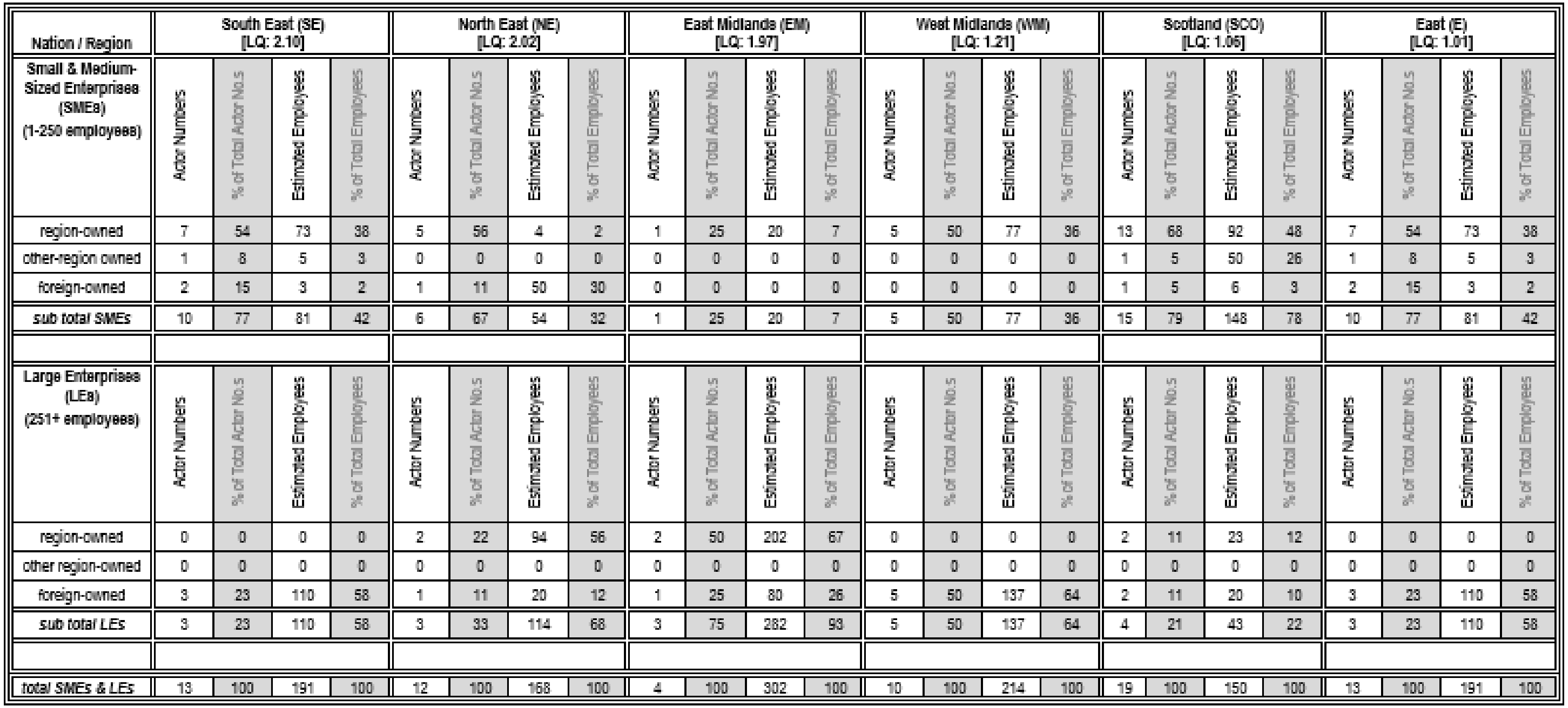
ii) visualisation of analysis via www.sthda.com:



Interpretation of Results' Range

Exactly –1	A perfect negative linear relationship
– 0.70	A strong negative linear relationship
– 0.50	A moderate negative relationship
– 0.30	A weak negative linear relationship
0	No linear relationship
+0.30	A weak positive linear relationship
+0.50	A moderate positive relationship
+0.70	A strong positive linear relationship
Exactly +1	A perfect positive linear relationship

Appendix Y: UK - Corporate HFC Actor Data (Numbers, Estimated Employees, Ownership) in 2012 (Part 1)



Nation / Region	South East (SE) [LQ: 2.10]				North East (NE) [LQ: 2.02]				East Midlands (EM) [LQ: 1.97]				West Midlands (WM) [LQ: 1.21]				Scotland (SCO) [LQ: 1.06]				East (E) [LQ: 1.01]			
Small & Medium-Sized Enterprises (SMEs) (1-250 employees)	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees
region-owned	7	54	73	38	5	56	4	2	1	25	20	7	5	50	77	36	13	68	92	48	7	54	73	38
other-region owned	1	8	5	3	0	0	0	0	0	0	0	0	0	0	0	0	1	5	50	26	1	8	5	3
foreign-owned	2	15	3	2	1	11	50	30	0	0	0	0	0	0	0	0	1	5	6	3	2	15	3	2
sub total SMEs	10	77	81	42	6	67	54	32	1	25	20	7	5	50	77	36	15	79	148	78	10	77	81	42
Large Enterprises (LEs) (251+ employees)	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees
region-owned	0	0	0	0	2	22	94	56	2	50	202	67	0	0	0	0	2	11	23	12	0	0	0	0
other region-owned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
foreign-owned	3	23	110	58	1	11	20	12	1	25	80	26	5	50	137	64	2	11	20	10	3	23	110	58
sub total LEs	3	23	110	58	3	33	114	68	3	75	282	93	5	50	137	64	4	21	43	22	3	23	110	58
total SMEs & LEs	13	100	191	100	12	100	168	100	4	100	302	100	10	100	214	100	19	100	150	100	13	100	191	100

Appendix Y: UK - Corporate HFC Actor Data (Numbers, Estimated Employees, Ownership) in 2012 (Part 2)

Nation / Region	Wales (WAL) [LQ: 0.74]				South West (SW) [LQ: 0.70]				Greater London (LON) [LQ: 0.57]				Yorkshire & Humberside (YH) [LQ: 0.54]				North West (NW) [LQ: 0.50]				Northern Ireland (NI) [LQ: 0.06]				Nation / Region totals			
Small & Medium-Sized Enterprises (SMEs) (1-250 employees)	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees
region-owned	3	75	64	70	0	0	0	0	5	42	80	53	5	50	77	36	13	68	92	48	7	54	73	38	56	51	580	30
other-region owned	1	25	20	22	0	0	0	0	0	0	0	0	0	0	0	0	1	5	50	26	1	8	5	3	5	5	82	4
foreign-owned	0	0	8	9	3	60	40	33	1	8	2	1	0	0	0	0	1	5	6	3	2	15	3	2	11	10	117	6
sub total SMEs	4	100	92	100	3	60	40	33	6	50	82	54	5	50	77	36	15	79	148	78	10	77	81	42	72	65	779	40
Large Enterprises (LEs) (251+ employees)	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees
region-owned	0	0	0	0	1	20	70	58	5	42	36	24	0	0	0	0	2	11	23	12	0	0	0	0	14	13	470	24
other region-owned	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
foreign-owned	0	0	0	0	1	20	10	8	1	8	33	22	5	50	137	64	2	11	20	10	3	23	110	58	24	22	699	36
sub total LEs	0	0	0	0	2	40	80	67	6	50	68	46	5	50	137	64	4	21	43	22	3	23	110	58	38	35	1168	60
total SMEs & LEs	4	100	92	100	5	100	120	100	12	100	150	100	10	100	214	100	19	100	150	100	13	100	191	100	110	100	1947	100

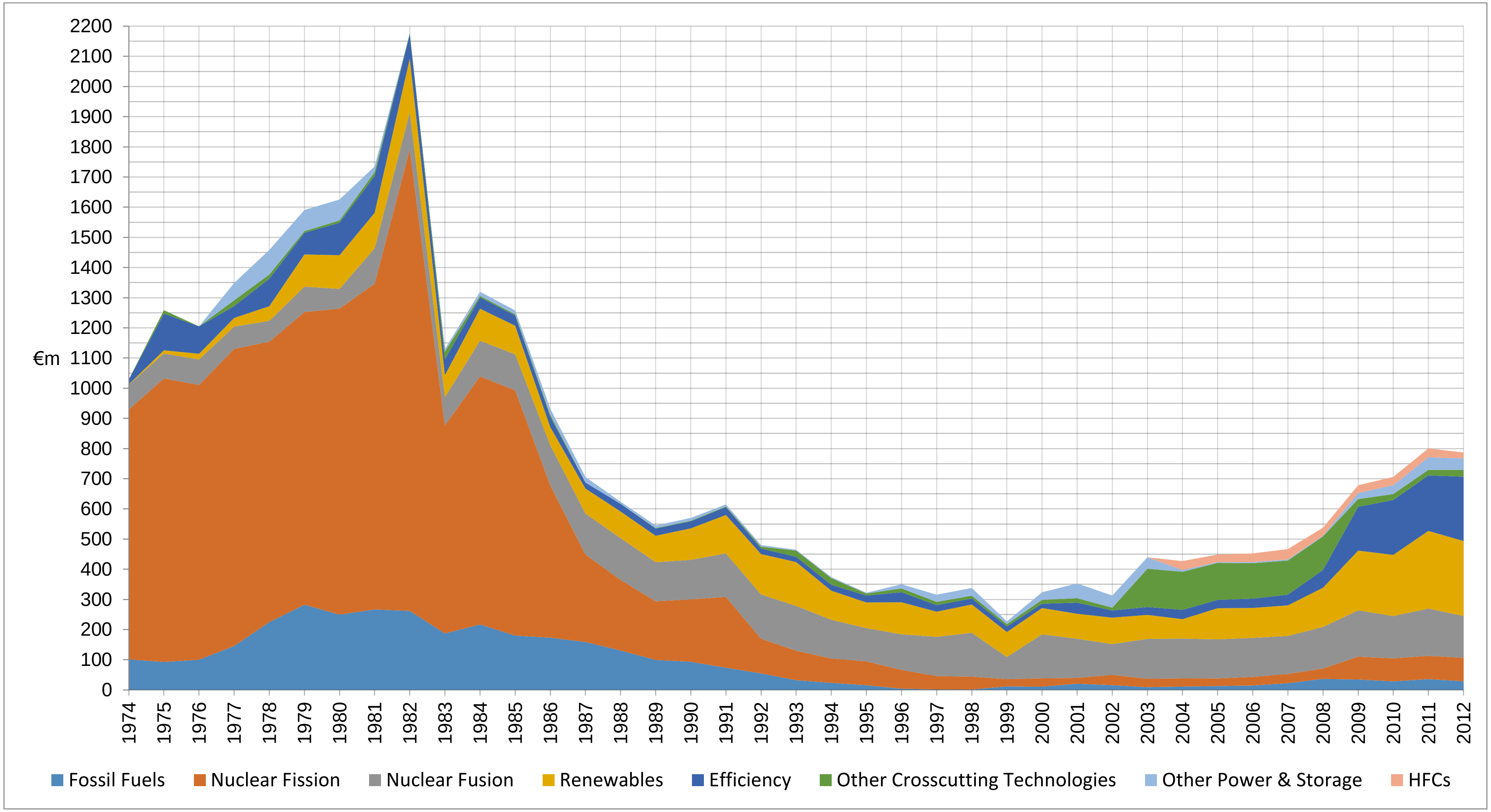
Appendix Z: Germany – All HFC TIS Event Data by Function, 1959-2012

	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976
F1 Entrepreneurial activities	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F2 Knowledge development	4	0	5	5	3	3	4	5	4	5	1	2	2	3	9	15	9	5
F3 Knowledge diffusion	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F4 Guidance of the search	0	0	0	0	0	0	0	0	0	0	1	0	2	1	0	1	0	0
F5 Market formation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F6 Resource mobilization	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
F7 Advocacy coalitions	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
annual total	4	0	5	5	3	3	4	5	4	5	2	2	4	4	9	17	9	5
cumulative total	4	4	9	14	17	20	24	29	33	38	40	42	46	50	59	76	85	90

	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994
F1 Entrepreneurial activities	0	0	0	2	0	0	-1	0	0	0	1	0	0	1	0	-1	0	0
F2 Knowledge development	8	8	10	11	10	3	4	3	2	4	6	7	6	8	3	10	12	15
F3 Knowledge diffusion	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	1	0
F4 Guidance of the search	0	0	0	0	1	0	0	0	0	0	0	0	0	0	3	0	0	1
F5 Market formation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F6 Resource mobilization	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
F7 Advocacy coalitions	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
annual total	8	8	10	13	11	3	3	3	3	4	7	7	6	9	8	10	13	16
cumulative total	98	106	116	129	140	143	146	149	152	156	163	170	176	185	193	203	216	232

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
F1 Entrepreneurial activities	0	0	1	0	-2	0	1	6	4	6	6	16	15	19	23	18	20	26
F2 Knowledge development	23	15	34	43	52	78	90	89	111	115	125	63	44	52	56	91	63	73
F3 Knowledge diffusion	0	0	0	0	0	0	2	2	3	6	4	7	6	4	0	6	6	10
F4 Guidance of the search	0	2	1	1	1	2	0	3	0	1	4	3	4	7	12	5	6	5
F5 Market formation	0	0	0	0	0	0	0	1	0	0	0	3	0	0	3	1	1	4
F6 Resource mobilization	0	0	3	1	-1	0	1	0	0	0	2	3	1	1	2	-1	5	3
F7 Advocacy coalitions	0	0	0	0	1	2	0	2	0	1	1	1	1	2	0	1	0	0
annual total	23	17	39	45	51	82	94	103	118	129	142	96	71	85	96	121	101	121
cumulative total	255	272	311	356	407	489	583	686	804	933	1075	1171	1242	1327	1423	1544	1645	1766

Appendix AA: Germany - Energy RD&D Spend 1974-2012 (€m 2014 prices)



source: International Energy Agency (2015a)

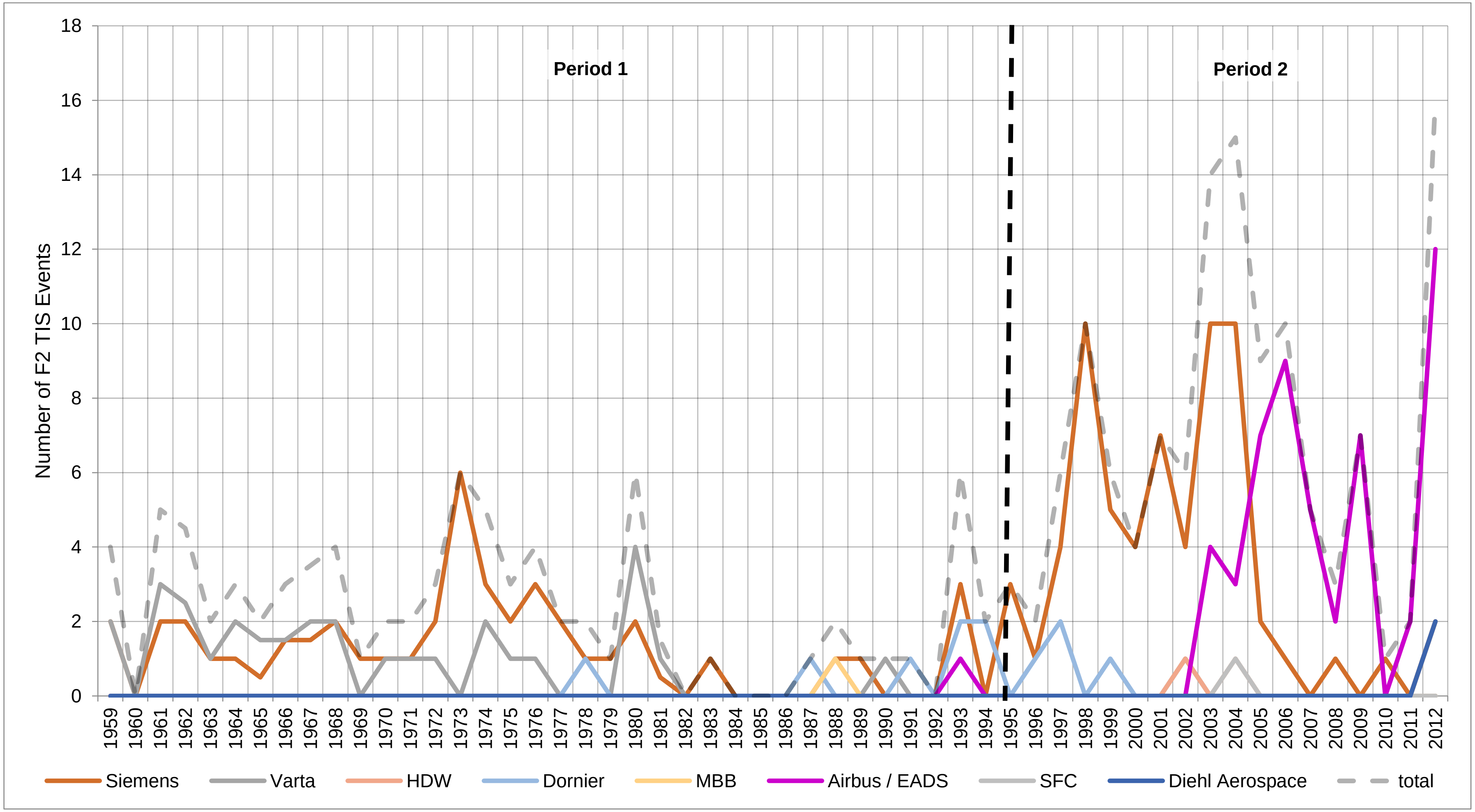
Appendix AB: Germany – Knowledge Development (F2) TIS Events by Actor for Defence and Aerospace, 1959-2012

	1959	**1960**	**1961**	**1962**	**1963**	**1964**	**1965**	**1966**	**1967**	**1968**	**1969**	**1970**	**1971**	**1972**	**1973**	**1974**	**1975**	**1976**
Airbus / EADS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Siemens	2	0	2	2	1	1	1	2	2	2	1	1	1	2	6	3	2	3
Varta	2	0	3	3	1	2	2	2	2	2	0	1	1	1	0	2	1	1
Diehl Aerospace	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dornier	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HDW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SFC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MBB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
annual total	4	0	5	5	2	3	2	3	4	4	1	2	2	3	6	5	3	4
cumulative total	4	4	9	14	16	19	21	24	27	31	32	34	36	39	45	50	53	57

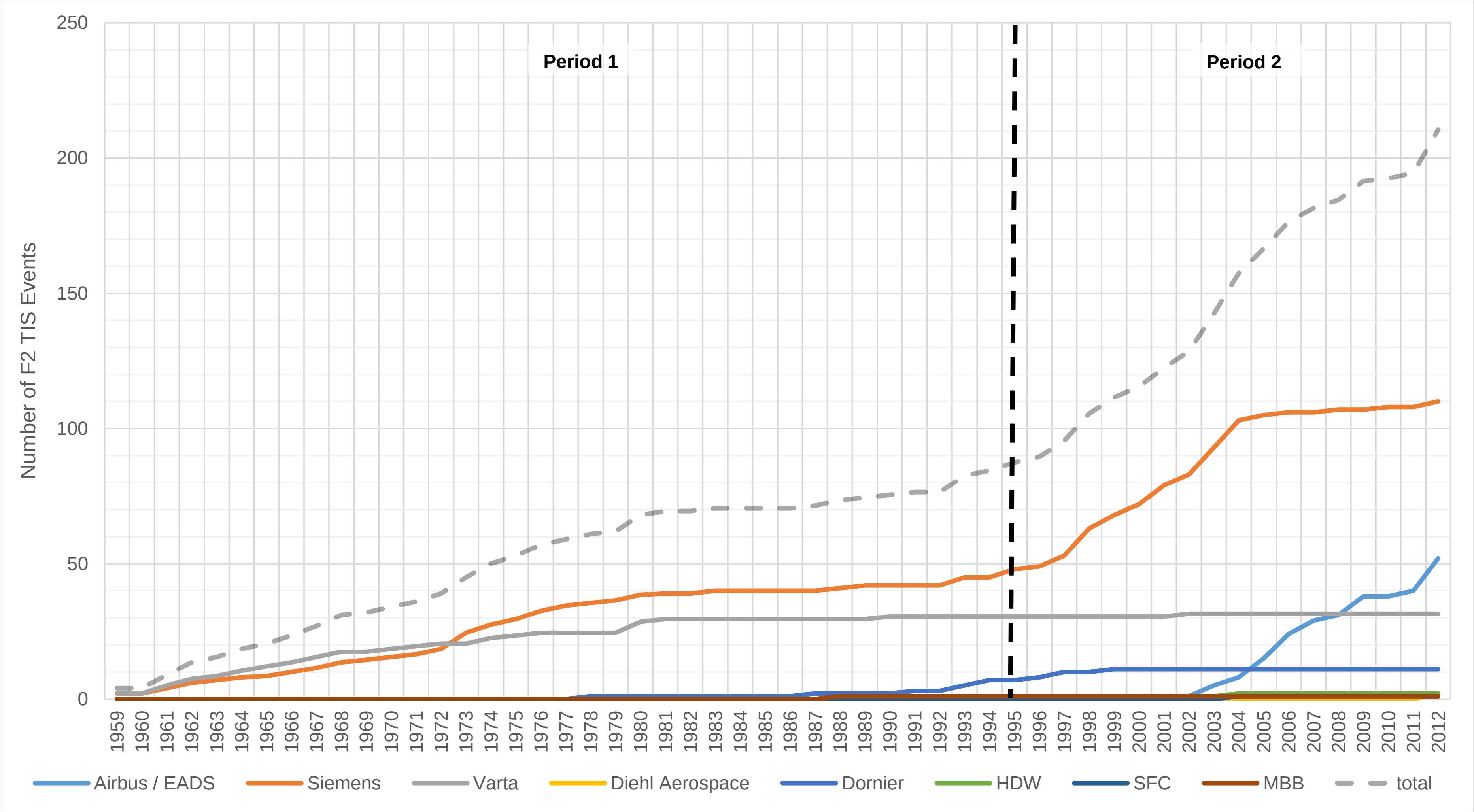
	1977	**1978**	**1979**	**1980**	**1981**	**1982**	**1983**	**1984**	**1985**	**1986**	**1987**	**1988**	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**
Airbus / EADS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Siemens	2	1	1	2	1	0	1	0	0	0	0	1	1	0	0	0	3	0
Varta	0	0	0	4	1	0	0	0	0	0	0	0	0	1	0	0	0	0
Diehl Aerospace	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dornier	0	1	0	0	0	0	0	0	0	0	1	0	0	0	1	0	2	2
HDW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SFC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MBB	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
annual total	2	2	1	6	2	0	1	0	0	0	1	2	1	1	1	0	6	2
cumulative total	59	61	62	68	70	70	71	71	71	71	72	74	75	76	77	77	83	85

	1995	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
Airbus / EADS	0	0	0	0	0	0	0	0	4	3	7	9	5	2	7	0	2	12
Siemens	3	1	4	10	5	4	7	4	10	10	2	1	0	1	0	1	0	2
Varta	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Diehl Aerospace	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
Dornier	0	1	2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
HDW	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0
SFC	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
MBB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
annual total	3	2	6	10	6	4	7	6	14	15	9	10	5	3	7	1	2	16
cumulative total	88	90	96	106	112	116	123	129	143	158	167	177	182	185	192	193	195	211

Appendix AC: Germany – Annual Totals of TIS Events (F2) by Actor for Defence and Aerospace Sector, 1954-2012



Appendix AD: Germany – Cumulative Totals of TIS Events (F2) by Actor for Defence and Aerospace Sector, 1954-2012



Appendix AE: Germany – HFC-Powered AIP Submarine Production

Class	Customer	Pennant	Name	Laid down	Launched	Commissioned	Builder	Cost (€m)[91] (2012)
Type 212A	German Navy	S181	*U-31*	1/7/98	20/3/02	19/10/05	Howaldtswerke-Deutsche Werft	371
		S182	*U-32*	11/7/00	4/12/03	19/10/05		371
		S183	*U-33*	30/4/01	9/04	13/6/06		371
		S184	*U-34*	12/01	7/06	3/5/07		371
		S185	*U-35*	21/8/07	15/11/11	23/3/15		371
		S186	*U-36*		6/2/13	planned 2016		371
Todaro (Type 212A)	Italian Navy	S526	*Salvatore Todaro*	3/7/99	6/11/03	29/3/2006	Fincantieri - Cantieri Navali Italiani S.p.A.	371
		S527	*Scirè*	27/5/00	18/12/04	19/2/07		371
		S528	*Pietro Venuti*	9/12/09	9/10/14	planned 2016		371
		S529	*Romeo Romei*	2012	4/7/15	planned 2016		371
Papanikolis (Type 214)	Greek Navy	S120	*Papanikolis*	27/2/01	4/04	2/11/10	Howaldtswerke-Deutsche Werft	335
		S121	*Pipinos*	2/03	10/06	2015	Hellenic Shipyards Co.	335
		S122	*Matrozos*	2/04	11/07	2015		335
		S123	*Katsonis*	2005	2007	pending		335
Son Won-Il (Type 214)	Korean Navy	SS072	*Son Won-il*	10/02	9/6/06	27/12/07	Hyundai Heavy Industries	335
		SS073	*Jeong Ji*	2004	13/6/07	2/12/08		335
		SS075	*An Jung-geun*		4/6/08	1/12/09		335
		SS076	*Kim Jwa-Jin*	2008	13/8/13	30/12/14	Daewoo Shipbuilding & Marine Engineering	335
		SS077	*Yun Bong-gil*	2009	3/7/14	2015	Hyundai Heavy Industries	335
		SS078	*Ryu Gwansun*	2010	7/5/2015	11/16	Daewoo Shipbuilding & Marine Engineering	335
		SS079		2011	2015		Hyundai Heavy Industries	335
		SS081		2012	2017		STX Offshore & Shipbuilding	335
		SS082		2013	2017	2018	Hyundai Heavy Industries	335
Tridente (Type 214)	Portuguese Navy	S160	NRP *Tridente*	2005		5/10	Howaldtswerke-Deutsche Werft	335
		S161	NRP *Arpão*	2005		28/4/11		335
Dolphin (Dolphin 2)	Israeli Navy[92]	n/a	INS *Tannin*	2/12	23/9/14	2014	Howaldtswerke-Deutsche Werft	650
		n/a	INS *Rahav*		29/4/13	2014		650
		n/a	INS *Dakar*			2018		Tbc
							total estimated turnover	*10,035*

sources: various

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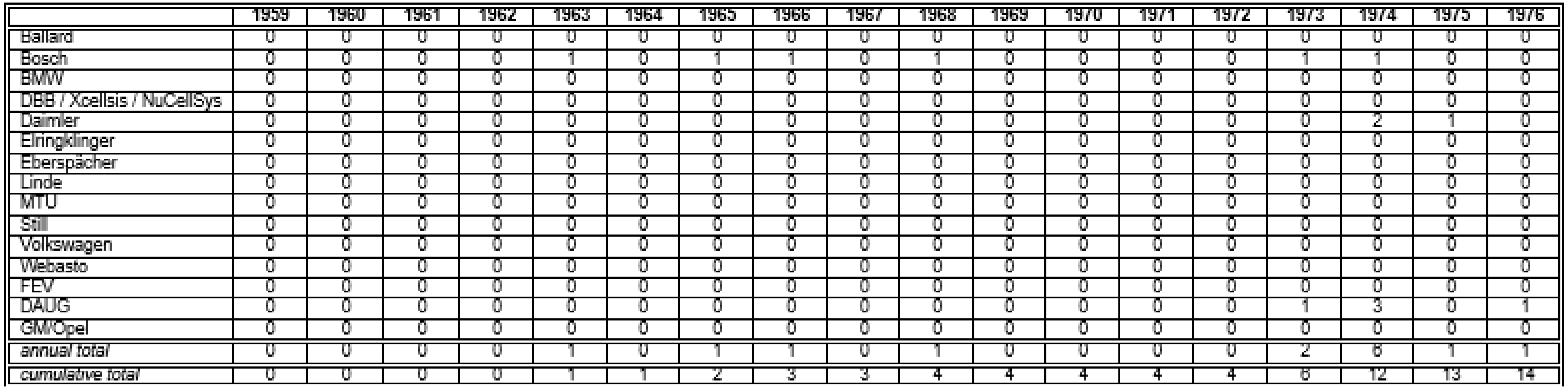
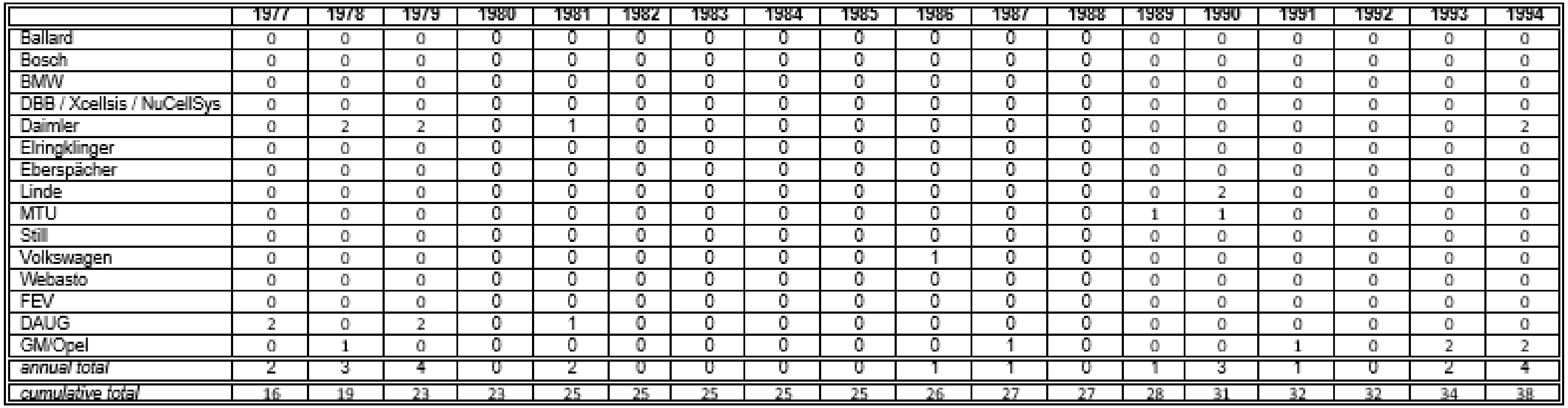
[91] Assuming 13% inflation between 2008 and 2012 and a February 2012 Dollar:Euro exchange rate of 1.00:0.89

[92] Sales to Israel were partly subsidized by the German state thanks to its political commitment to its political ally. Allegations of corrupt payments have since been made.

Appendix AF: Germany – HFC TIS Events (F2) by Actor for Transport Sector, 1959-2012 (Part 1)

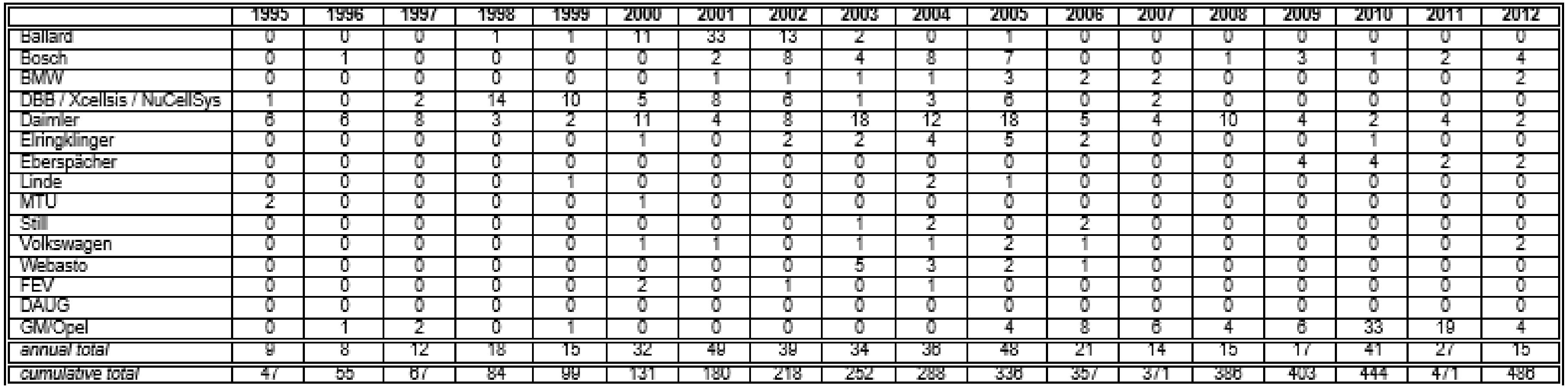


	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976
Ballard	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bosch	0	0	0	0	1	0	1	1	0	1	0	0	0	0	1	1	0	0
BMW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DBB / Xcellsis / NuCellSys	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Daimler	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0
Elringklinger	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Eberspächer	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Linde	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MTU	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Still	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Volkswagen	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Webasto	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FEV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DAUG	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	0	1
GM/Opel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
annual total	0	0	0	0	1	0	1	1	0	1	0	0	0	0	2	6	1	1
cumulative total	0	0	0	0	1	1	2	3	3	4	4	4	4	4	6	12	13	14



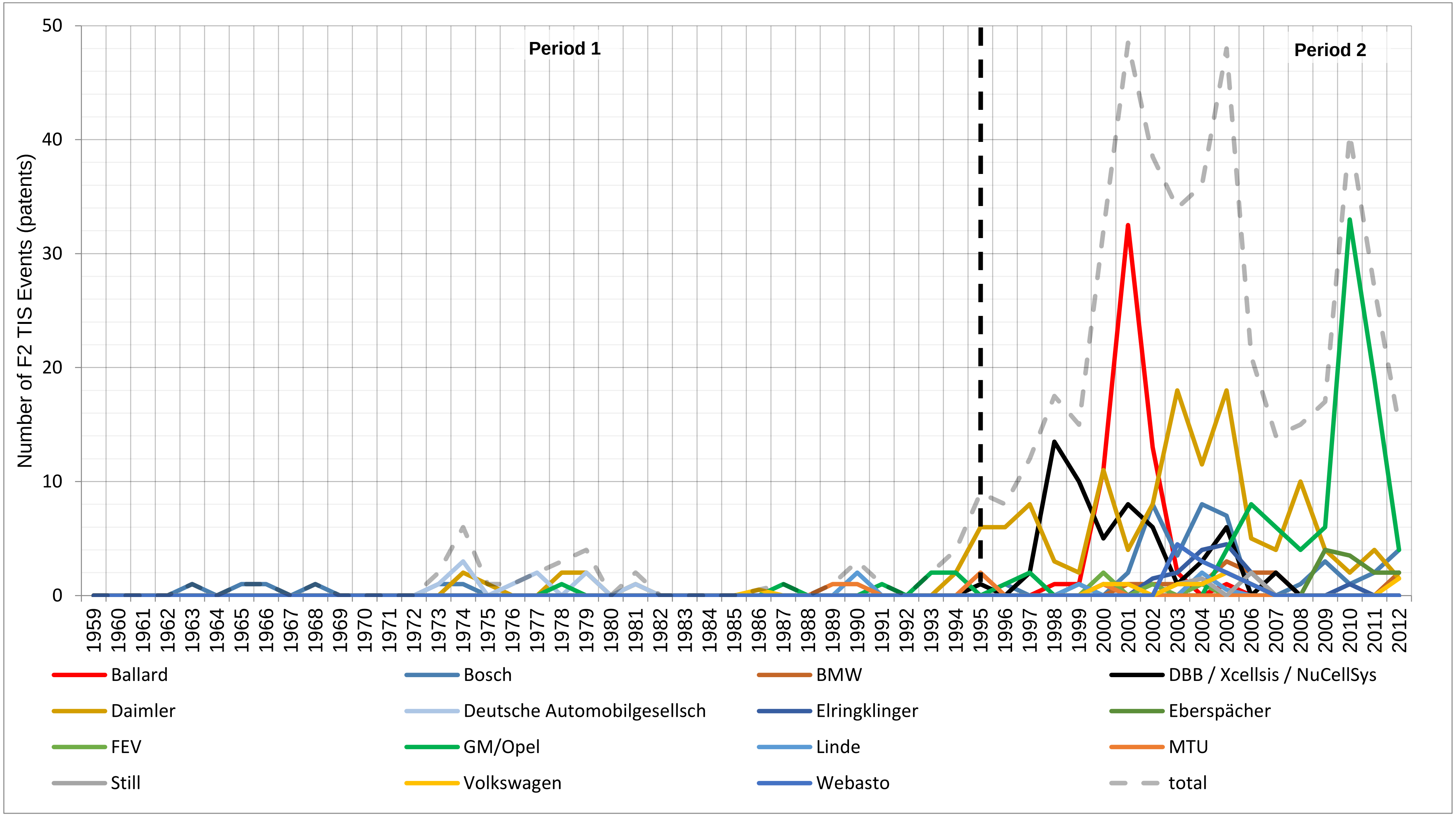
	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994
Ballard	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bosch	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BMW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DBB / Xcellsis / NuCellSys	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Daimler	0	2	2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	2
Elringklinger	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Eberspächer	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Linde	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0
MTU	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
Still	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Volkswagen	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Webasto	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FEV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DAUG	2	0	2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
GM/Opel	0	1	0	0	0	0	0	0	0	0	1	0	0	0	1	0	2	2
annual total	2	3	4	0	2	0	0	0	0	1	1	0	1	3	1	0	2	4
cumulative total	16	19	23	23	25	25	25	25	25	26	27	27	28	31	32	32	34	38

Appendix AF: Germany – HFC TIS Events (F2) by Actor for Transport Sector, 1959-2012 (Part 2)

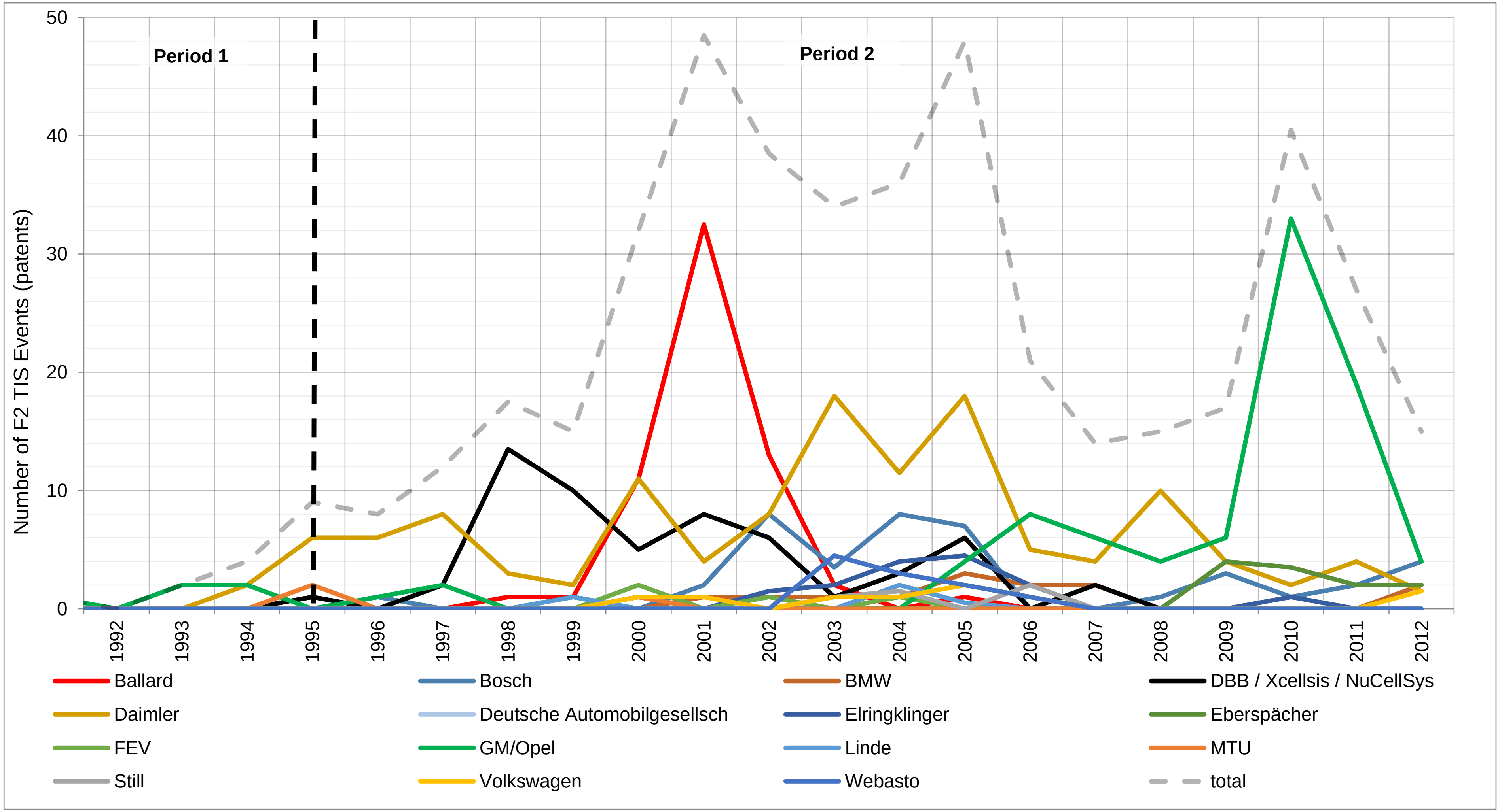


	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Ballard	0	0	0	1	1	11	33	13	2	0	1	0	0	0	0	0	0	0
Bosch	0	1	0	0	0	0	2	8	4	8	7	0	0	1	3	1	2	4
BMW	0	0	0	0	0	0	1	1	1	1	3	2	2	0	0	0	0	2
DBB / Xcellsis / NuCellSys	1	0	2	14	10	5	8	6	1	3	6	0	2	0	0	0	0	0
Daimler	6	6	8	3	2	11	4	8	18	12	18	5	4	10	4	2	4	2
Elringklinger	0	0	0	0	0	1	0	2	2	4	5	2	0	0	0	1	0	0
Eberspächer	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	4	2	2
Linde	0	0	0	0	1	0	0	0	0	2	1	0	0	0	0	0	0	0
MTU	2	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Still	0	0	0	0	0	0	0	0	1	2	0	2	0	0	0	0	0	0
Volkswagen	0	0	0	0	0	1	1	0	1	1	2	1	0	0	0	0	0	2
Webasto	0	0	0	0	0	0	0	0	5	3	2	1	0	0	0	0	0	0
FEV	0	0	0	0	0	2	0	1	0	1	0	0	0	0	0	0	0	0
DAUG	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
GM/Opel	0	1	2	0	1	0	0	0	0	0	4	8	6	4	6	33	19	4
annual total	9	8	12	18	15	32	49	39	34	36	48	21	14	15	17	41	27	15
cumulative total	47	55	67	84	99	131	180	218	252	288	336	357	371	386	403	444	471	486

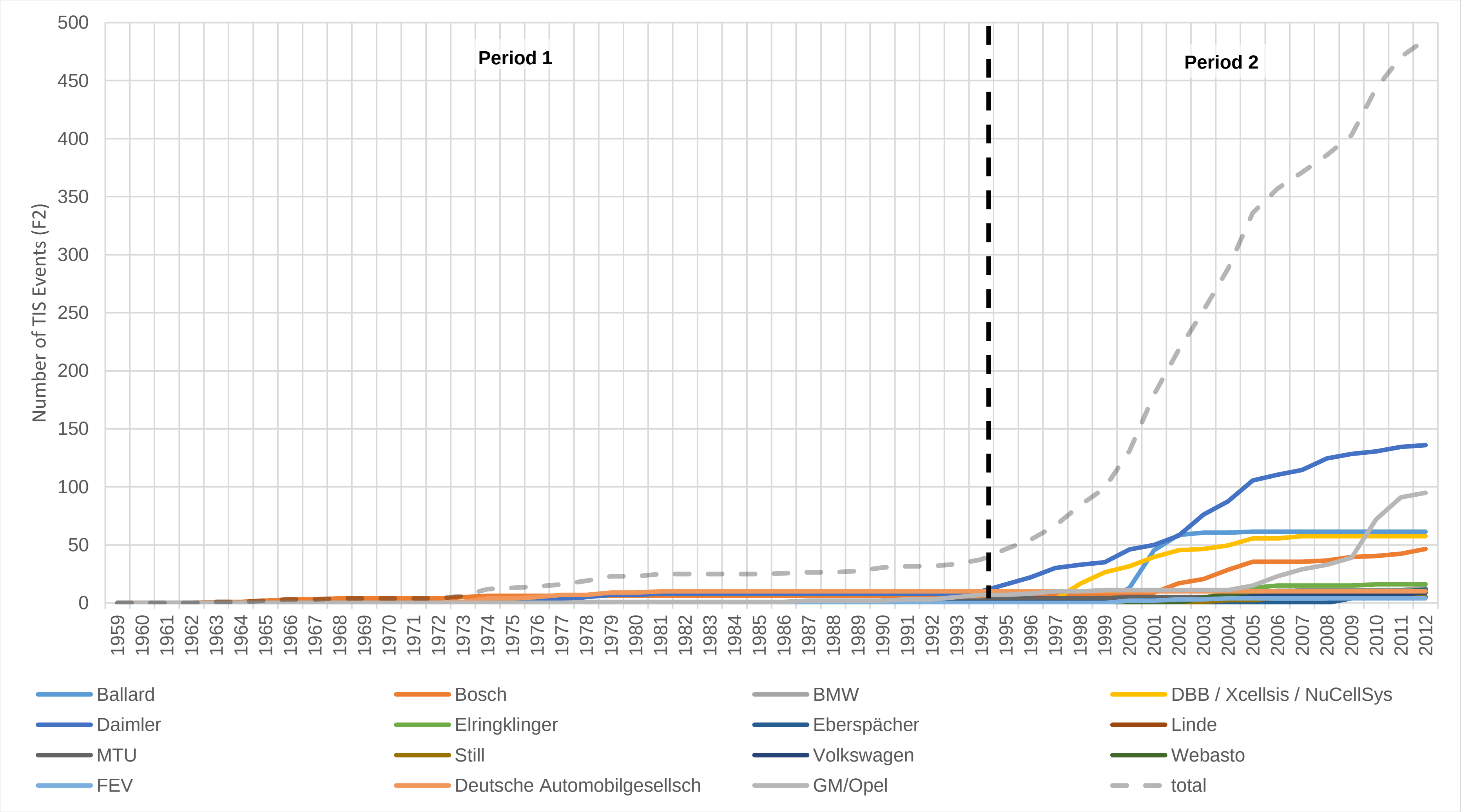
Appendix AG: Germany – Annual Knowledge Development Activity (F2) by Actor in the Transport Sector, 1959-2012



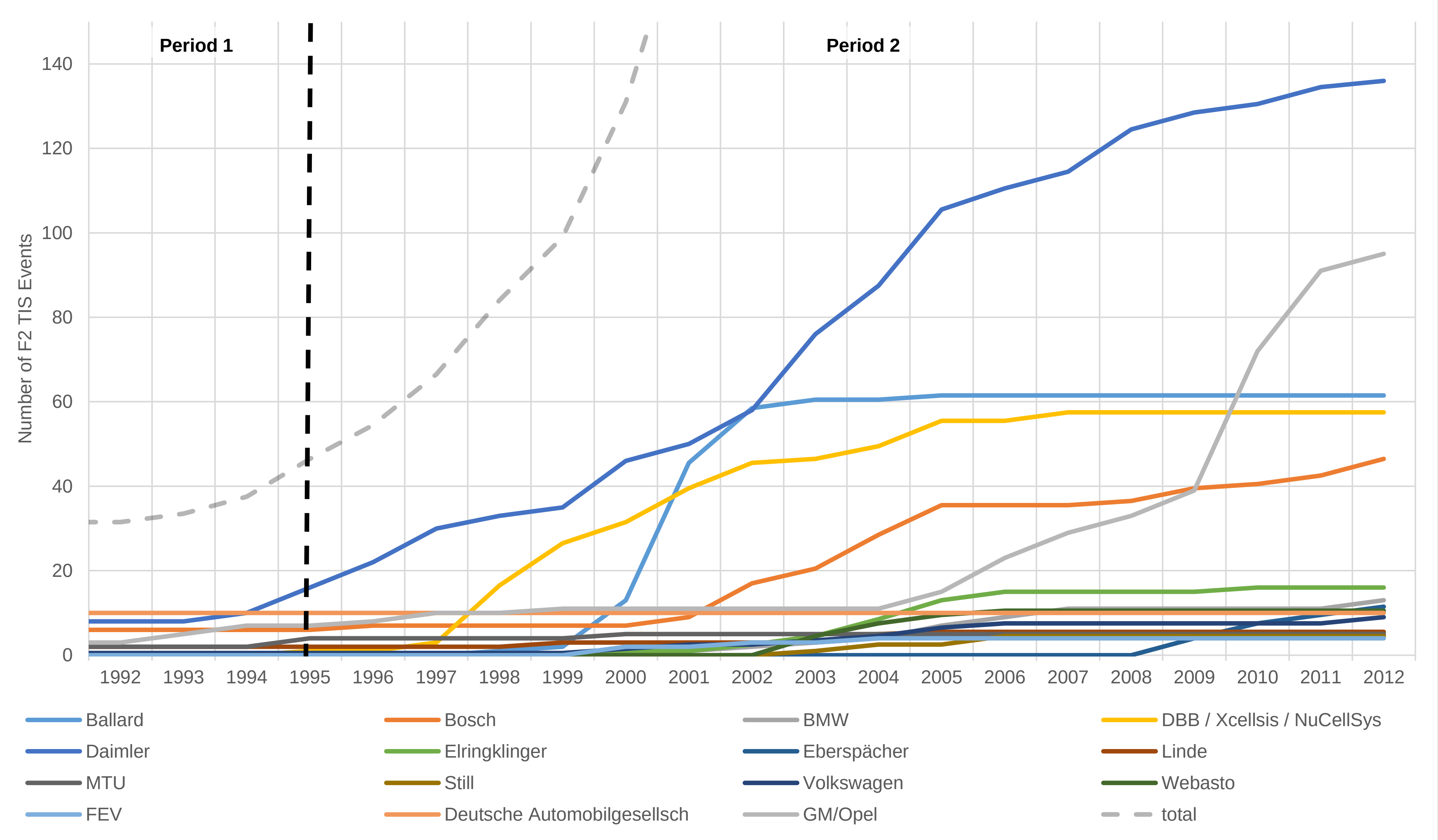
Appendix AH: Germany – Annual Knowledge Development Activity (F2) by Actor in the Transport Sector, 1992-2012



Appendix AI: Germany – Cumulative Knowledge Development Activity (F2) by Actor in the Transport Sector, 1959-2012



Appendix AJ: Germany – Cumulative Knowledge Development Activity (F2) by Actor in the Transport Sector, 1992-2012



Appendix AK: Germany – TIS Events by Organisational Funding Type, 1959-2012

	1959	**1960**	**1961**	**1962**	**1963**	**1964**	**1965**	**1966**	**1967**	**1968**	**1969**	**1970**	**1971**	**1972**	**1973**	**1974**	**1975**	**1976**
Public only (inc. academia)	0	0	0	0	0	0	0	0	0	0	1	0	1	1	0	1	0	1
Public & Private (no partnership)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Private (only)	4	0	5	5	3	3	4	5	4	5	1	2	3	4	8	13	8	4
PPPs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0
annual total	4	0	5	5	3	3	4	5	4	5	2	2	4	5	8	16	9	5
cumulative total	4	4	9	14	17	20	24	29	33	38	40	42	46	51	59	75	84	89

	1977	**1978**	**1979**	**1980**	**1981**	**1982**	**1983**	**1984**	**1985**	**1986**	**1987**	**1988**	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**
Public only (inc. academia)	0	1	0	0	4	1	1	1	0	1	0	1	1	1	1	3	2	2
Public & Private (no partnership)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Private (only)	8	6	8	9	6	2	2	1	3	3	5	5	5	6	6	6	11	13
PPPs	0	0	2	4	1	0	0	1	0	1	1	1	0	2	1	1	0	1
annual total	8	7	10	13	11	3	3	3	3	5	6	7	6	9	8	10	13	16
cumulative total	97	104	114	127	138	141	144	147	150	155	161	168	174	183	191	201	214	230

	1995	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
Public only (inc. academia)	2	0	6	2	9	7	5	12	7	10	6	8	3	7	10	10	6	6
Public & Private (no partnership)	0	0	0	0	0	0	2	2	2	2	2	2	2	2	3	2	2	1
Private (only)	19	17	32	42	41	67	81	79	98	108	126	70	54	53	62	89	70	80
PPPs	2	0	1	1	2	7	7	10	13	11	8	16	12	24	21	21	23	34
annual total	23	17	39	45	52	81	95	103	120	131	142	96	71	86	96	122	101	121
cumulative total	253	270	309	354	406	487	582	685	805	936	1078	1174	1245	1331	1427	1549	1650	1771

Appendix AL: Germany – HFC Public-Private Partnership Types, 1959-2012

	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976
Public Leverage	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Contracting-Out	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
Public JV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Strategic Partnering	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
total	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0
cumulative total	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	3	3

	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994
Public Leverage	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Contracting-Out	0	0	1	3	1	0	0	0	0	0	1	1	0	0	0	1	0	0
Public JV	0	0	1	1	0	0	0	1	0	1	0	0	0	1	0	0	0	0
Strategic Partnering	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1
total	0	0	2	4	1	0	0	1	0	1	1	1	0	2	1	1	0	1
cumulative total	3	3	5	9	10	10	10	11	11	12	13	14	14	16	17	18	18	19

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Public Leverage	1	0	0	0	0	0	0	1	0	0	0	0	0	2	0	1	1	7
Contracting-Out	2	0	0	0	1	1	0	1	0	3	0	4	4	7	3	1	5	4
Public JV	0	0	0	0	-2	0	0	1	6	0	0	3	2	5	1	1	3	5
Strategic Partnering	0	0	1	1	2	7	7	7	7	8	8	9	6	10	17	18	14	17
total	3	0	1	1	1	8	7	10	13	11	8	16	12	24	21	21	23	33
cumulative total	22	22	23	24	25	33	40	50	63	74	82	98	110	134	155	176	199	232

Appendix AM: Germany - 2012 List of Research Bodies Working on HFCs by Region

HE Institution / Research Institute	Region	Location	Postcode	Latitude	Longitude	Easting	Northing
Technical University Munich	BAV	Brunnthal	80333	48.1441028	11.5695647	691137	5335510
Universität Augsburg	BAV	Augsburg	86159	48.3509500	10.8950000	640394	5357043
University of Erlangen (The institute of fluid mechanics)	BAV	Erlangen	91058	49.5500200	11.0036200	644924	5490530
ZAE Bayern eV	BAV	Wurzburg	97074	49.7801362	9.9647348	569454	5514632
Technische Universität Berlin	BER	Berlin	10587	52.5154000	13.3194000	385959	5819692
Fördergesellschaft Erneuerbare Energien e.V. (FEE)	BER	Berlin	12555	52.5167000	13.4000000	391431	5819712
Fraunhofer Institute for Reliability and Microintegration	BER	Berlin	13355	52.5418460	13.3854890	390510	5822531
Fraunhofer Institut - IFAM	BRE	Bremen	28359	53.1003000	8.8752000	491644	5883435
Centre for Solar Energy & Hydrogen Research (ZSW)	BW	Ulm	89081	48.4357306	9.9795403	572451	5365195
Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR)	BW	Stuttgart	70569	48.7483277	9.0899180	506609	5399483
European Institute for Energy Research (EIFER)	BW	Karlsruhe	76131	49.0116951	8.4303821	458346	5428912
fem Research Institute Precious Metals & Metal Chemistry	BW	Schwäbisch Gmünd	73525	48.7937685	9.7988852	558673	5404838
FH Wiesbaden (Hydrogen & Fuel Cell Laboratory)	BW	Rüsselsheim	65428	49.9806833	8.4320167	459278	5536637
Forschungszentrum Karlsruhe, Institute for Nanotechnology (KIT)	BW	Karlsruhe	76021	52.9154943	12.1869671	310868	5866575
Fraunhofer Institute for Chemical Technology (ICT)	BW	Pfinztal	76327	49.0045931	8.5277146	465459	5428073
Fraunhofer Institute for Interfacial Engineering and Biotechnology	BW	Stuttgart	70569	48.7483277	9.0899180	506609	5399483
Fraunhofer Inst. for Manufacturing Engineering & Automation (IPA)	BW	Stuttgart	70569	48.7483277	9.0899180	506609	5399483
Fraunhofer Institute for Physical Measurement Techniques (IPM)	BW	Freiburg	79110	48.0211860	7.8115101	411380	5319338
Fraunhofer Institut - ISI	BW	Karlsruhe	76139	49.0047000	8.3858300	455082	5428159
Fraunhofer-Institut für Solare Energiesysteme ISE	BW	Freiburg im Breisgau	79110	48.0206500	7.8167500	411770	5319272
Fraunhofer Institute for Systems and Innovation Research	BW	Karlsruhe	76139	49.0297476	8.4613212	460623	5430902
Fuel Cell Education & Training Centre (WBZU)	BW	Ulm	89081	48.4357306	9.9795403	572451	5365195
IMTEK-INstitute for MICROSYSTEM Technology	BW	Freiburg im Breisgau	79110	48.0206500	7.8167500	411770	5319272
Karlsruhe Institute of Technology	BW	Karlsruhe	76131	49.0078000	8.4198500	457573	5428485
Max Planck Institute for Solid State Research	BW	Stuttgart	70569	48.7667000	9.1833300	513471	5401537
University of Esslingen (Institute for Fuel Cells Technology) (IBZ)	BW	Esslingen	73728	48.7384056	9.3081095	522653	5398422
University of Karlsruhe (Institute of Materials for electrical Engineering) (IWE)	BW	Karlsruhe	76131	49.0116951	8.4303821	458346	5428912
University of Stuttgart (Institute of Chemical Process Engineering)	BW	Stuttgart	70199	48.7608788	9.1548908	511383	5400885
University of Stuttgart (Institute of Energy Economics & Rational Use of Energy)	BW	Stuttgart	70550	48.7494853	9.0811656	506609	5399611
University of Stuttgart (Institute of Aircraft Design)	BW	Stuttgart	70569	48.7483277	9.0899180	506609	5399483
University of Stuttgart (Institute of Plastics Engineering)	BW	Stuttgart	70550	48.7494853	9.0811656	505966	5399611
University of Stuttgart (Institute of Physical Chemistry)	BW	Stuttgart	70569	48.7483277	9.0899180	506609	5399483
University of Stuttgart (Institute for Space Systems (IRS)	BW	Stuttgart	70550	48.7494853	9.0811656	505966	5399611

University of Stuttgart (Institute of Textile Technology & Process Engineering)	BW	Denkendorf	73770	48.6973450	9.3178943	523392	5393860
University of Stuttgart (Institute of Thermodynamics) (ITT)	BW	Stuttgart	70550	48.7494853	9.0811656	505966	5399611
University of Ulm (Department of Organic Chemistry III)	BW	Ulm	89081	48.4365897	9.9810019	572558	5365291
University of Ulm (Institute for Surface Chemistry and Catalysis)	BW	Ulm	89081	48.4365897	9.9810019	572558	5365291
FH Hamburg	HAM	Hamburg	20099	53.5500000	10.0000000	566253	5933921
Johann Wolfgang Goethe - Universität	HES	Frankfurt am Main	60439	50.1574000	8.6355000	473962	5556194
Deutsches Kunststoff-Institut (Plastics)	HES	Darmstadt	64289	49.9131520	8.7053298	478843	5529016
Fachhochschule Gießen-Friedberg	HES	Gießen	35390	50.5874057	8.6787386	477257	5603993
Fraunhofer Institut für Windenergie und Energiesystemtechnik (IWES)	HES	Kassel	34119	51.3181165	9.4631757	532278	5685303
Hochschule Darmstadt	HES	Darmstadt	64289	49.9131520	8.7053298	478843	5529016
Hochschule RheinMain	HES	Rüsselsheim	65468	49.9112155	8.3828584	455690	5528941
Justus-Liebig-Universität Gießen	HES	Gießen	35392	50.5698008	8.6699031	476623	5602038
Technische Universität Darmstadt (Center for Construction Materials)	HES	Darmstadt	64283	49.8695282	8.6506852	474897	5524182
Technische Universität Darmstadt (Materials Science Dept)	HES	Darmstadt	64287	49.8682541	8.6848114	477349	5524030
Technische Universität Darmstadt (Department of Electrical and Computer Engineering)	HES	Darmstadt	64283	49.8695282	8.6506852	474897	5524182
University of Kassel - ISET (Institute of solar energy supply technology)	HES	Kassel	34119	51.3152000	9.4646500	532382	5684979
Institute of Solar Energy Distribution Technology (ISET)	HES	Kassel	34119	51.3152000	9.4646500	532382	5684979
Technische Universität Clausthal	LOS	Clausthal-Zellerfeld	38678	51.8000000	10.3333000	591937	5739634
Fraunhofer Institut - IPT	NRW	Aachen	52074	50.7479000	6.0485500	291795	5625945
Technische Universität Darmstadt (Institut für Mechanik)	NRW	Darmstadt	64289	49.8972000	8.6809000	477082	5527249
FH Osnabrück (Labor für Angewandte Thermodynamik)	NRW	Osnabrück	49076	52.2832000	7.9485000	428271	5793057
Landesinstitut für Bauwesen NRW	NRW	Dortmund	44135	51.5125000	7.4769500	394312	5707918
Regionalbüro Bergisches Städtedreieck	NRW	Wuppertal	42275	51.2718286	7.2039857	374716	5681586
Rhein-Erft-Kreis (der Landrat)	NRW	Bergheim	50126	50.9562500	6.6349500	333899	5647622
Handwerkskammer Bildungszentrum Münster (Institut für Umweltschutz)	NRW	Münster	48151	51.9510000	7.6181000	405030	5756490
Handwerkskammer Dortmund (Bildungszentrum Ardeystrasse)	NRW	Dortmund	44135	51.5125000	7.4769500	394312	5707918
Handwerkskammer Düsseldorf	NRW	Düsseldorf	40221	51.2002000	6.7564000	343254	5674480
Nationale Koordinierungsstelle Jülich für Wasserstoff und Brennstoffzelle (NKJ)	NRW	Jülich	52425	50.9228365	6.3659002	314873	5644548
Fraunhofer Institut - IMS	NRW	Duisburg	47057	51.4216000	6.7957000	346739	5699015
University of Duisburg (The institute of energy technology)	NRW	Duisburg	47057	51.4216000	6.7957000	346739	5699015
Bergische Universität Wuppertal	NRW	Wuppertal	42119	51.2441000	7.1661000	371997	5678568
Deutsches Zentrum für Luft- und Raumfahrt e.V.	NRW	Köln	51147	50.9333000	6.9500000	355952	5644408
FH Bielefeld	NRW	Bielefeld	33602	52.0245000	8.5326250	467932	5763866
FH Dortmund	NRW	Dortmund	44139	51.4995333	7.4717000	393918	5706484
FH Gelsenkirchen (Energie Institut)	NRW	Gelsenkirchen	45897	51.5717000	7.0471000	364662	5715210
FH Köln (Institut für Technische Gebäudeausrüstung, Elektrische Gebäudesystemtechnik und Green Building)	NRW	Köln	50679	50.9318000	6.9715000	357458	5644200

FH Südwestfalen (Abteilung Soest)	NRW	Soest	59494	51.5601583	8.0884750	436812	5712513
FH Südwestfalen (Standort Soest)	NRW	Soest	59494	51.5601583	8.0884750	436812	5712513
Forschungszentrum Jülich GmbH (Projektträger Jülich (PTJ)	NRW	Jülich	52425	50.9228365	6.3659002	314873	5644548
Forschungszentrum Jülich GmbH (Institut für Energieforschung - Systemforschung für Technologische Entwicklung (IEF-STE))	NRW	Jülich	52425	50.9228365	6.3659002	314873	5644548
Forschungszentrum Jülich GmbH (Institut für Energie- und Klimaforschung – Brennstoffzellen (IEK-3))	NRW	Jülich	52425	50.9228365	6.3659002	314873	5644548
Institut für Galvano- und Oberflächentechnik Solingen GmbH (IGOS)	NRW	Solingen	42657	51.1532250	7.0595250	364292	5668654
IUTA Institut für Energie- und Umwelttechnik e.V.	NRW	Duisburg-Rheinhausen	47229	51.3910000	6.7071000	340473	5695801
Max-Planck-Institut für Bioanorganische Chemie	NRW	Mülheim an der Ruhr	45470	51.4194000	6.8937000	353545	5698570
Max-Planck-Institut für Kohlenforschung	NRW	Mülheim an der Ruhr	45470	51.4194000	6.8937000	353545	5698570
Ruhr-Universität Bochum (Lehrstuhl für Technische Chemie)	NRW	Bochum	44801	51.4833000	7.2166700	376173	5705079
Ruhr-Universität Bochum (Lehrstuhl für Maschinenelemente u. Konstruktionslehre)	NRW	Bochum	44801	51.4833000	7.2166700	376173	5705079
Ruhr-Universität Bochum (Lehrstuhl Energiesysteme und Energiewirtschaft)	NRW	Bochum	44801	51.4833000	7.2166700	376173	5705079
OWI Oel-Waerme-Institut GmbH	NRW	Herzogenrath	52134	50.8626500	6.0916125	295335	5638581
RWTH Aachen (Institut für Kraftfahrzeuge) (IKA)	NRW	Aachen	52074	50.7869200	6.0463500	291814	5630289
RWTH Aachen (Institut für Verfahrenstechnik) (AVT)	NRW	Aachen	52056	50.7782670	6.0609340	532282	5258495
Technische Universität Dortmund (FG Fluidenergiemaschinen)	NRW	Dortmund	44227	51.4440000	7.4546000	392601	5700334
Technische Universität Dortmund (Lehrstuhl Technische Chemie A)	NRW	Dortmund	44227	51.4440000	7.4546000	392601	5700334
Universität Duisburg-Essen (FB Ingenieurwissenschaften, Abt. Bauwissenschaften, Fachgeb. Abfallwirtschaft)	NRW	Essen	45141	51.4704778	7.0221000	362625	5704001
Universität Duisburg-Essen (Fertigungstechnik)	NRW	Duisburg	47057	51.4216000	6.7957000	346739	5699015
Universität Duisburg-Essen (Institut für Angewandte Thermodynamik und Klimatechnik)	NRW	Essen	45141	51.4704778	7.0221000	362625	5704001
Universität Duisburg-Essen (Transferstelle Hochschule-Praxis)	NRW	Duisburg	47057	51.4216000	6.7957000	346739	5699015
Universität Duisburg-Essen (Energietechnik)	NRW	Duisburg	47057	51.4216000	6.7957000	346739	5699015
Universität Duisburg-Essen (Lehrstuhl für Elektrische Anlagen und Netze)	NRW	Duisburg	47048	51.4216000	6.7957000	346739	5699015
Universität Siegen (Fakultät IV, Institut für Automatisierungstechnik, Lehrstuhl für Elektrische Maschinen, Antriebe und Steuerungen)	NRW	Siegen	57068	50.9108200	8.0273000	431615	5640358
Wuppertal Institut für Klima, Umwelt, Energie GmbH	NRW	Wuppertal	42103	51.2569111	7.1505444	370947	5680019
Zentrum für Elektrochemie der Ruhr-Universität Bochum	NRW	Bochum	44780	51.4458090	7.2625630	379260	5700834
Fuel cell research center (ZBT) - Zentrum für BrennstoffzellenTechnik ZBT GmbH	NRW	Duisburg	47057	51.4216000	6.7957000	346739	5699015
Technologie- und Gründerzentrum Region Kaisersesch GmbH	RHP	Kaisersesch	56759	50.2333000	7.1500000	368062	5566208
Martin-Luther-Universität Halle-Wittenberg	SAN	Halle (Saale)	6120	51.5124000	11.9055500	701608	5710811
ILK Dresden gGmbH	SAX	Dresden	1309	51.0491316	13.7874211	415005	5655988
Fraunhofer Institut - IKTS	SAX	Dresden	1277	51.0374106	13.7964562	415617	5654674
Technical University Dresden	SAX	Dresden	1062	51.0391349	13.7376748	411499	5654934

Appendix AN: Germany - 2012 List of Corporate HFC Actors by Region

Corporate HFC Actor	Region	Location	Postcode	Latitude	Longitude	Easting	Northing	Est Employees Affected
Audi AG	BAV	Ingolstadt	85045	48.808109	11.373707	674278	5408842	172
BMW AG	BAV	Munich	80788	48.13528	11.5743	691522	5334541	53
Clariant (Germany) GmbH	BAV	Bruckmuhl-Heufeld	83052	47.874722	11.968056	721929	5306641	80
Dana Holdings GmbH	BAV	Neu-Ulm	89229	52.30646	10.81679	623865	5796679	4
EDAG GmbH & Co KG aA	BAV	München	80937	48.1974	11.5721	691126	5341439	16
Gardner Denver Thomas GmbH (Rietschle brand)	BAV	Fürstenfeldbruck	82256	48.178707	11.23683	666276	5338582	13
GfE Metalle und Materialien GmbH	BAV	Nürnberg	90431	49.445947	11.026757	646909	5479006	20
Linde Group (Gas)	BAV	München	80331	48.13452	11.571	691278	5334448	63
MAN Nutzfahrzeuge AG	BAV	München	80995	48.211504	11.513181	686697	5342862	63
Modine Wackersdorf GmbH	BAV	Wackersdorf	92442	49.302065	12.190587	295770	5464833	4
N-ERGIE	BAV	Nuremberg	90429	49.451179	11.052556	648764	5479638	60
Plansee Composite Materials GmbH	BAV	Lechbruck am See	86983	47.699072	10.793817	634585	5284413	70
Rehau AG & Co	BAV	Rehau	95119	50.330188	11.684154	691032	5578789	40
Reinz-Dichtungs-GmbH	BAV	Neu-Ulm	89233	48.388696	10.067222	579010	5360054	13
Schaeffler AG	BAV	Herzogenaurach	91074	49.578242	10.881903	636043	5493441	2
Schaeffler Technologies AG & Co. KG	BAV	Herzogenaurach	91074	49.578242	10.881903	636043	5493441	15
Schaeffler Technologies AG & Co. KG	BAV	Schweinfurt	97421	50.044488	10.22584	587770	5544297	15
Schmack Group Ltd	BAV	Allendorf	35108	51.033333	8.683333	477796	5653579	31
SGL Carbon GmbH	BAV	Meitingen	86405	48.54671	10.855689	636954	5378730	50
Siemens AG	BAV	München	80333	48.144099	11.569553	691135	5335509	4
Thüga AG	BAV	München	80335	48.144338	11.554824	690039	5335500	5
Truma Gerätetechnik GmbH & Co. KG	BAV	Putzbrunn	85640	48.086169	11.705443	701470	5329419	25
TÜV SÜD	BAV	München	80686	48.13805	11.50705	686508	5334683	63
Varta Storage GmbH	BAV	Nördlingen	86720	48.856102	10.499217	609970	5412543	8
Webasto SE	BAV	Stockdorf	82131	48.092778	11.400556	678744	5329400	35
Alantum Europe GmbH	BAV	München	80807	48.1827	11.5759	691464	5339815	6
Burow Mobil KG	BAV	Mering	86415	48.265361	10.986147	647393	5347701	1
Crystec Technology Trading GmbH	BAV	Altötting	84503	48.2262	12.6586	326112	5344092	10
Elcomax GmbH	BAV	München	81737	48.096693	11.627407	695619	5330387	70
Elcore GmbH	BAV	München	81737	48.096693	11.627407	695619	5330387	60
EnviTech GmbH	BAV	Dachau	85221	48.262998	11.433902	680627	5348396	10
ET GmbH	BAV	Brunnthal	85649	48.006312	11.683149	700119	5320486	20

Fodiator Brennstoffzellen- Antriebstechnik GmbH	BAV	Büchenbach	91186	49.266633	11.06074	649917	5459140	1
FuelCell Solutions GmbH (Manufacturing)	BAV	Ottobrunn	85521	48.047755	11.652208	697653	5325011	7
Fuel Cell Ceramics GmbH	BAV	Dorfen	84405	48.27368	12.153793	288821	5350636	25
FutureCamp Holding GmbH (consultancy/incubator)	BAV	Munich	81549	48.096541	11.604288	693898	5330311	5
H. C. Starck Ceramics GmbH & Co. KG	BAV	Selb	95100	50.171311	12.133932	295343	5561611	-
Leoni Kabel Holding GmbH	BAV	Roth	91154	49.21753	11.105398	653317	5453771	33
Life Safety Germany GmbH	BAV	Munich	80687	48.137884	11.519242	687416	5334695	5
Modl GmbH	BAV	Pappenheim	91788	48.92531	10.96329	643811	5421011	12
My Cell Brennstoffzellen AG	BAV	Munich	81241	48.140896	11.46454	683336	5334898	11
Nash - Zweigniederlassung der Gardner Denver Deutschland GmbH	BAV	Nuremberg	90461	49.426938	11.090434	651583	5477019	4
PASM Power and Air Condition Solution Management GmbH & Co. KG	BAV	München	80538	48.144581	11.589527	692620	5335613	9
Porextherm Dämmstoffe GmbH	BAV	Kempten	87437	47.742432	10.346008	599654	5286355	9
Proton Motor Fuel Cell GmbH	BAV	Puchheim	82178	48.169	11.350967	674792	5337756	55
S++ Simulation Services	BAV	Murnau am Staffelsee	82418	47.67751	11.20414	665245	5283160	1
SFC Energy AG	BAV	Brunnthal	85649	48.006312	11.683149	700119	5320486	60
Testnet GmbH	BAV	Garching	85748	48.239882	11.630583	695311	5346308	2
WEH GmbH	BAV	Illertissen	89257	48.225331	10.10127	581791	5341932	160
Praxair Deutschland GmbH	BER	Berlin	12439	52.452178	13.521707	399543	5812360	15
Siemens AG	BER	Berlin	13629	52.540028	13.265336	382357	5822518	4
Total Deutschland GmbH	BER	Berlin	12347	52.456909	13.436633	393774	5813008	300
Deutscher Wasserstoff- und Brennstoffzellenverband e.V.	BER	Berlin	12203	52.442627	13.310337	385155	5811612	2
Heliocentris Energy Solutions AG	BER	Berlin	12489	52.437018	13.547051	401231	5810639	36
NOW GMBH (Nationale Organisation Wasserstoff- und Brennstoffzellentechnologie)	BER	Berlin	10623	52.507039	13.328395	386549	5818748	20
SHS Solar Hydrogen Systems	BER	Berlin	10439	52.55305	13.41415	392480	5823734	10
Enertrag AG	BRA	Schenkenberg	17291	53.363329	13.948457	430025	5913204	2
ENERTRAG HyTec GmbH	BRA	Schenkenberg	17291	53.363329	13.948457	430025	5913204	40
ABB	BW	Mannheim	68309	49.514663	8.530585	466021	5484777	10
Agilent Technologies GmbH	BW	Böblingen	71034	48.676259	8.977315	498330	5391468	45
Bosch Engineering GmbH (Fuel Cell)	BW	Heilbronn	74003	49.14216	9.2212	516133	5443283	94
Bürkert & Co. KG	BW	Ingelfingen	74653	49.3006	9.655	547619	5461079	10
Burstner Reisemobil	BW	Kehl	77694	48.578873	7.816082	412678	5381319	9
BWT Wassertechnik GmbH	BW	Schriesheim	69198	49.473767	8.66125	475459	5480180	4
CeramTec AG	BW	Plochingen	73207	48.721015	9.4278276	531467	5396531	54
Daimler AG	BW	Kirchheim / Teck-Nabern	73230	48.642513	9.4594184	533842	5387818	63
Delta Energy Systems (Germany) GmbH	BW	Teningen	79331	48.125525	7.8138237	411732	5330932	8
Diehl Aerospace GmbH	BW	Überlingen	88662	47.766175	9.1702772	512759	5290326	39

Eberspaecher Group	BW	Esslingen am Neckar	73730	48.742053	9.3089308	522712	5398828	21
Egelhof Otto GmbH & Co.KG	BW	Fellbach	70736	48.840509	9.2677632	519647	5409760	23
Elringklinger	BW	Dettingen an der Erms	72581	48.527536	9.3488325	525755	5374995	28
EnBW Energie Baden-Württemberg AG	BW	Karlsruhe	70173	52.915494	12.186967	310868	5866575	63
Enmech GmbH & Co. KG	BW	Weinham	69469	49.540747	8.6620453	475550	5487626	76
EPH Elektronik GmbH	BW	Besigheim	74354	48.998834	9.1483944	510854	5427336	63
Freudenberg Fuel Cell Component Technologies (FCCT) SE & Co. KG	BW	Weinheim	69465	49.546873	8.672441	476305	5488304	27
Leoni Kabel Holding GmbH	BAV	Roth	91154	49.21753	11.105398	653317	5453771	38
Life Safety Germany GmbH	BAV	Munich	80687	48.137884	11.519242	687416	5334695	43
Harro Höfliger Verpackungsmaschinen GmbH	BW	Allmersbach	71573	48.906854	9.470497	534477	5417207	31
KACO new energy GmbH	BW	Neckarsulm	74172	49.192258	9.2287089	516663	5448853	31
MAHLE International GmbH	BW	Stuttgart	70376	48.820353	9.2031939	514915	5407505	31
Mann + Hummell Group (Filterwerk)	BW	Ludwigsburg	71638	48.890888	9.1898375	513915	5415343	3
Manz Automation Tübingen GmbH (Manz Automatisierungstechnik GmbH)	BW	Tübingen	72072	48.493679	9.052606	503886	5371174	63
Micronas	BW	Freiburg	79108	48.043005	7.8205932	412095	5321753	80
Nitto Kohki Deutschland GmbH	BW	Steinenbronn	71144	48.66185	9.12175	508965	5389873	15
Robert Bosch GmbH	BW	Stuttgart	70469	48.811764	9.1521703	511172	5406542	21
Schiller Automation GmbH & Co. KG	BW	Sonnenbühl	72820	48.381695	9.1941993	514379	5358744	63
Siemens Power Generation GmbH	BW	Erlangen	91058	49.561397	11.004377	644946	5491797	10
SSB AG	BW	Stuttgart	70565	48.715743	9.117814	508666	5395863	17
Trumpf Werkzeugmaschinen Gmbh + Co	BW	Ditzingen	71254	48.83875	9.0356681	502617	5409531	30
USK Karl Utz Sondermaschinen GmbH	BW	Korb	71404	48.841411	9.3608907	526480	5409889	6
Varta Microbattery GmbH	BW	Ellwagen	73479	48.967172	10.171149	585716	5424467	2
Abfallwirtschaftsbetrieb Landkreis Böblingen	BW	Böblingen	71006	48.6823	9.00954	500702	5392139	5
AppliedSensor	BW	Reutlingen	72770	48.4942	9.1666	512308	5371244	25
Dorfmüller Solar GmbH	BW	Kernen	71394	48.814019	9.3182543	523364	5406830	4
enymotion	BW	Heilbronn	74078	49.173955	9.1699726	512388	5446807	4
ESI Engineering System International GmbH	BW	Stuttgart	70565	48.7667	9.18333	513471	5401537	25
FIX Maschinebau GmbH	BW	Korb	71404	48.841411	9.3608907	526480	5409889	24
FuMA-Tech GmbH	BW	Vaihingen	71665	48.933436	8.961208	497158	5420056	100
FutureE Fuel Cell Solutions GmbH	BW	Nürtingen	72622	48.624421	9.3469069	525564	5385764	51
Hexis GmbH	BW	Konstanz	78462	47.661095	9.1764916	513251	5278648	11
Kerafol Keramische Folien GmbH	BW	Eschenbach in der Oberpfalz	92676	49.754469	11.830418	703865	5515177	5
Mahler BGS GmbH	BW	Stuttgart	70327	48.775801	9.252913	518582	5402564	36
Modine Kirchentellinsfurt GmbH	BW	Kirchentellinsfurt	72138	48.542332	9.1382919	510207	5376590	10
MS2 Engineering und Anlagenbau GmbH	BW	Kirchheim / Teck	73230	48.6442	9.4304	531704	5387993	160

Mulag Fahrzeugwerk Heinz Wössner GmbH u. Co. KG	BW	Appenau	77728	48.474283	8.1615834	438034	5369356	10
nucellsys GmbH	BW	Kirchheim unter Teck	73230	48.642513	9.459418	533843	5387819	15
openVPP.org (University of Karlsruhe)	BW	Karlsruhe	76131	49.0078	8.41985	457573	5428485	10
QuinTech e.K.	BW	Göppingen	73035	48.693406	9.637832	546938	5393570	13
ROWO Coating GmbH	BW	Herbolzheim	79336	48.22705	7.75075	407222	5342290	30
SKF ECONOMOS Deutschland GmbH	BW	Bietigheim-Bissingen	74321	49.659025	8.9961819	499724	5500720	2
SMART TESTSOLUTIONS GmbH	BW	Stuttgart	70197	48.7667	9.18333	513471	5401537	2
Udomi GmbH	BW	Neuenstein	74632	49.206526	9.581622	542365	5450578	20
Ulmer Brennstoffzellen- Manufaktur GmbH (UBZM)	BW	Ulm	89077	48.392039	9.9716658	571930	5360331	7
Harro Höfliger Verpackungsmaschinen GmbH	BW	Allmersbach	71573	48.906854	9.470497	534477	5417207	13
KACO new energy GmbH	BW	Neckarsulm	74172	49.192258	9.2287089	516663	5448853	160
MAHLE International GmbH	BW	Stuttgart	70376	48.820353	9.2031939	514915	5407505	4
Mann + Hummell Group (Filterwerk)	BW	Ludwigsburg	71638	48.890888	9.1898375	513915	5415343	9
Wenger Engineering GmbH	BW	Ulm	89077	48.392039	9.9716658	571930	5360331	31
WS Reformer GmbH	BW	Renningen	71272	48.771663	8.934396	495180	5402075	1
Zebotec GmbH	BW	Konstanz	78467	47.680701	9.1486795	511159	5280823	43
Airbus Operations GmbH	HAM	Hamburg	21129	53.515527	9.8514063	556455	5929958	63
Aircraft Fuel Cell Systems GmbH (AFCS)	HAM	Hamburg	22587	53.561038	9.7964715	552756	5934979	4
Germanischer Lloyd AG	HAM	Hamburg	20457	53.531648	9.9852574	565304	5931866	36
Hamburger Hochbahn AG	HAM	Hamburg	20095	53.550752	10.001726	566366	5934006	25
Pricap Venture Partners AG	HAM	Hamburg	20354	53.559627	9.9936835	565820	5934987	10
Siemens AG (Industrial Solutions and Services Marine Solutions)	HAM	Hamburg	20099	53.558085	10.011979	567034	5934832	1
Still GmbH	HAM	Hamburg	22113	53.517068	10.092991	572470	5930348	6
Alster-Touristik GmbH	HAM	Hamburg	20354	53.559627	9.9936835	565820	5934986	80
Baxi Innotech GmbH	HAM	Hamburg	20539	53.5389	10.03435	568547	5932719	63
Deutsche Shell GmbH	HAM	Hamburg	22284	53.54859	9.94657	562716	5933716	63
H2messe.de / H2fair.net	HAM	Hamburg	22767	53.550925	9.9425	562442	5933972	8
HySolutions GmbH	HAM	Hamburg	20095	53.550752	10.001726	566366	5934006	21
N2telligence	HAM	Hamburg	22767	53.548889	9.942607	562453	5933746	31
Adam Opel AG	HES	Rüsselsheim am Main	65423	49.998388	8.4182478	458306	5538613	16
Air Liquide Forschung und Entwicklung GmbH	HES	Frankfurt	60388	51.2301	6.82165	347911	5677668	8
Dalkia Energie Service GmbH	HES	Neu-Isenburg	63263	50.048341	8.6945226	478129	5544050	42
DEK Printing Machines GmbH	HES	Bad Vilbel	61118	50.176433	8.7358	481134	5558281	15
Deutsche Telekom AG	HES	Darmstadt	64295	49.848344	8.6063932	471702	5521843	23
E.ON Mitte Wärme GmbH	HES	Kassel	34131	51.311076	9.4032861	528108	5684495	14
EDAG GmbH & Co KG	HES	Fulda	36039	50.5732	9.6824	548321	5602587	19

ESI Engineering System International GmbH	HES	Eschborn	65760	50.146747	8.5614555	468666	5555038	26
HEAG Südhessische Energie AG	HES	Darmstadt	64293	49.877635	8.6285365	473310	5525091	6
Heraeus Precious Metals GmbH & Co. KG	HES	Hanau	63450	50.126822	8.921645	494399	5552734	6
Hyundai Motor Europe Technical Center GmbH	HES	Rüsselsheim	65428	49.98875	8.4216976	458545	5537540	6
Infraserv GmbH & Co. Höchst KG	HES	Frankfurt	65929	50.101348	8.538966	467028	5550000	2
Messer Industriegase GmbH	HES	Bad Soden am Taunus	65812	50.146146	8.498569	464173	5555000	14
Pfeiffer Vacuum GmbH	HES	Asslar	35614	50.58525	8.4763	462925	5603835	18
Rittal GmbH & Co. KG	HES	Herborn	35745	50.67616	8.2855	449515	5614057	13
Schunk Kohlenstofftechnik GmbH	HES	Heuchelheim	35452	50.5867	8.6416	474628	5603927	8
SGL Carbon SE	HES	Wiesbaden	65203	50.040899	8.2312667	444954	5543461	19
SGL Technologies GmbH	HES	Wiesbaden	65203	50.040899	8.2312667	444954	5543461	6
Siemens AG	HES	Stuttgart	70499	48.813033	9.1044082	507665	5406677	63
SMA Solar Technology AG	HES	Niestetal	34266	51.30835	9.56685	539511	5684268	12
SMC Pneumatik GmbH	HES	Egelsbach	63329	49.96595	8.6736	476591	5534895	25
TB&C Outsert Center GmbH	HES	Herborn-Burg	35745	50.67616	8.2855	449515	5614057	3
TÜV SÜD Akademie GmbH (training)	HES	Frankfurt	60437	50.19953	8.6818147	477291	5560864	46
Umicore AG & Co KG	HES	Hanau-Wolfgang	63457	50.106267	8.9494667	496386	5550447	1
Underwriters Laboratories (UL) International Germany GmbH	HES	Neu-Isenburg	63263	50.052166	8.6952446	478183	5544475	1
Viessmann Werke GmbH & Co KG	HES	Allendorf (Eder)	35108	51.0333	8.67917	477503	5653576	9
ANSYS Germany GmbH	HES	Darmstadt	64295	49.848344	8.6063932	471702	5521843	12
Bosch Thermotechnik GmbH [BBT Thermotechnic GmbH (2004-8)]	HES	Wetzlar	45602	50.555052	8.5040604	464868	5600464	12
BSI Management Systems und Umweltgutachter Deutschland GmbH	HES	Hanau	63542	50.145301	9.1128033	406394	5367546	22
DiWiTech - Ingenieurpraxis für technische und wissenschaftliche Dienstleistungen	HES	Breitenbach am Herzberg	36287	50.7667	9.51667	536435	5624008	11
Eichhoff GmbH	HES	Schlitz	36110	50.6759	9.55925	539514	5613933	10
ELB Elektrolysetechnik GmbH	HES	Butzbach	35510	51.72702	10.25211	586478	5731419	10
Energiezentrale Universitatsklinikum Gießen GmbH	HES	Gießen	35392	50.569801	8.6699031	476623	5602038	33
EW Medien und Kongresse GmbH	HES	Frankfurt am Main	60326	50.101933	8.6342333	473842	5550028	5
Gaskatel GmbH	HES	Kassel	34127	51.333041	9.4909559	534202	5686975	12
Gas-Union GmbH	HES	Frankfurt	65929	50.101348	8.538966	467028	5550000	11
GHR Hochdruck-Reduziertechnik GmbH	HES	Ober-Mörlen	61239	50.3646	8.6644	476130	5579223	4
hessenEnergie GmbH (consultancy)	HES	Wiesbaden	65189	50.072672	8.2570237	446833	5546975	9
Hoerbiger Automatisierungstechnik GmbH	HES	Altenstadt	86972	47.826668	10.872756	639737	5297614	30
Honda Germany (Honda R&D Europe research institute)	HES	Offenbach Am Main	63073	50.080943	8.810722	486458	5547648	15
IBR Ingenieurbüro Redlich und Partner GmbH	HES	Schlangenbad	65388	50.092381	8.1024225	435797	5549287	8
ITM Power GmbH	HES	Schmitten	61389	50.2868	8.4608	461587	5570658	10
Magnum Fuel Cell AG	HES	Darmstadt	64293	49.877635	8.6285365	473311	5525092	76

Max Planck Innovation GmbH	HES	Munich	80799	48.151023	11.575701	691567	5336295	25
Messer Group GmbH	HES	Sulzbach	65843	50.133644	8.522376	465865	5553599	2
NANO ENERGY GmbH	HES	Steinbach	61449	50.169016	8.5695775	469261	5557512	27
NRG plan GmbH	HES	Offenbach	63067	50.10685	8.7344	481007	5550544	5
Ralos New Energy GmbH	HES	Darmstadt	64297	49.824348	8.651518	474934	5519159	10
Schunk Bahn- und Industrietechnik GmbH	HES	Wettenberg	35435	50.616667	8.65	475238	5607256	4
sera ComPress GmbH	HES	Immenhausen	34376	51.428658	9.4771217	533169	5697603	9
SKF Sealing Solutions GmbH (vorm. CR Elastomere GmbH)	HES	Erbach	64711	49.637578	9.0064354	500465	5498336	5
SolviCore GmbH & Co. KG	HES	Hanau-Wolfgang	63457	50.118019	8.957516	496962	5551753	9
Technlife Europe GbR.	HES	Schwalbach am Taunus	65824	50.151139	8.5310143	466495	5555540	55
WINGAS GmbH	HES	Kassel	34119	51.31651	9.45807	531923	5685123	10
Meyer Werft GmbH	LOS	Papenburg	26871	53.072614	7.423268	394366	5881510	10
Sartorius AG	LOS	Göttingen	37075	51.536667	10.002289	569515	5709983	25
TÜV Nord	LOS	Hanover	30519	52.335814	9.7737388	552719	5798671	25
Volkswagen AG	LOS	Isenbüttel	38550	52.4336	10.5865	607855	5810449	10
Kromschröder AG	LOS	Osnabrück	49504	52.313843	7.930488	427093	5796484	63
Bioconstruct GmbH	LOS	Melle	49328	52.252684	8.425131	460758	5789299	15
Container Products GmbH	LOS	Lehre	38165	52.326858	10.669431	613767	5798705	28
TB&C Outsert Center GmbH	HES	Herborn-Burg	35745	50.67616	8.2855	449515	5614057	2
TÜV SÜD Akademie GmbH (training)	HES	Frankfurt	60437	50.19953	8.6818147	477291	5560864	10
FF Fluidforming GmbH	LOS	Lastrup/Nieholte	49688	52.7941	7.8961	425566	5849937	10
High-Speed (HS)Turbomaschinen GmbH	LOS	Braunschweig	38126	52.234858	10.56545	606902	5788315	2
MT-Biomethan GmbH	LOS	Zeven	27404	53.293969	9.275948	518393	5905009	25
MT-Energie GmbH	LOS	Zeven	27404	53.293969	9.275948	518393	5905009	25
nass Magnet GmbH	LOS	Hanover	30179	52.412401	9.757545	551526	5807178	13
NEXT ENERGY EWE-Forschungszentrum für Energietechnologie e. V.	LOS	Oldenburg	26129	53.147946	8.175364	444848	5889046	5
Overspeed GmbH & Co. KG	LOS	Oldenburg	26129	53.147946	8.175364	444848	5889046	5
PLANET - Planungsgruppe Energie und Technik GbR	LOS	Oldenburg	26123	53.156725	8.233325	448735	5889979	10
SST Neue Energien GmbH	LOS	Visbeck	49429	52.819386	8.3136295	453746	5852400	3
Statoil Deutschland Storage GmbH	LOS	Emden	26723	53.362927	7.1084736	374133	5914312	10
DEEP Underground Engineering GmbH	LOS	Bad Zwischenahn	26160	53.185602	8.0205892	434554	5893365	15
balticFuelCells GmbH	MV	Schwerin	19061	53.599171	11.404043	659080	5941613	25
HNP Mikrosysteme GmbH	MV	Schwerin	19053	53.624938	11.408534	659280	5944490	15
New Enerday GmbH	MV	Neubrandenburg	17033	53.532928	13.262319	384830	5932962	25
3M Deutschland GmbH	NRW	Neuss	41453	51.201371	6.6944	338927	5674744	25
AEG Power Solutions GmbH	NRW	Warstein-Belecke	59581	51.4662	8.310775	452123	5701895	18

Air Liquide GmbH	NRW	Düsseldorf	40235	51.2301	6.82165	347911	5677668	63
Air Products GmbH	NRW	Hattingen	45527	51.382835	7.2097807	375422	5693919	63
b+w Electronic Systems GmbH & Co. KG	NRW	Oberhausen	46047	51.48343	6.87983	352787	5705717	19
BAYER Technology Services GmbH	NRW	Leverkusen	51368	51.0167	6.9833	358545	5653617	25
Buschjost GmbH	NRW	Bad Oeynhausen	32545	52.1917	8.8093	486964	5782377	19
Corus Special Strip - Hille & Müller GmbH	NRW	Düsseldorf	40589	51.1668	6.8253	347957	5670622	25
Creavis (Evonik Industries)	NRW	Marl	45764	51.210774	7.8627431	420562	5673879	39
Delta Energy Systems (Germany) GmbH	NRW	Soest	59494	51.560158	8.088475	436812	5712513	16
Deutsche Mechatronics GmbH	NRW	Mechernich	53894	50.591704	6.653072	333885	5607052	23
Deutz AG	NRW	Köln	51149	50.899825	7.04165	362293	5640511	25
E.ON Gas storage GmbH	NRW	Essen	45136	51.435644	7.0355606	363457	5700103	62
E.ON New Build & Technology GmbH	NRW	Gelsenkirchen	45896	51.60715	7.0488	364885	5719149	40
E.ON Ruhrgas	NRW	Essen	45131	51.4273	6.996675	360728	5699247	38
EDAG GmbH & Co KG	NRW	Recklinghausen	45665	51.6017	7.2183	376607	5718243	9
Eltek Deutschland GmbH	NRW	Herford	32052	52.09197	8.650066	476026	5771325	12
Emitec Gesellschaft für Emissionstechnologie mbH	NRW	Lohmar	53797	50.837802	7.2126649	374151	5633310	9
Emschergenossenschaft / Lippeverband	NRW	Essen	45128	51.44568	7.01028	361730	5701265	25
Emscher-Lippe Energie GmbH (ELE)	NRW	Herten	45699	51.58688	7.1548905	372175	5716704	20
Evonik Industries AG	NRW	Essen	45128	51.44568	7.01028	361730	5701265	31
FEV GmbH (RWTH Aachen spinoff)	NRW	Aachen	52078	50.762357	6.1380429	298170	5627304	25
Flughafen Köln/Bonn GmbH	NRW	Köln	51147	50.9333	6.95	355952	5644408	13
Gebr. Becker GmbH	NRW	Wuppertal	42279	51.3077	7.2522	378174	5685493	4
Gelsenwasser AG	NRW	Gelsenkirchen	45891	51.55925	7.0841167	367191	5713758	6
Gräbener Maschinentechnik GmbH & Co. KG	NRW	Netphen-Werthenbach (Bhf.)	57250	50.899833	8.1513	440319	5639029	17
Hella KGaA Hueck & Co.	NRW	Hamm Bockum-Hövel	59075	51.6866	7.73595	412619	5726938	31
HOPPECKE Carl Zoellner & Sohn GmbH	NRW	Brilon	59929	51.405533	8.5824667	470958	5695006	31
Hydrogenics Deutschland Gmbh	NRW	Gladbeck	45966	51.5842	6.9746	359677	5716737	130
KROHNE Messtechnik GmbH & Co KG	NRW	Duisburg	47058	51.43465	6.7858	346095	5700487	13
Leybold Vacuum GmbH	NRW	Köln	50968	50.91085	6.96155	356695	5641890	10
Linde AG, Geschäftsbereich Linde Gas	NRW	Düsseldorf	40599	51.1809	6.8598	350415	5672119	63
Mark-E AG	NRW	Hagen	58095	51.360627	7.4784727	394067	5691028	5
Masterflex AG/SE	NRW	Gelsenkirchen	45891	51.559677	7.0850515	367257	5713804	5
Messer Industriegase GmbH	NRW	Siegen	57074	50.87493	8.063329	434098	5636335	26
Praxair Industriegase GmbH	NRW	Düsseldorf	40476	51.248009	6.779017	344995	5679749	15
PROGAS GmbH & Co KG	NRW	Dortmund	44141	51.504375	7.4998	395879	5706982	19
RheinEnergie AG	NRW	Köln	50823	50.9488	6.9195	353858	5646192	31

RWE Gas Storage GmbH	NRW	Dortmund	44139	51.496111	7.4654343	393475	5706113	11
Schmidt + Clemens GmbH & Co. KG	NRW	Lindlar	51789	51.0332	7.3665	385463	5654786	8
Siemens Energy Automation GmbH	NRW	Dortmund	44143	51.5208	7.5184	397207	5708782	19
SKF Sealing Solutions GmbH (vorm. CR Elastomere GmbH)	NRW	Leverkusen	51379	51.066536	7.0039727	360145	5659119	19
Vaillant Deutschland GmbH & Co. KG	NRW	Remscheid	42859	51.161978	7.2060462	374562	5669367	112
Vaillant GmbH	NRW	Remscheid	42859	51.161978	7.2060462	374562	5669367	50
VOSS Automotive GmbH	NRW	Wipperfürth	51688	51.102728	7.397241	387787	5662470	63
Westfalen AG	NRW	Münster	48155	51.9597	7.6349	406203	5757436	63
Wickeder Westfalenstahl GmbH	NRW	Wickede	58739	51.492	7.8646333	421178	5705150	13
WILO SE	NRW	Dortmund	44263	51.48174	7.48165	394568	5704492	30
aixcon Elektrotechnik GmbH	NRW	Stolberg (Rheinland)	52222	50.77745	6.220925	304077	5628759	10
Andreas HOFER Hochdrucktechnik GmbH	NRW	Mülheim / Ruhr	45478	51.436971	6.835237	349539	5700643	70
APtronic AG	NRW	Bad Sassendorf-Lohne	59505	51.5817	8.1708	442546	5714841	4
AVL Pierburg Instruments Flow Technology GmbH	NRW	Neuss	41460	51.201371	6.6944	338927	5674744	4
BEG BioEnergie GmbH	NRW	Herten	45701	51.5996	7.0962	368145	5718223	10
Benning GmbH & Co KG	NRW	Bocholt	46397	51.841267	6.6241667	336332	5746052	36
BEOS Elektronik-Technologie GmbH	NRW	Pr. Oldendorf	32361	52.3412	8.5253	467660	5799094	10
Biogas Nord Anglagenbau GmbH	NRW	Bielefeld	33719	52.01993	8.613452	473475	5763325	40
BlueSens	NRW	Herten	45699	51.595467	7.1468667	371642	5717673	10
borit Leichtbau-Technik GmbH	NRW	Herzogenrath	52134	50.86265	6.0916125	295335	5638581	10
Bronkhorst Mättig GmbH	NRW	Kamen	59174	51.580644	7.6594111	407112	5715249	36
FEV GmbH (RWTH Aachen spinoff)	NRW	Aachen	52078	50.762357	6.1380429	298170	5627304	35
Flughafen Köln/Bonn GmbH	NRW	Köln	51147	50.9333	6.95	355952	5644408	5
Ceramic Fuel Cells GmbH	NRW	Heinsberg	52525	51.060038	6.1183729	298076	5660452	10
Coatema Coating Machinery GmbH	NRW	Dormagen	41539	51.09968	6.8453187	349138	5663117	10
COMET NanoTec GmbH	NRW	Bochum	44801	51.4833	7.21667	376173	5705079	31
D.M.2 Verwertungstechnologien (Dr. Mühlen GmbH & Co. KG)	NRW	Herten	44651	51.55	7.21667	376354	5712497	10
Dynetek Europe GmbH	NRW	Ratingen	40885	51.33945	6.852775	350439	5689762	10
ECG GmbH (Elektrochemische Generatoren)	NRW	Cologne	50825	50.951664	6.911027	353272	5646528	36
EEZ	NRW	Haltern am See	45721	51.72868	7.16662	373382	5732452	10
EMC Test NRW GmbH	NRW	Dortmund	44227	51.444	7.4546	392601	5700334	10
EMCEL GmbH	NRW	Köln	50672	50.9466	6.9391	355227	5645908	4
Energy Hills e.V.	NRW	Aachen	52072	50.80338	6.06274	293041	5632073	10
ETW Energietechnik GmbH	NRW	Moers	47445	51.486622	6.6138604	334333	5706641	24
EUtech Scientific Engineering GmbH	NRW	Aachen	52068	50.778675	6.10845	296154	5629199	9
FCPower Fuel Cell Power Systems GmbH	NRW	Aachen	52070	50.795933	6.0958906	295345	5631153	28

Fernwärmeversorgung (District Heating) Niederrhein GmbH	NRW	Dinslaken	46537	51.5774	6.7465	343852	5716443	2
Ford Forschungszentrum Aachen GmbH	NRW	Aachen	52072	50.80338	6.06274	293041	5632073	9
Gas- und Wärme-Institut Essen e.V. (GWI)	NRW	Essen	45356	51.492382	6.9694303	359036	5706537	9
GKN Sinter Metals Filters GmbH	NRW	Radevormwald	42477	51.20025	7.356375	385168	5673377	36
GSR Ventiltechnik GmbH & Co. KG	NRW	Vlotho	32602	52.1388	8.7806	484984	5776498	9
Hese Umwelt GmbH	NRW	Gelsenkirchen	45881	51.521333	7.0747	366427	5709558	10
HKO Isolier- und Textiltechnik GmbH	NRW	Oberhausen	46049	51.477271	6.8413143	350093	5705111	10
HyCologne - Wasserstoff Region Rheinland e.V.	NRW	Hürth	50354	50.8772	50.8772	351361	5638295	4
HyPower GmbH	NRW	Herten	45699	51.595467	7.1468667	371642	5717673	9
Inficon GmbH	NRW	Cologne	50968	50.903769	6.968225	357143	5641090	5
Innecken Elektrotechnik GmbH	NRW	Euskirchen	53879	50.661133	6.7938667	344079	5614464	10
Inoviscoat GmbH i.G.	NRW	Leichlingen	40789	51.11189	6.96879	357820	5664229	5
iplas GmbH	NRW	Troisdorf	53842	50.8189	7.1189	367495	5631372	10
IWAKI Europe GmbH	NRW	Willich	47877	51.2592	6.515575	326653	5681581	5
LG Technology Center Europe	NRW	Neuss	41460	51.201371	6.6944	338927	5674744	8
M & C Techgroup Germany GmbH	NRW	Ratingen	40885	51.341137	6.8516544	350367	5689953	23
Mannesmann Cylinder Systems (MCS) Technologies GmbH	NRW	Dinslaken	46535	51.559128	6.7313988	342743	5714444	3
McPhy Deutschland GmbH	NRW	Willich	47877	51.2592	6.515575	326653	5681581	10
Meyra-Ortopedia Vertriebsgesellschaft mbH	NRW	Kalletal	32689	52.116667	8.949722	496557	5774016	5
MFC Energie- & Brennstoffzellentechnologie	NRW	Dortmund	44139	51.499533	7.4717	393918	5706484	4
Munk GmbH	NRW	Hamm-Rhynern	59069	51.645033	7.8608333	421179	5722173	50
PASM Power and Air Condition Solution Management GmbH & Co. KG	NRW	Münster	48153	51.9268	7.6313	405886	5753781	10
PlanET Biogastechnik GmbH	NRW	Vreden	48691	52.035394	6.824549	350781	5767209	3
ProPuls GmbH	NRW	Gelsenkirchen	45897	51.5717	7.0471	364662	5715210	27
Ritter Elektronik GmbH	NRW	Remscheid	42897	51.18326	7.25556	378080	5671650	8
Ceramic Fuel Cells GmbH	NRW	Heinsberg	52525	51.060038	6.1183729	298076	5660452	8
Coatema Coating Machinery GmbH	NRW	Dormagen	41539	51.09968	6.8453187	349138	5663117	4
RWE Fuel Cells GmbH	NRW	Essen	45128	51.445223	7.0070083	361501	5701221	9
Schmöle GmbH	NRW	Fröndenberg	58730	51.4746	7.7853	415638	5703304	10
Schwarzer Precision GmbH + Co. KG	NRW	Essen	45141	51.478026	7.0328812	363397	5704820	5
SensoriC Gas Sensors	NRW	Bonn	53121	50.7317	7.0575333	362918	5621788	8
Steag encotec GmbH	NRW	Essen	45128	51.44568	7.01028	361730	5701265	2
Sustamo GmbH (Gernweit)	NRW	Dormagen	41542	51.113	6.7752	344274	5664744	10
Swarco Fuel Cell GmbH	NRW	Duisburg	19281	51.434649	6.765098	344656	5700531	4
Tedatex Industrie GmbH	NRW	Wiehl	51674	50.948255	7.5158602	395745	5645119	26
Theisen Versorgungstechnik GmbH	NRW	Ochtrup	48607	52.2162	7.1771	375465	5786650	51

Timcal Deutschland GmbH	NRW	Düsseldorf	40212	51.223	6.7827	345168	5676959	3
Toptron GmbH	NRW	Menden	58706	51.440829	7.7887143	415813	5699544	10
TS Testingservice GmbH	NRW	Würselen, Aachen	52146	50.819381	6.146232	298992	5633621	10
TUTTAHS & MEYER Ingenieurgesellschaft für Wasser-, Abwasser- und Energiewirtschaft mbH	NRW	Aachen	52066	50.756433	6.0914	294855	5626774	1
TÜV Immissionsschutz und Energiesysteme GmbH	NRW	Köln	51105	50.914767	6.9939667	358985	5642263	9
VGB Power Tech e.V. (Assoc. of Large Boiler Makers)	NRW	Essen	45136	51.435644	7.0355606	363457	5700103	124
Wegmann (Fa. Siegfried Wegmann e. K.)	NRW	Haan	42781	51.20766	7.0169	361474	5674786	36
Wissenschaftspark Gelsenkirchen GmbH	NRW	Gelsenkirchen	45886	51.4967	7.1136	369055	5706749	33
Witt-Gasetechnik GmbH & Co. KG	NRW	Witten	58454	51.464357	7.3738857	387042	5702719	15
Zentrum für Brennstoff- Zellen-Technik GmbH (ZBT)	NRW	Duisburg	47057	51.4216000	6.7957000	346739	5699015	10
Zoz Group	NRW	Wenden	57482	50.988	7.845	418934	5649125	10
Fronius International GmbH	RHP	Neuhof Dorfborn bei Fulda	36119	50.45352	9.459418	533843	5387819	19
Oerlikon Balzers Coating Germany GmbH	RHP	Bingen	55411	49.943702	7.9225329	422692	5532928	7
ÖKOBIT GmbH	RHP	Föhren	54343	49.859115	6.764129	339301	5525364	36
Technische Werke Ludwigshafen (TWL) AG	RHP	Ludwigshafen	**67063**	49.48486	8.42659	458468	5481516	6
Thomas Magnete GmbH	RHP	Herdorf	57562	50.7814	7.9589	426604	5626032	40
FWB Kunstofftechnik GmbH	RHP	Pirmasens	66955	49.181228	7.603118	398201	5448542	17
thinXXS Microtechnology AG	RHP	Zweibrücken	66482	49.24895	7.364875	381002	5456417	60
Moehwald GmbH	SAA	Homburg	66424	49.325354	7.3448047	379728	5464943	10
FuelCon	SAN	Magdeburg-Barleben	39179	52.1955	11.599354	677654	5785968	20
Karl Utz Sondermaschinen GmbH	SAN	Limbach-Oberfrohna	9212	50.85775	12.78895	344385	5636336	16
Verbundnetz Gas AG	SAX	Leipzig	4347	51.358485	12.423949	320649	5692841	7
EBZ Entwicklungs- und Vertirebsgesellschaft Brennstoffzelle MBH GmbH (Fuel Cells & Process Technology)	SAX	Dresden	1307	51.050429	13.759358	413715	5656848	10
eZelleron	SAX	Dresden	1277	51.029989	13.782421	417048	5656440	10
Flexiva GmbH	SAX	Amtsberg	9439	51.645199	11.765718	691348	5725200	6
FuelCell Solutions GmbH (Sales, HQ)	SAX	Dresden	1277	51.029989	13.782421	414619	5653865	36
Marine Hydrogen and Fuel Cell Association e.V. (MHFCA e.V.)	SAX	Leipzig	4157	51.37081	12.36233	316266	5695113	6
Riesar Brennstoffzellentechnik GmBH	SAX	Glaubitz	1612	51.330732	13.36124	385832	5687879	31
SITEC Industrietechnologie GmbH	SAX	Chemnitz	9114	50.86716	12.90747	352756	5637139	48
RWE Fuel Cells GmbH	NRW	Essen	1237	51.027433	13.787495	415737	5651957	22
Schmöle GmbH	NRW	Fröndenberg	4720	51.117468	13.104581	367340	5664596	30
staxera GmbH	SAX	Dresden	23812	53.95285	10.209909	579397	5978954	30
Wagner Sanitär - Heizung - Solartechnik GmbH	SAX	Mochau	24143	54.305968	10.148004	574697	6018172	15
Grundfos Pumpenfabrik GmbH	SHO	Wahlstedt	23558	53.86055	10.6611	609243	5969285	8
Howaldtswerke-Deutsche Werft (HDW)	SHO	Kiel	23558	53.86055	10.6611	609243	5969285	10

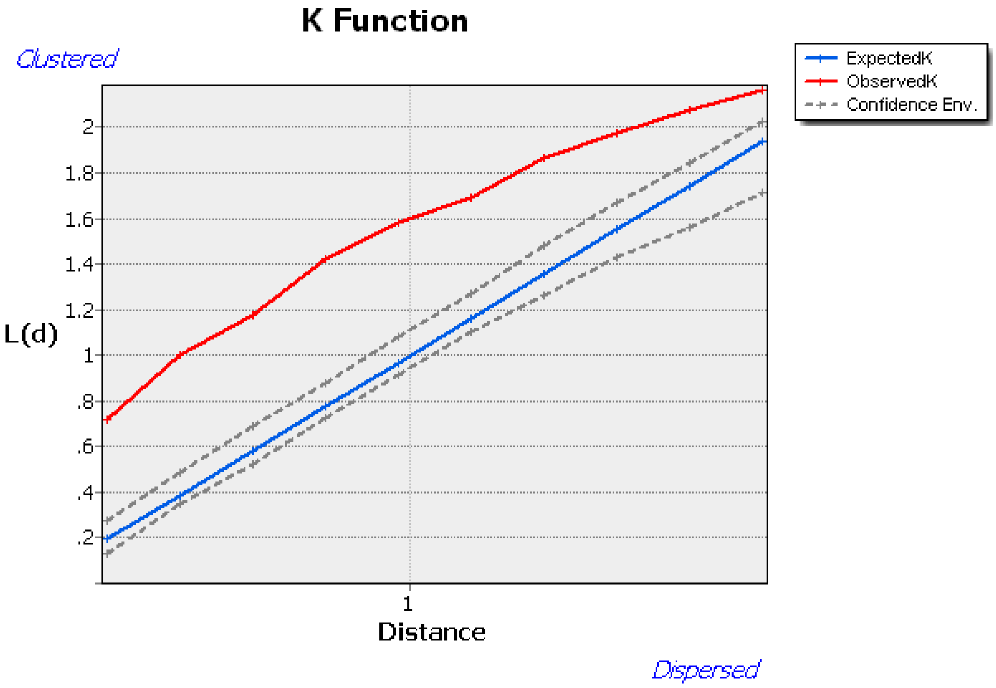
H-Tec Education GmbH	SHO	Lübeck	45128	51.445223	7.0070083	361501	5701221	76
H-Tec System GmbH	SHO	Lübeck	58730	51.4746	7.7853	415638	5703304	25

Appendix AO: Germany - Employee Location Quotients for HFC Corporate Activity by Land

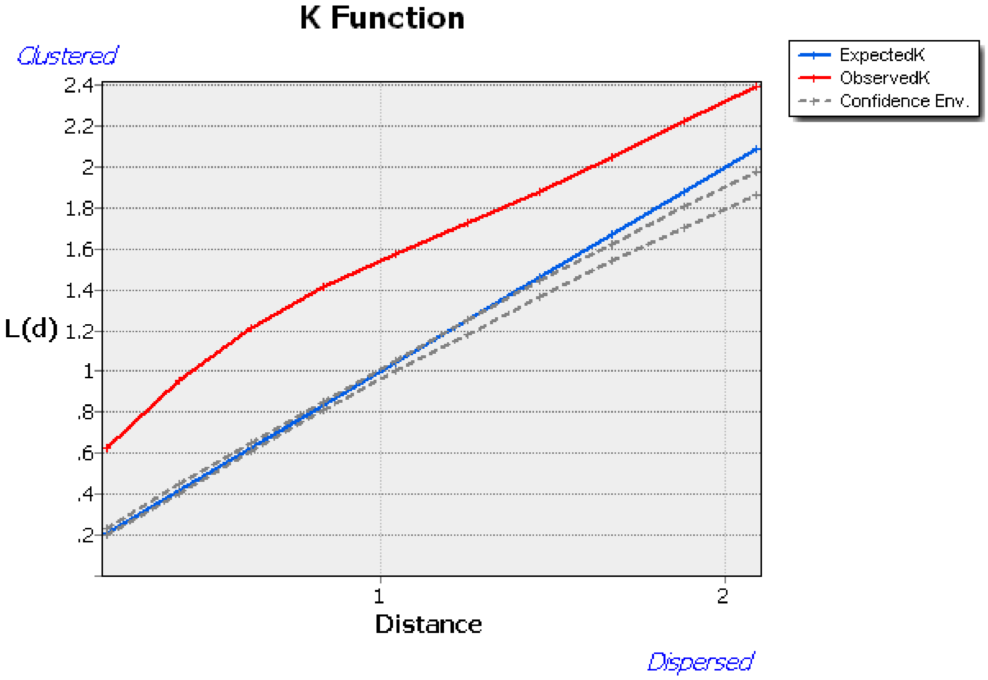
Land	Code	Total HFC Employee (estimate only)	Total All Employment (2012)	Employee Location Quotients (LQs)	Rank Order
Bavaria	BAV	1,519	6,606,000	1.09	6
Berlin	BER	387	1,661,000	1.11	5
Brandenburg	BRA	42	1,234,000	0.16	12
Baden-Württemberg	BW	1,698	5,568,000	1.45	3
Hamburg	HAM	392	913,000	2.04	1
Hessen	HES	1,026	3,026,000	1.61	2
Lower Saxony	LOS	299	3,820,000	0.37	9
Mecklenburg-Vorpommern	MVP	65	764,000	0.4	13
North Rhine-Westphalia	NRW	2,527	8,322,000	1.44	4
Rhineland-Palatinate	RHP	130	1,970,000	0.31	10
Saarland	SAA	6	469,000	0.06	14
Sachsen-Anhalt	SAN	57	1,082,000	0.25	11
Saxony	SAX	181	1,944,000	0.44	8
Schleswig-Holstein	SHO	131	1,379,000	0.45	7
Thuringia	THU	0	1,098,000	0	15=
Bremen	BRE	0	303,000	0	15=
totals		8,461	40,159,000	-	-

Appendix AP: Germany - Clustering Analysis (Ripley's K) of Actors in 2012

a) higher education bodies and research institutes:

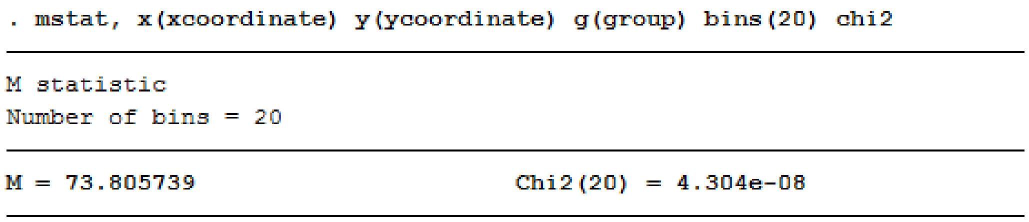


b) corporate HFC actors:



Appendix AQ: Germany - Interpoint Distribution Analysis (*M*) of Actors in 2012

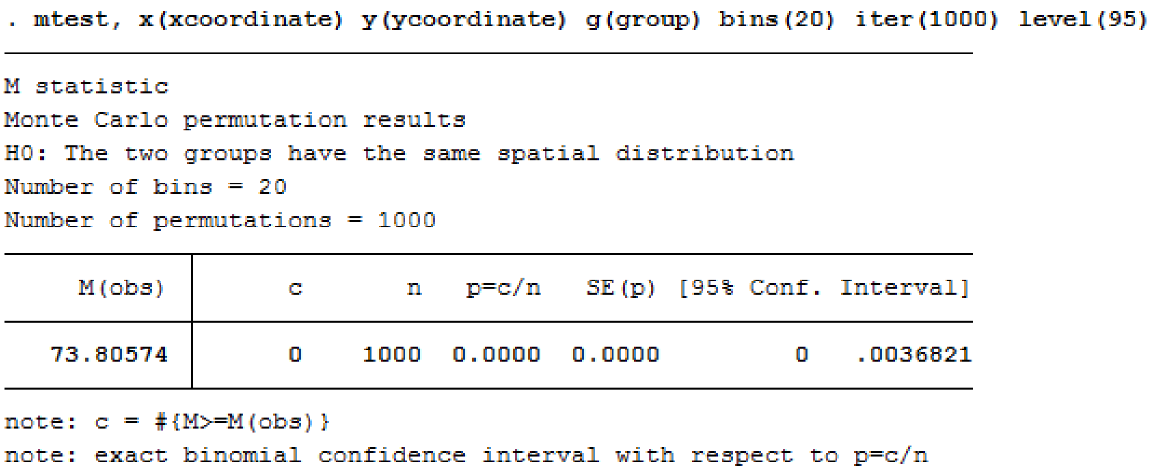
a) results for both groups via *mstat* (chi^2) and *mtest* (Monte Carlo) in StataMP14:



```
. mstat, x(xcoordinate) y(ycoordinate) g(group) bins(20) chi2

M statistic
Number of bins = 20

M = 73.805739                        Chi2(20)  = 4.304e-08
```



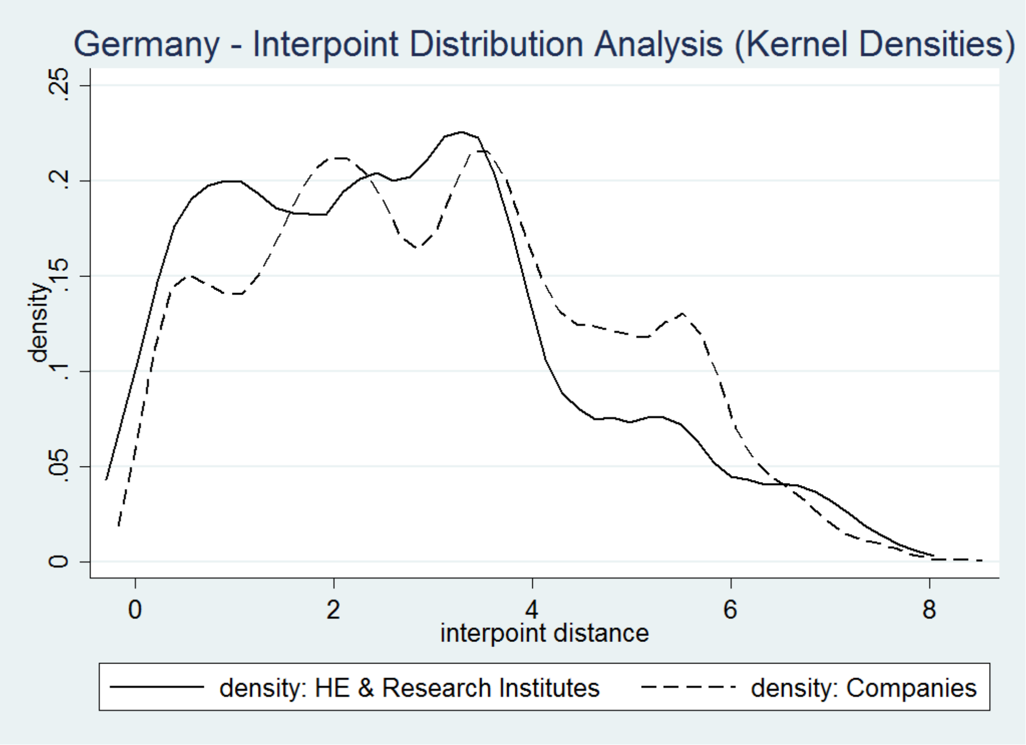
```
. mtest, x(xcoordinate) y(ycoordinate) g(group) bins(20) iter(1000) level(95)

M statistic
Monte Carlo permutation results
H0: The two groups have the same spatial distribution
Number of bins = 20
Number of permutations = 1000

      M(obs) |        c        n    p=c/n    SE(p)  [95% Conf. Interval]
-------------+----------------------------------------------------------
    73.80574 |        0     1000   0.0000   0.0000          0    .0036821

note: c = #{M>=M(obs)}
note: exact binomial confidence interval with respect to p=c/n
```

b) kernel density results in *mtest* for both groups of HFC actors:



Appendix AR: Germany – Cumulative Totals of Regional Diffusion of HFC Knowledge Development Activity (F2), 1959-2012 (Part 1)

	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976
Baden-Württemberg	0	0	0	0	1	1	2	3	3	4	4	4	4	5	6	12	16	15
Bavaria	2	2	4	6	7	8	9	11	13	15	16	17	18	20	25	28	32	35
Berlin	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Brandenburg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bremen	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hamburg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hesse	2	2	5	8	9	11	13	14	17	19	19	20	21	22	22	24	25	26
Lower Saxony	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	4	4	5
Mecklenburg-Vorpommeran	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
North Rhine-Westphalia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	2
Rhineland-Palatinate	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
Saarland	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sachsen-Anhalt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Saxony	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Schleswig-Holstein	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Thuringia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
total of cumulative totals	4	4	9	14	17	20	25	29	34	39	40	42	44	48	55	70	80	84

	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994
Baden-Württemberg	16	19	24	28	34	35	36	39	40	40	41	44	46	49	52	59	64	74
Bavaria	39	41	42	44	44	45	46	46	46	53	53	53	55	59	59	61	65	65
Berlin	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Brandenburg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bremen	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hamburg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hesse	26	26	26	30	31	31	31	32	32	32	34	34	34	36	36	36	36	37
Lower Saxony	7	7	9	9	9	9	9	9	9	10	10	10	10	10	10	10	10	10
Mecklenburg-Vorpommeran	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
North Rhine-Westphalia	2	4	6	6	8	9	9	10	10	11	11	11	12	12	12	12	14	15
Rhineland-Palatinate	2	2	2	2	2	2	2	2	3	3	5	5	5	5	5	5	5	5
Saarland	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sachsen-Anhalt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Saxony	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Schleswig-Holstein	0	0	0	0	1	1	2	2	2	2	3	4	4	4	4	5	5	5
Thuringia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
total cumulative totals	91	98	108	119	129	132	135	140	142	150	156	160	165	174	177	187	198	210

Appendix AR: Germany – Cumulative Totals of Regional Diffusion of HFC Knowledge Development Activity (F2), 1959-2012 (Part 2)

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Baden-Württemberg	84	92	107	129	147	181	236	278	312	344	401	416	429	445	460	473	485	499
Bavaria	68	70	78	91	101	115	126	135	156	179	196	206	214	220	223	227	230	245
Berlin	1	1	1	1	1	2	2	4	4	6	6	6	7	12	17	22	24	24
Brandenburg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bremen	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hamburg	0	0	0	0	1	1	2	2	13	19	28	39	46	49	59	62	65	76
Hesse	41	43	49	52	63	67	81	94	110	129	154	167	173	179	187	222	246	257
Lower Saxony	10	10	10	10	10	11	12	13	14	17	20	23	24	24	25	26	27	27
Mecklenburg-Vorpommeran	0	0	0	0	0	0	0	0	1	2	2	2	2	2	2	2	2	2
North Rhine-Westphalia	17	17	23	25	34	48	54	64	76	93	99	103	111	114	121	129	131	140
Rhineland-Palatinate	5	5	5	7	7	11	11	18	26	34	39	41	42	43	46	60	70	75
Saarland	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Sachsen-Anhalt	0	0	0	0	0	0	0	0	1	1	2	2	2	4	4	5	5	5
Saxony	3	3	3	3	3	3	3	3	3	4	4	5	5	6	9	15	16	17
Schleswig-Holstein	7	8	8	8	8	9	9	12	13	15	15	16	16	16	16	16	16	17
Thuringia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
total of cumulative totals	234	247	282	324	372	448	535	623	729	843	966	1026	1069	1114	1169	1259	1316	1386

Appendix AS: Germany – Entrepreneurial Activity TIS Events (F1) by Region, 1999-2012 (Part 1)

Land	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Baden-Württemberg	0	0	-1	0	0	0	0	0	0	0	0	1	0	1	0	1
Bavaria	1	0	0	0	0	0	0	1	0	-2	0	0	2	0	1	1
Berlin	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0
Brandenburg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bremen	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hamburg	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
Hesse	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	1
Lower Saxony	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mecklenburg-Vorpommeran	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
North Rhine-Westphalia	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1
Rhineland-Palatinate	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Saarland	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sachsen-Anhalt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1
Saxony	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Schleswig-Holstein	0	0	0	0	0	0	0	0	0	0	0	0	1	1	2	0
Thuringia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
annual total	1	0	-1	0	0	0	0	1	0	-2	0	1	6	4	6	5
cumulative total	1	1	0	0	0	0	0	1	1	-1	-1	0	6	10	16	21

Appendix AS: Germany – Entrepreneurial Activity TIS Events (F1) by Region, 1999-2012 (Part 2)

Land	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**total**	**share**
Baden-Württemberg	0	2	1	4	0	-1	1	9	6%
Bavaria	5	7	10	8	12	5	8	59	38%
Berlin	0	1	2	2	1	5	2	16	10%
Brandenburg	0	0	0	0	0	0	2	2	1%
Bremen	0	0	0	0	0	0	0	0	0%
Hamburg	0	0	0	3	-1	2	1	7	5%
Hesse	1	0	1	1	0	1	1	5	3%
Lower Saxony	2	0	0	0	0	0	0	2	1%
Mecklenburg-Vorpommeran	0	0	0	0	0	0	0	0	0%
North Rhine-Westphalia	2	4	2	4	6	6	8	35	23%
Rhineland-Palatinate	0	0	0	0	0	0	0	0	0%
Saarland	0	0	0	0	0	0	0	0	0%
Sachsen-Anhalt	3	0	0	1	0	0	0	7	5%
Saxony	0	0	1	0	0	1	3	5	3%
Schleswig-Holstein	3	1	0	0	0	0	0	8	5%
Thuringia	0	0	0	0	0	0	0	0	0%
annual total	16	15	17	23	18	19	26	155	100%
cumulative total	37	52	69	92	110	129	155	-	-

Appendix AT: Germany – Strategic Partnering PPP Activity for All TIS Events by Region, 1999-2012 (Part 1)

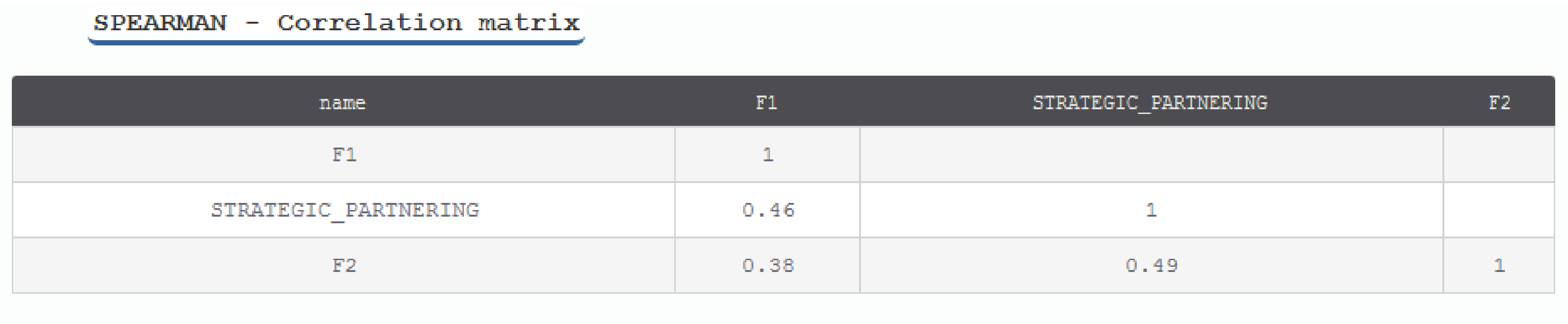
Land	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**
Baden-Württemberg	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Bavaria	1	0	0	0	0	0	0	1	0	1	1	0	0	0	0	0
Berlin	0	0	0	0	0	0	0	0	1	0	1	1	2	1	0	1
Brandenburg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bremen	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hamburg	0	0	0	0	0	0	0	0	0	0	0	1	2	2	0	2
Hesse	0	0	0	0	0	0	0	0	0	0	0	1	0	0	2	0
Lower Saxony	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mecklenburg-Vorpommeran	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
North Rhine-Westphalia	0	0	0	0	1	0	0	0	0	0	5	4	3	1	5	5
Rhineland-Palatinate	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Saarland	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sachsen-Anhalt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Saxony	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Schleswig-Holstein	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Thuringia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
annual total	1	1	0	0	1	0	0	1	1	1	7	7	7	6	8	8
cumulative total	1	2	2	2	3	3	3	4	5	6	13	20	27	33	41	49

Appendix AT: Germany – Strategic Partnering PPP Activity for All TIS Events by Region, 1999-2012 (Part 2)

Land	2006	2007	2008	2009	2010	2011	2012	total	share
Baden-Württemberg	0	1	0	2	0	2	0	0	1
Bavaria	1	2	1	1	1	1	3	1	2
Berlin	2	0	5	4	6	2	5	2	0
Brandenburg	0	0	0	0	0	0	1	0	0
Bremen	0	0	0	0	0	0	0	0	0
Hamburg	0	0	2	1	3	4	3	0	0
Hesse	2	0	0	2	1	0	1	2	0
Lower Saxony	1	0	0	2	0	0	0	1	0
Mecklenburg-Vorpommeran	0	0	0	0	0	0	0	0	0
North Rhine-Westphalia	3	3	2	5	5	5	2	3	3
Rhineland-Palatinate	0	0	0	0	0	0	0	0	0
Saarland	0	0	0	0	0	0	0	0	0
Sachsen-Anhalt	0	0	0	0	0	0	0	0	0
Saxony	0	0	0	0	2	0	0	0	0
Schleswig-Holstein	0	0	0	0	0	0	1	0	0
Thuringia	0	0	0	0	0	0	0	0	0
annual total	9	6	10	17	18	14	16	9	6
cumulative total	58	64	74	91	109	123	139	58	64

Appendix AU: Germany – Correlation Matrix for Strategic Partnering PPP and Functional Activity, 1999-2012

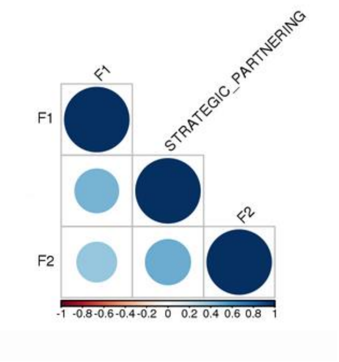
i) tabulated analysis in R (online via www.sthda.com) (1999-2012 data in Appendices AY, BB and BA compared):



SPEARMAN - Correlation matrix

name	F1	STRATEGIC_PARTNERING	F2
F1	1		
STRATEGIC_PARTNERING	0.46	1	
F2	0.38	0.49	1

ii) correlogram visualisation of analysis via www.sthda.com:



Interpretation of Results' Range

Exactly –1	A perfect negative linear relationship
– 0.70	A strong negative linear relationship
– 0.50	A moderate negative relationship
– 0.30	A weak negative linear relationship
0	No linear relationship
+0.30	A weak positive linear relationship
+0.50	A moderate positive relationship
+0.70	A strong positive linear relationship
Exactly +1	A perfect positive linear relationship

Appendix AV: Germany - Corporate HFC Actor Data (Numbers, Estimated Employees, Ownership) in 2012

Land / Firm	**Hamburg (HAM)**				**Hesse (HES)**				**Baden-Württemberg (BW)**				**North Rhine-Westphalia (NRW)**				**Bavaria (BAV)**				***grand totals***			
Small & Medium-Sized Enterprises (SMEs) (1-250 employees)	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees
Länder-owned	4	31	21	4	15	28	263	25	23	41	585	41	56	50	923	38	20	40	548	36	118	42	2340	32
other Länder-owned	0	0	0	0	2	4	26	2	0	0	0	0	0	0	0	0	2	4	14	1	4	1	40	1
foreign-owned	2	15	61	11	10	19	334	32	1	2	4	2	13	12	178	7	3	6	37	2	29	10	614	8
sub total SMEs	6	46	82	15	27	51	623	59	24	44	589	44	69	61	1101	45	25	50	599	39	151	53	2994	41

Land / Firm	**Hamburg (HAM)**				**Hesse (HES)**				**Baden-Württemberg (BW)**				**North Rhine-Westphalia (NRW)**				**Bavaria (BAV)**				***grand totals***			
Large Enterprises (LEs) (251+ employees)	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees	Actor Numbers	% of Total Actor No.s	Estimated Employees	% of Total Employees
Länder-owned	5	39	248	45	19	36	232	22	22	40	817	48	31	27	909	37	18	36	549	36	95	33	2755	38
other Länder-owned	1	8	63	11	1	2	46	4	1	2	17	1	1	1	19	1	1	3	172	11	5	2	317	4
foreign-owned	1	8	160	29	6	11	158	15	8	16	274	16	12	11	425	17	6	12	199	13	33	12	1216	17
sub total LEs	7	54	470	85	26	49	436	41	31	56	1109	65	44	39	1354	55	25	50	920	61	133	47	4289	59
grand total	13	100	552	100	53	100	1059	100	55	100	1698	100	113	100	2455	100	50	100	1519	100	284	100	7283	100

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