A Systemic Perspective on Innovation from Energy Efficiency Policy efforts

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Ph.d. thesis

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A SYSTEMIC PERSPECTIVE ON INNOVATION FROM ENERGY EFFICIENCY POLICY EFFORTS

Ph.D. thesis

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ENGLISH SUMMARY

In order to reduce climate change, resource scarcity and other global environmental issues major increases in energy efficiency are necessary throughout our energy system. Despite this daunting outlook and the fact that energy efficiency in most instances makes economic and environmental sense, these energy efficiency improvements do not occur by themselves. This challenge of low diffusion for energy-efficient solutions has been the subject of policy efforts since the oil crisis in the 1970s and they are gaining in attention.

In certain sectors, however, it seems like energy efficiency is starting to make a differences and businesses appear especially innovative in this field (Borup et al., 2009). This thesis therefore investigates the dynamics of energy efficiency innovation and, in particular, their relation to public policy efforts.

These innovation activities in energy efficiency have not been the subject of much research in the innovation studies field, where most attention is given towards energy supply technologies and energy end-use technologies tend to be left in the dark. This thesis applies different qualitative and quantitative research methods to analyse how actors are collaborating on innovation activities within energy efficiency. It furthermore investigates the long and complex process of innovation activities in energy efficiency with attention to the co-evolutionary dynamics of technology development, policy and market transformation.

The findings cover different aspects of the research topic. At the cross-sectoral level it contributes with insights into the collaborative RD&D activities in energy efficiency and how the structure of these development activities has an impact on the innovation output of the RD&D projects. It furthermore identifies the driving forces of energy efficiency innovation activities where market demand and policy efforts appear to have the most impact. The thesis also goes in depth with a single sector to describe the complexities of innovation processes in energy efficiency and the noticeable role of policy.

Overall the doctoral thesis provides an insight into the dynamics of energy efficiency innovation and the necessity of policy efforts. For innovation and market transformation to occur, strategic and integrated policies are absolutely crucial in order to overcome the barriers towards energy efficiency and thereby enabling energy efficiency innovation for the benefit of firms and the environment.

DANSK RESUMÉ

Bekæmpelse af klimaforandringer, ressourcemangel og andre miljøproblemer kræver store forbedringer af energieffektiviteten overalt i vores energisystem. På trods af den skræmmende udsigt for klimaet, og det faktum at energieffektivitet i de fleste tilfælde giver god økonomisk og miljømæssig mening, sker store forbedringer i energieffektivitet ikke af sig selv. Udfordringen med lav udbredelse af energieffektive løsninger har været genstand for politiske tiltag lige siden oliekrisen i 1970'erne og er gradvist blevet mere og mere italesat.

I bestemte sektorer ser det dog ud til at energieffektivitet begynder at gøre en forskel og virksomhederne virker til at være særligt innovative netop på det område (Borup et al., 2009). Denne afhandling undersøger derfor innovationsdynamikkerne indenfor energieffektivitet med særligt fokus på samspillet med politik og lovmæssige tiltag.

Innovationsaktiviteterne indenfor energieffektivitet har ikke været genstand for meget forskning indenfor feltet af innovationsstudier, hvor der typisk er størst interesse for energiproduktionsteknologier frem for energiforbrugende teknologier. Denne afhandling anvender forskellige kvalitative og kvantitative forskningsmetoder til at analysere hvordan aktører samarbejder i innovationsaktiviteter indenfor energieffektivitet. Derudover undersøges den lange og komplekse innovationsproces med særligt hensyn til de co-evolutionære dynamikker omkring teknologiudvikling, politik og markedstransformation.

Resultaterne i afhandlingen dækker flere aspekter af forskningsemnet. På det tværsektorielle niveau bidrager studiet med indsigt i tværorganisatorisk samarbejde på offentligt støttede F&U-projekter indenfor energieffektivitet og hvordan strukturen af disse udviklingsaktiviteter har indflydelse på F&U-projekternes innovationsoutput. Derudover identificerer afhandlingen nogle af driverkræfterne for innovationsaktiviteterne, og finder frem til at markedsbehov og politiske tiltag har den største indflydelse. Samtidig går afhandlingen i dybden med en enkelt sektor for at beskrive kompleksiteten af innovationsprocessen for energieffektive produkter og den afgørende rolle som politiske tiltag spiller i forbindelse med markedstransformationen.

Samlet set bidrager denne afhandling med indsigt i de komplekse innovationsdynamikker indenfor energieffektive produkter og det tætte samspil med politiske tiltag. Det kræver strategiske, integrerede og stabile politiske tiltag for at innovation og markedstransformation kan ske, således at barriererne for energieffektivitet reduceres og energieffektivitetsinnovation kan iværksættes til fordel for virksomheder og miljøet.

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First and foremost I would like to thank my wonderful girlfriend Mette, without her support I would not have been able to complete the long and lonely process of doing a Ph.D. degree. I am forever grateful of her love and support.

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A great deal of appreciation must also go to the organisations and firms, which have contributed with empirical data and knowledge about the reality of collaborative innovation activities in energy efficiency. In particular I would like to thank Dansk Energi, ELFORSK, Grundfos, Smedegaard, Teknologisk Institut, Exhausto, Dong Energy and Københavns Energi.

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The project has been a part of *EIS - The Strategic research alliance for Energy Innovation Systems and their dynamics*. This affiliation has given access to insightful researchers from several international institutions and provided formal and informal contact between junior and senior academics.

I am appreciative to everyone who have contributed to the completion of this Ph.D. thesis.

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1 INTRODUCTION

The world is facing a series of challenges with issues such as climate change, resource scarcity, energy security, environmental degradation, loss of biodiversity and deteriorating air quality, along with continuous economic, social and health issues. These challenges are large and ambiguous, and will undoubtedly require change at every level in every societal system.

One of the key areas where sustainable development (Brundtland, 1987) is greatly needed is in our energy systems. The way we produce and use energy has tremendous impact on our local and global environment. In terms of greenhouse gas emissions, energy production and consumption in transport, buildings and industry account for more than 60% of global emissions (Metz and Davidson, 2007) – see figure 1. The imperative for drastic change in our energy systems is therefore ever present.

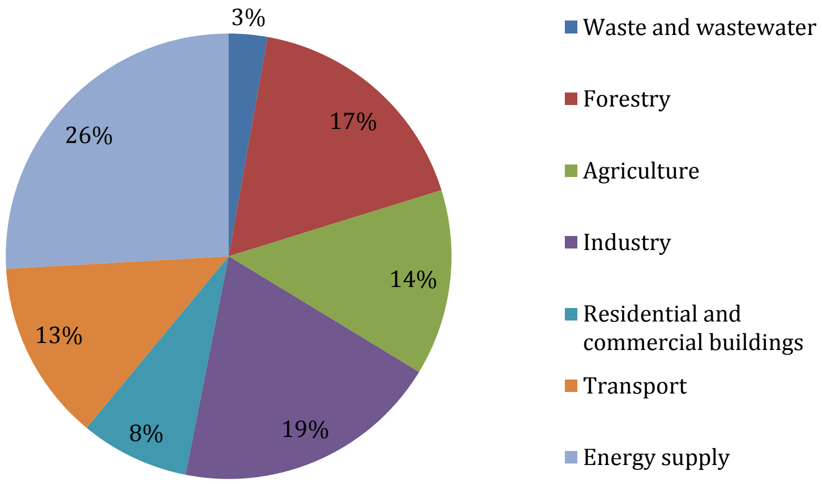


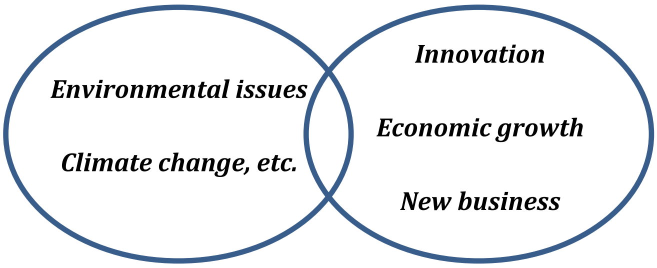
FIGURE 1 - GLOBAL GREENHOUSE GAS EMISSIONS BY SECTOR IN 2004 (METZ AND DAVIDSON, 2007).

Since the 1970s oil crisis, efforts have been made to reduce the consumption of both electricity and heat in all parts of the energy system, which has had some impact on our final consumption (Geller et al., 2006). Denmark, for example, has been able to decouple economic growth, energy consumption and environmental impact, something which was previously thought impossible (NORDEN, 2013). It is, however, one of only a few countries to do so.

Still, there are vast areas where cost-effective energy savings are possible, which is why the recent IPCC Mitigation of Climate Change report states so clearly: '*Efficiency enhancements and behavioural changes, in order to reduce energy demand compared to baseline scenarios without compromising development, are a key mitigation strategy in scenarios reaching atmospheric CO2 eq. concentrations of about 450 or 500 ppm by 2100*' p. 21 (Edenhofer et al., 2014). According to estimates by the International Energy Agency (IEA), cost-effective energy savings can be still be improved by two-thirds throughout the energy system, despite increasing efforts since the 1970s (IEA, 2013a).

This makes energy efficiency improvements sound easy, but in reality they are very hard to actualise. Increases in energy efficiency and energy savings do not occur by themselves – despite the immediate economic and environmental benefits – because of inherent economic, organisational and behavioural barriers (Hirst and Brown, 1990; Weber, 1997). The recent IPCC report acknowledges this as '*strong barriers, such as split incentives (e.g., tenants and builders), fragmented markets and inadequate access to information and financing, hinder the market-based uptake of cost-effective opportunities. Barriers can be overcome by policy interventions addressing all stages of the building and appliance lifecycles (robust evidence, high agreement)*' p. 24 (Edenhofer et al., 2014). The IPCC elaborate further on the role of "well designed" policy efforts as the main tool to reduce the barriers of energy efficiency and enable emissions reductions: '*The development of portfolios of energy efficiency policies and their implementation has advanced considerably since AR4 (Recent IPCC report). Building codes and appliance standards, if well designed and implemented, have been among the most environmentally and cost-effective instruments for emission reductions (robust evidence, high agreement)*' p.24 (Edenhofer et al., 2014).

With the grand challenge of moving towards efficient energy systems, the need for innovation and sustainable development is enormous. Innovation and socio-technical change is needed on multiple fronts as a driver of technological change, new business and economic growth in order to meet the grand challenge of a sustainable energy system.



The imperative for innovation in energy efficiency is obvious. New and efficient technologies, products, services and processes are needed, but as this thesis will point out, this is not necessarily enough for energy efficiency innovation and change towards sustainability to occur. Institutional change, dynamic and iterative policy support and a systemic understanding of innovation processes are equally important in order to aid sustainable development (Colombier and Menanteau, 1997; Kiss and Neij, 2011).

This doctoral thesis will form a scientific contribution to the field of innovation studies specifically on the dynamics of energy efficiency innovation and the role of public policy efforts. Earlier studies have shown that the area of energy-efficient technologies in Denmark is a highly innovative field. New product introductions and new business activities appear more frequently than in many other energy technology areas (Borup et al., 2009). However, these innovation dynamics pose many largely unanalysed questions. The objective of this Ph.D. project is to analyse the innovation dynamics in the field, departing empirically from policy efforts in Denmark and Europe.

1.1 ENERGY USE, EFFICIENCY AND ENERGY SYSTEMS

This thesis positions energy efficiency in the context of an overall energy system, where energy is produced and consumed. FIGURE 2 shows a rough simplification of the energy system, where energy originates from different primary energy sources. The energy goes through a series of steps before its final consumption as different energy services. It is the efficiency of technologies, products and services at the final conversion to energy services that forms the empirical context of this thesis – although excluding the transport sector.

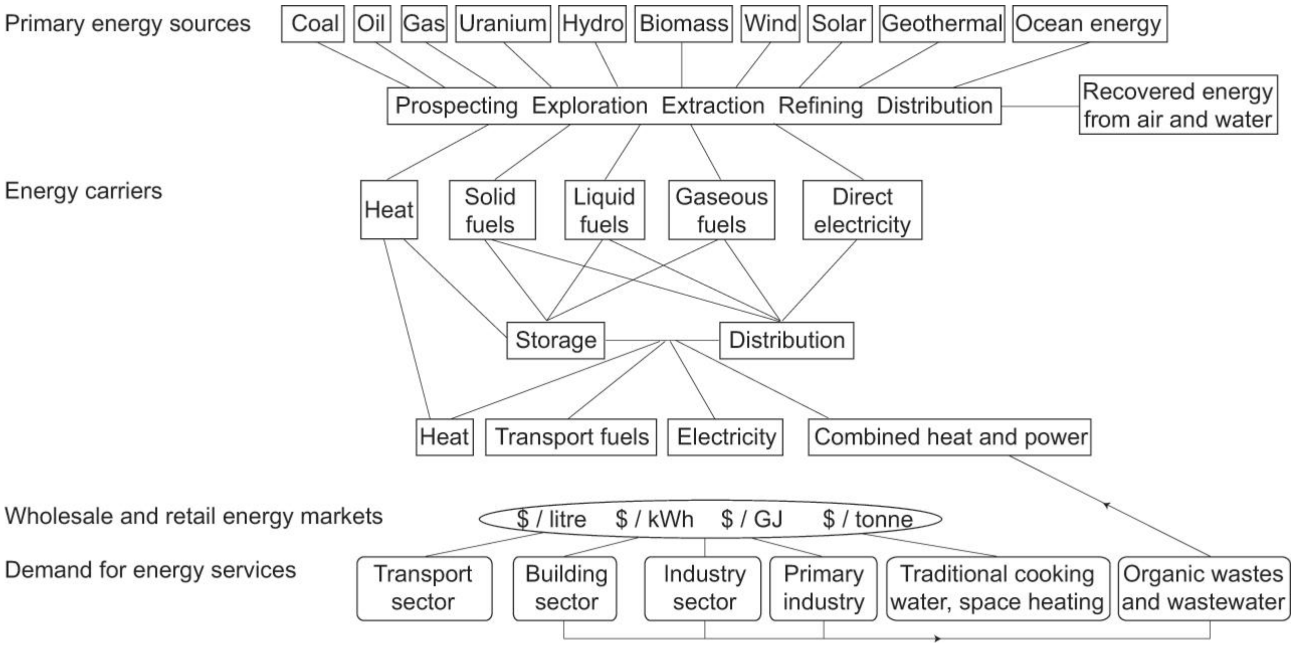


FIGURE 2 - SIMPLE OVERVIEW OF ENERGY SYSTEMS, ILLUSTRATING RELATIONS BETWEEN ENERGY SUPPLY AND END-USE ENERGY SERVICES [IPCC AR4 2007 - WG III]

In energy systems it is important to make the distinction between the supply of energy and the use of energy services. Wilson put it as '*energy-supply technologies are used to extract, process, transport and convert energy resources into a form useful to end-users*' as opposed to '*end-use technologies are used to convert energy into a useful final service like heating, mobility or communication*' p. 780 (Wilson et al., 2012). This distinction is not often pointed out in energy innovation studies or public policy efforts. In general, energy-supply technologies receive the most attention from researchers and policymakers, despite the obvious relevance of both aspects.

Achieving end-use savings in energy systems can basically be actualised in two ways: either by increasing the efficiency of an energy-using service or by energy conservation where the service is removed altogether. Both are necessary in the pursuit of sustainability in energy systems, but this thesis will narrow its scope to the energy efficiency of energy services only. Furthermore, this project has excluded the transport sector from its empirical scope because the transport, or mobility, sector shares little with industry or household sectors in terms of technologies, organisations, user practices, policies, etc. A few concepts from energy efficiency, such as rebound effects, also apply in mobility but often it is an area and empirical context which should be investigated separately. This thesis therefore looks at innovation activities in the context of industry and buildings, which roughly accounts for approximately 51.9% of European energy use (EEA, 2012).

1.2 FRAMING ENERGY EFFICIENCY INNOVATION

There is a challenge in properly framing the diverse and multifaceted nature of energy efficiency innovation. Increased energy efficiency can more or less be a feature in any energy-using product. This means that it covers multiple sectors and industries with different innovation dynamics and market. As FIGURE 3 shows there are several sectors involved in energy efficiency efforts, which are interlinked because of three elements. *1)* Energy efficiency barriers impact throughout the sector although with varying impact. *2)* Energy efficiency policy efforts are not only sector specific policies but can impact across the different areas 3) certain common actors (such as energy companies and energy consultants), institutions and markets cover the different sectors. In this study the focus is on how public policy efforts interplay with the strategic innovation efforts at the level of research institutions and private companies in the different areas – not including Transport & Mobility.

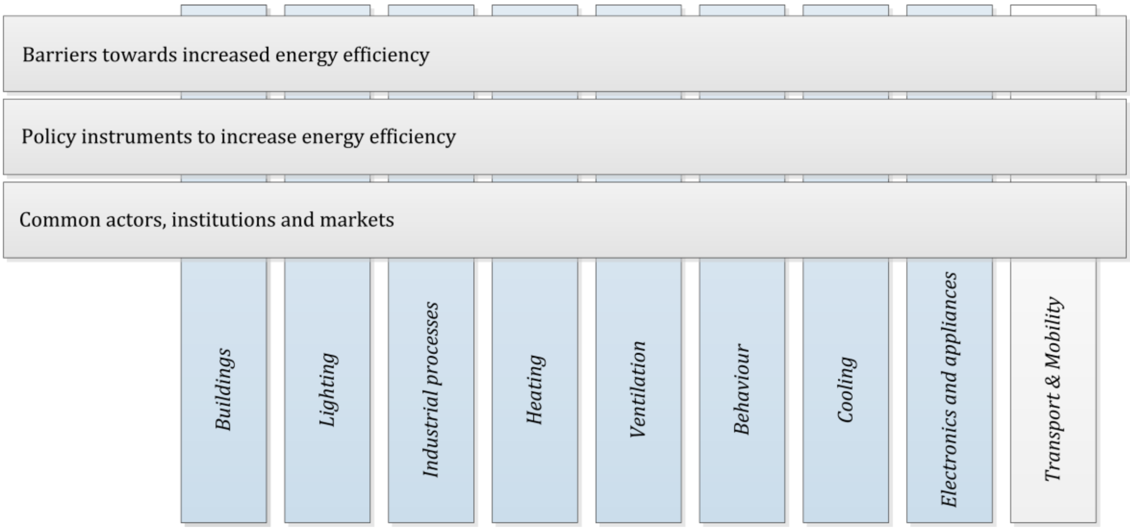


FIGURE 3 – AN OVERVIEW OF SUBAREAS RELEVANT FOR ENERGY EFFICIENCY AND CROSS-GOING ELEMENTS

From a societal perspective, energy efficiency innovation can be characterised as ‘innovation efforts for reducing emissions in (energy) end-use – (are) to improve the energy efficiency of devices and applications’ p. 780 (Wilson et al., 2012). This statement seems accurate, but it should be acknowledged that at the firm level, these innovation efforts in energy efficiency also feed into the overall competitiveness of firms. A firm’s innovation efforts in this regard tend to be about technically increasing products’ and systems’ energy with the intention of gaining a competitive advantage in the market and ensuring profits (Porter and Linde, 1995a). Energy efficiency performance must therefore always be seen in the context of an existing product category, with competitive parameters such as product performance, price, maintenance, usability and quality. This integration of energy efficiency as a strategic parameter in the innovation activities of firms and organisations must be seen in contrast with energy efficiency integrated only as end-of-pipe abatement and compliance to market and policy demands. With an outset in the linear model (Tidd et al., 2005) of the firm-level innovation process, the difference between strategically working with energy efficiency and only complying to regulation would be to determine when energy efficiency efforts are included and integrated in a firms innovation process. The earlier in the process, the more integrated energy efficiency is assumed to be. The strategic innovation efforts in increasing energy efficiency at both the firm and inter-organisational level will form the framing of this thesis. Energy efficiency innovation is therefore a dual concept that, on one hand, describes the goal-orientated nature of increasing technical efficiency for the benefit of society and the environment, and, on the other hand, creates new competitive parameters for firms to secure their earnings in competitive markets.

The notion of eco-innovation and environmental innovation has gained considerable interest recently in both research and policymaking (Carrillo-Hermosilla et al., 2010; Seebode et al., 2012). The notion is defined by Klaus Rennings as 'eco-innovations are all measures of relevant actors (firms, politicians, unions, associations, churches, private households) which; develop new ideas, behaviour, products and processes, apply or introduce them and which contribute to a reduction of environmental burdens or to ecologically specified sustainability targets' p.322 (Rennings, 2000). While this concept also covers energy and resource efficiency, it tends to generalise the underlying dynamics of energy efficiency in order to frame the overall concept for policymakers and businesses. The societal goal of sustainability is the same, but the dynamics of energy efficiency are distinctive, as will be pointed out in this thesis. Innovation and increased energy efficiency can and should be regarded as type of eco-innovation but this thesis will highlight the specific characteristics of energy efficiency innovation, which are not generally the same as those of eco-innovation.

The thesis uses a combination of innovation systems theory (RR Nelson and Winter, 1982; Freeman, 1987; Lundvall, 1992)and socio-technical systems and transition theory (Bijker et al., 1987; Bijker, 1997; Geels, 2004; Markard et al., 2012). Originally, the concept of an innovation system started within a national context to describe the national setup and 'the network of institutions in the public and private sectors whose activities and interactions initiate, import, modify and diffuse new technologies' (Freeman, 1987). Since then, specific theories of sectoral (Malerba, 2002), technological (Bergek et al., 2008) and regional (Cooke et al., 1997) innovation systems have been added. Several studies have framed energy innovation systems (Newell, 2008; Gallagher et al., 2012), wind innovation systems, PV innovation systems, etc. Essentially, there are studies framed for every type of energy-supply technology, but no innovation systems framing for energy efficiency. When looking at the innovation activities in Denmark, it can however be discussed whether Christopher Freeman's definition (Freeman, 1987) can frame an energy efficiency innovation system similarly to energy-supply technologies.

Most innovation literature greatly simplifies the dynamics of the innovation processes in order to generalise research findings; in the extreme case, as just innovation inputs (e.g. research and development funding) and innovation outputs (e.g. products, patents, citations, etc.). In innovation system's literature, however, analysis is generally more holistic and empirically rich, with the emphasis on informing policy makers. Attention to formal and informal institutions is important in this study as it enables a more integrated view of policy and regulation (Kemp et al., 1998) and its role in supporting innovation and socio-technical change towards sustainability. This thesis furthermore uses theories from socio-technical systems and transitions literature to deeper analyse of the dynamics of innovation and change.

In the case of innovation activities for improved energy efficiency, only a few studies have been made. Some looked specifically at linking environmental policy and technological change in the cases of home appliances (Jaffe et al., 2002; Popp et al., 2010) and building components (Kemp, 1997; Noailly and Batrakova, 2010; Noailly, 2011). Despite these efforts to evaluate the technological change associated with energy efficiency, little attention has been given to the innovation dynamics of energy-efficient products.

1.3 RESEARCH RELEVANCE AND TIMING

With the current state of great environmental and economic challenges, policy makers are struggling with making policies that ensure long-term sustainable development and sustainable transitions while at the same time delivering economic growth and the creation of new jobs. Therefore, the need for research that tackles these issues is great.

This Ph.D. project contributes novel knowledge on how public policy best supports innovation and energy efficiency. It informs policymakers about theoretical and empirical findings in the topic and highlights the kind of policy experiences that have proven successful in the past, and builds policy recommendations from it. This provides input to how policies are best designed in order to support energy efficiency innovation and overall sustainable development. Specifically the study has relevance in the current policy discussions on setting a European energy-saving target, increased white certificate programmes as well as the Horizon2020 research and development funding programme.

1.4 RESEARCH QUESTIONS AND PROJECT SCOPE

This thesis makes a scientific contribution based on the scope of a main research question. The research question have guided the overall Ph.D. project with the three article contributions going deeper into subjects relevant to where specific knowledge gaps exist in the current literature.

> *How are innovation activities within energy-efficient technology characterised, especially with respect to the relations between public energy efficiency policy efforts and innovation?*

The geographical scope of the project will take its outset in Denmark as a part of the European Union in an international context. This is necessary because of Denmark's export based economy where Danish organisations, cannot be seen as isolated from external resources and ties. At the same time, Denmark also contains the historical characteristics necessary to include in an analysis of innovation dynamics (Wallace, 1995). This will be elaborated on in Chapter 5.

1.5 THESIS OUTLINE AND READING GUIDE

This article-based thesis concludes a three-year Ph.D. project as the main output. Chapter 1 acts a broad introduction to the context of the research contribution and the overall scientific and societal necessity of it. Chapter 2 positions the thesis in the literature on innovation theory and energy efficiency, and furthermore pinpoints the gap in the current literature. Chapter 3 summarises the research methods applied in the project and the coherence between them. Chapter 4 provides a quick overview of public policy efforts in energy efficiency and their impact on energy consumption. Chapter 5 provides a contextual introduction to Denmark and some of the Danish innovation activities within energy efficiency. The empirical material used in chapter 5 did not fit directly into a specific paper but was deemed relevant for the contextual understanding of the thesis. Chapter 6 contains an overview and summaries of the individual article contributions. Chapter 7 consists of the three individual papers – an additional conference paper is in the appendix. Chapter 8 discusses the findings of the three articles through three main topics and suggests issues for further research. Chapter 9 concludes with the work done in the Ph.D. project and its scientific contributions. Chapter 10 summarises the implications on industry and public policy. The thesis ends with an appendix containing an overview of interviewees, completed Ph.D. courses, participation in conferences, an additional case study within the ventilation industry as well as a conference paper (#4) relevant for the empirical context of the thesis.

2 THESIS POSITIONING

Chapter 2 consists of a three-part positioning in the literature. Part 1 presents the theoretical frameworks applied in innovation studies and how the thesis is positioned partly in innovation systems theory and partly in the theory of socio-technical systems and transitions. Part 2 reviews the literature on energy efficiency and introduces the important characteristics of the concept. Part 3 reviews the studies, specifically investigating the interrelations between energy efficiency and environmental policy, technological change and innovation.

2.1 THEORETICAL FRAMEWORKS ON INNOVATION AND SOCIO-TECHNICAL CHANGE

In industrial and post-industrial economies, innovation is a well-known driver for economic development and growth (Schumpeter, 1934, 1942; Arrow, 1962; Freeman, 1974). The '"new combinations" of new or existing knowledge, resources, equipment…' as Joseph Schumpeter (1934) defined innovation, is truly at the core of our economy and embedded into our industrial and social systems. Schumpeter also proposed that innovation was not merely about cost-reduction at the product level but was equally about new machinery (process innovation) or new ways of organising (organisational innovation). This has led to the four most well-known types of innovation – product innovation, process innovation, organisational innovation and marketing innovation (Malkin et al., 2005). These four types of innovation, however, only mostly apply to a firm's perspective and do not include wider societal interactions and change.

Schumpeter also emphasised the concept of creative destruction (1942), which explains how innovation kills existing technologies, products and markets, by making them obsolete. These concepts have since been used to assess the scale or impact of an innovation, leading to established dichotomies such as incremental vs. breakthrough (Tushman and Anderson, 1986) and conservative vs. radical (Abernathy and Clark, 1985). Schumpeter initially saw innovation activities occurring among entrepreneurs and new small entrants (Schumpeter, 1934). In his later work, however, he revised this to point out the link between a firm's research and development activities, innovation, and economic development (Schumpeter, 1942). These are now known as the Mark 1 and Mark 2 theories, where Mark 1 emphasises the role of entrepreneurial activity and Mark 2 emphasises the resource-intensive R&D capabilities in large firms.

Innovation was initially conceptualised and modelled with the aim of understanding its role modern industrial and post-industrial economies, but also for application in firms. This has led to numerous models of innovation. One of the original, but also much debated, models is the linear model of innovation. The linear model theorises innovation as Basic research → Applied research → Development → (Production and) Diffusion. This has the advantage of simplicity, but scholars agree that it is insufficient in explaining the complexities of innovation. The chain-linked innovation model developed by Kline and Rosenberg is widely recognised as one of the better models (Kline and Rosenberg, 1986) because of its more dynamic interaction between technology-push and market-pull (Peters et al., 2012) – see figure 4. Efforts to create better models of innovation are ongoing, e.g. the 5th generation innovation model (eg. Rothwell, 1994), but they tend to not reach wider application.

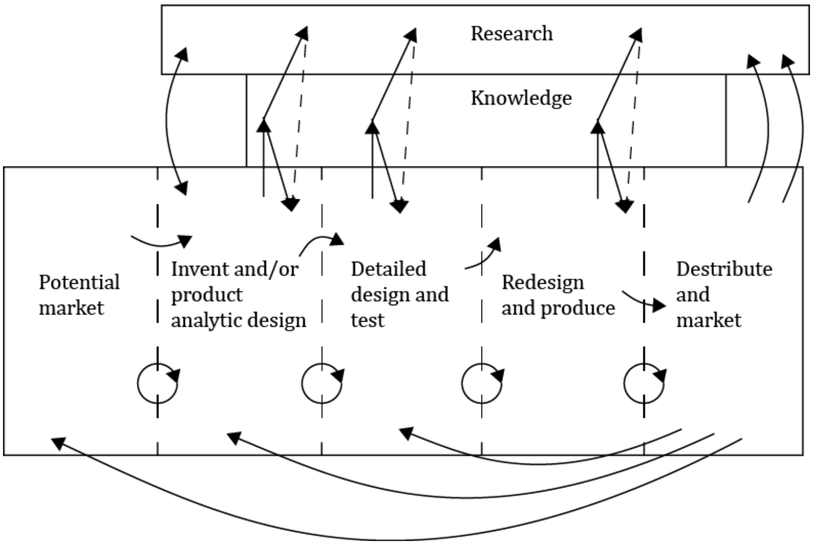


FIGURE 4 – CHAIN-LINKED MODEL OF INNOVATION - REDRAWN (KLINE AND ROSENBERG, 1986)

Innovation is a complex concept, referring to both an ambiguous and risky process (Van de Ven et al., 1999; Garud et al., 2013) as well as types of outcomes that can be more or less successful. Innovation models tend to remove these elements of risk and uncertainty, leaving an ideal picture of something that is rarely easy or straightforward. Socio-technical perspectives on innovation and change tend to be less positivistic about innovation activities and outcomes more dealing with the complexities and interactions involved.

At the level of firms and industries, innovation is seen as one of the main contributors to technological change, competitiveness and economic growth (Richard Nelson and Winter, 1982; Penrose, 1995). The operationalization of innovation at firm level, i.e. the management of R&D, innovation and allocation of resources, is, therefore, a key task for modern firms (Tidd et al., 2005).

2.1.1 THE SCIENTIFIC FIELD OF INNOVATION RESEARCH

Fundamentally, the overall field of innovation research consists of two different perspectives with different aims. On one hand, there are those that aim to explain *what innovation is?* On the other hand, you have those that aim to explain *how to innovate?* from a more practical perspective. This is basically the difference between the field of innovation studies (Fagerberg and Verspagen, 2008) and the field of innovation management (Tidd et al., 2005). As this thesis is primarily about what characterises innovation in a certain context, it lies primarily in the field of innovation studies and draws much of its theoretical understanding from science and technology studies (Callon, 1986; Bijker et al., 1987; Latour, 1988) to emphasise the heterogeneous networks of actors and relations involved in innovation.

The innovation studies field is a diverse scientific field based in social science and economics, where innovation management is more rooted in management and organisational science. The two fields do however share significant theoretical foundations. The innovation studies field is very broad, ranging from in-depth studies in innovation management to broad national and international studies in innovation systems. However, the majority of research is done at the meso- or macro-level, using statistics and econometrics on well-established datasets (e.g. Community Innovation Survey). Relatively few studies are made at the meso/micro-level with qualitative data and with attention to the differences between organisations and individuals. The trade-off is, as always, the ability to explain the determinants of a phenomenon – large studies might be generalizable but lack dynamics, and vice versa with micro-level qualitative studies (Pavitt, 1984).

2.1.2 INNOVATION SYSTEMS THEORY

In the late 1980s, several efforts went into investigating the increasing national competitiveness of Japan, which at the time was significantly outpacing the US and Europe in terms of economy and technological development (Freeman, 1987). This paved the way for research in national innovation dynamics and introduced the concept of a national innovation system (Lundvall, 1992; Nelson, 1993; Sharif, 2006). Some would even argue that it started earlier with inspiration from OECD development in the 1960s (Godin, 2009).

A key OECD report defines it as *'… national innovation systems rests on the premise that understanding the linkages among the actors involved in innovation is key to improving technology performance. Innovation and technical progress are the result of a complex set of relationships among actors producing, distributing and applying various kinds of knowledge. The innovative performance of a country depends to a large extent on how these actors relate to each other as elements of a collective system of knowledge creation and use as well as the technologies they use. These actors are primarily private enterprises, universities and public research institutes and the people within them. The linkages can take the form of joint research, personnel exchanges, cross-patenting, purchase of equipment and a variety of other channels.'* p.9 (OECD, 1997)

The innovation systems theory is based on an evolutionary theory of economic change, in contrast to conventional neo-classic economic theories of firms and economic growth (Richard Nelson and Winter, 1982). Innovation systems theory therefore also rejects the linear innovation model in favour of a more systemic understanding of innovation. In innovation systems theory, the emphasis is on flow of knowledge between public and private institutions. Whether the knowledge is science-based or practice-based (Jensen et al., 2007), the importance is on the creation and diffusion of new knowledge.

The evolution of innovation systems theory is linked with science and research policymaking and the work of the OECD (Sharif, 2006; Godin, 2009). These theories have always been aimed at informing policy makers through normative elements of how well-functioning national systems (Freeman, 1987) are characterised. This is especially articulated in the technological innovation systems theory, which argues that technological innovation systems consist of seven functions where system weaknesses can be found and remediated through policy (Carlsson and Stankiewicz, 1991; Hekkert et al., 2007; Bergek et al., 2008).

Since the introduction of the national innovation systems theory, several sub-theories have emerged from it: sectoral innovation systems (Malerba, 2002), regional innovation systems (Cooke, 2001) and technological innovation systems (Carlsson and Stankiewicz, 1991; Hekkert et al., 2007; Bergek et al., 2008).

This thesis uses innovation systems theory as one of its main theoretical foundations of how innovation *occurs* and in which collaborative and societal context. Furthermore, as pointed out by Smith et al., innovation systems theory is especially beneficial for the analysis of green technology because '*innovation systems analysis can help explain the relative success of specific cleaner technologies, analysis is often in a situation of needing to explain the difficulties of making such "green" innovation systems come about. Analysis needs to focus on the way broader contexts put pressure on innovation systems to become greener and inform their reconfiguration*' p. 438 (Smith et al., 2010). Elements such as selection environment, institutional setting and policy impact are crucial when analysing sustainable innovation where an industry or firm-level perspective will not suffice.

2.1.3 SOCIO-TECHNICAL SYSTEMS AND SUSTAINABILITY TRANSITIONS

This thesis also draws on theories and frameworks from the socio-technical systems and sustainability transitions literature. The transitions literature (Markard et al., 2012) has its outset in science and technology studies (Bijker et al., 1987; Hughes, 1987; Martin et al., 2012), evolutionary economics (Richard Nelson and Winter, 1982) and innovation systems (Freeman, 1987; Lundvall, 1992), among others. Transition researchers argue that specific theories, frameworks and concepts are required to analyse sustainability transitions as there are strong path dependencies, carbon lock-in (Unruh, 2000; Berkhout, 2002) and because *'established technologies are highly intertwined with user practices and life styles, complementary technologies, business models, value chains, organizational structures, regulations, institutional structures, and even political structures'* p. 955 (Markard et al., 2012); which certainly is the case in the energy sector with regards to energy supply, infrastructure and energy end-use (Sagar and van der Zwaan, 2006).

The core concept is based around the conceptualisation of socio-technical systems for analysing complex change processes. A socio-technical system *'… consists of (networks of) actors (individuals, firms, and other organizations, collective actors) and institutions (societal and technical norms, regulations, standards of good practice), as well as material artifacts and knowledge (Geels, 2004; Markard, 2011; Weber, 2003). 'The different elements of the system interact, and together they provide specific services for society'* p. 956 (Markard et al., 2012). This notion of a system consisting of both social and technical elements adds complexity to the analysis of change processes, and is crucial in the understanding of transitions. The actual change process or transition is seen as *'…a set of processes that lead to a fundamental shift in socio-technical systems (e.g., Geels and Schot, 2010; Kemp, 1994). A transition involves far-reaching changes along different dimensions: technological, material, organizational, institutional, political, economic, and socio-cultural. Transitions involve a broad range of actors and typically unfold over considerable time-spans (e.g., 50 years and more). In the course of such a transition, new products, services, business models, and organizations emerge, partly complementing and partly substituting for existing ones. Technological and institutional structures change fundamentally, as well as the perceptions of consumers regarding what constitutes a particular service (or technology)'* p. 956 (Markard et al., 2012).

In the sustainability transitions research field, there are four dominating theoretical frameworks that highlight specific aspects of sustainability transitions (Markard et al., 2012): the multi-level perspective (Geels, 2002), strategic niche management (Kemp et al., 1998; Smith and Raven, 2012), technological innovation systems

(Carlsson and Stankiewicz, 1991; Hekkert et al., 2007; Bergek et al., 2008), and transitions management (Rotmans et al., 2001).

The field of transitions research utilises a wide range of research methodologies, both quantitative and qualitative, but tends to apply a more mixed-methods approach than innovation research in general. Specifically, the scientific field relies on historical case studies to create narratives of long transitions (Geels, 2002). This thesis draws inspiration from the research methods applied in sustainability transitions research.

2.1.4 'ENERGY' IN INNOVATION AND TRANSITION STUDIES

The empirical context of energy and energy-related sectors has had some attention in innovation studies and transition studies. The study by Sagar and van der Zwaan (2006) describes innovation dynamics in the energy sector and emphasises the deployment and demonstration part of new innovative energy solutions as something that is crucial for innovation and the learning-processes in the energy sector. They do, however, also argue that these dynamics of the energy sector haven't received much attention in the current literature. There are different studies at diverse geographical levels and on numerous energy technologies, but as energy systems most often are of national character, so should the studies be. There are national, e.g. Denmark (Borup et al., 2009) and UK (Foxon et al., 2005; Foxon and Pearson, 2007), and an few international studies (Sagar and Holdren, 2002; Gallagher et al., 2006, 2012; Johnstone et al., 2009; GEA, 2012) using the innovation systems approach and they tend to emphasise the dynamics of national R&D[1] efforts, collaboration and market penetration of new energy-supply technologies. Also in the field of sustainability transitions research is energy technology, a common topic (Chappin et al., 2007; Verbong and Geels, 2007; Tainter, 2011; Markard et al., 2012; Araújo, 2014), and, in particular, the technological innovation systems perspective (Geels et al., 2008; Dewald and Truffer, 2011; Musiolik et al., 2012).

The coverage of empirical areas in renewable energy technology (solar, wind and biomass), fuel cell technology and mobility is therefore quite good. What these studies are missing is the end-use dimension of energy systems (Wilson et al., 2012; Kim et al., 2013). Energy efficiency and energy end-use are not common topics in innovation studies. Actually there are only a couple of instances where an innovation systems perspective has been applied on energy efficiency related technologies; e.g. on the residential building sector in the Netherlands (Beerepoot, 2007; Beerepoot and Beerepoot, 2007) and in the UK (Gann et al., 2010).

There are economic studies, mostly from a technological change perspective, that look at, for instance, household appliances (Jaffe et al., 1993, 2002; Popp et al., 2010) or building regulations (Noailly, 2011), but there have been no evolutionary or systemic innovation perspectives applied to any context involving energy efficiency. This illustrates a significant gap in the current knowledge concerning innovation and increased energy efficiency. Some of these studies will be presented more in-depth in Chapter 2.3.

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[1] The notions of R&D, RD&D and Research, development and demonstration are used interchangeably.

2.2 CHARACTERISING ENERGY EFFICIENCY

The second part of the thesis positioning chapter will go into the scientific literature on the characteristics of energy efficiency and why it tends to be a challenge to increase. These characteristics are important for the understanding of the challenging innovation dynamics of energy-efficient products.

There is a significant amount of literature on the social and economic aspects of energy efficiency, ranging from micro-level studies of energy use and energy savings to system-wide studies. This thesis attempts to utilise the existing knowledge concerning energy efficiency in order to understand its impact on the innovation dynamics of energy-efficient technology. It is therefore not a full review of the literature – please see Sorrell (2004) for a comprehensive overview.

2.2.1 CHARACTERISING INNOVATION IN ENERGY EFFICIENCY

At the product level, improved energy efficiency is merely an additional technical feature on top of the product's primary service, and only becomes an innovation if it has an impact on the market dynamics and selection parameters of consumers – whether '*the innovation appears superior to prior innovations fulfilling the same needs*' p. 155-156 (Shama, 1983). The challenge is whether increased energy efficiency is seen as a relative advantage or value proposition (Lanning and Michaels, 1988), which might be difficult because of the complementarity and energy-supply context dependence as pointed out by Shama: '*Energy conservation (i.e. energy efficiency) innovations may be used in various combinations with fossil fuels to 'provide' energy services such as space heating and cooling to the different sectors of the economy. In most cases, these services are presently provided by electricity, oil, and natural gas (...) Energy conservation innovations include a diversity of services, which may be applied, in combination with other fuels, to offer different end uses at different costs. Therefore, the advantage of a specific innovation such as attic insulation must be established relative to other energy services such as electric heat. An important aspect of establishing relative advantage is the availability of reliable audits, products, and installation services'* p. 156 (Shama, 1983). The complementarity of energy efficiency is a challenge when the consumer's primary aim is to save energy, regardless of where and how. But if the consumer is in a selection process where the products supply the same primary service, e.g. ventilate a house, then energy efficiency can become a preferable product feature. The analytical challenge is however that both of these dimensions play into the diffusion of energy efficiency innovations.

A user's perception, perspective and information level can make all the difference in determining the attractiveness of an energy efficiency innovation as *'relative advantage may relate to lower price, ease of use, reliability, and social desirability. This advantage, however, must be perceived as such by prospective users before adoption can take place. In view of the high potential/low adoption paradox, it may be concluded that many potential users are not aware of the relative advantage of energy conservation (i.e. energy efficiency). Consequently, policy makers and business executives interested in accelerating the rate of adoption of conservation energy must effectively communicate these relative advantages*' p. 156 (Shama, 1983). The final part of the quote frames the challenge for energy efficiency innovation well, a challenge that I will go deeper into in the following section.

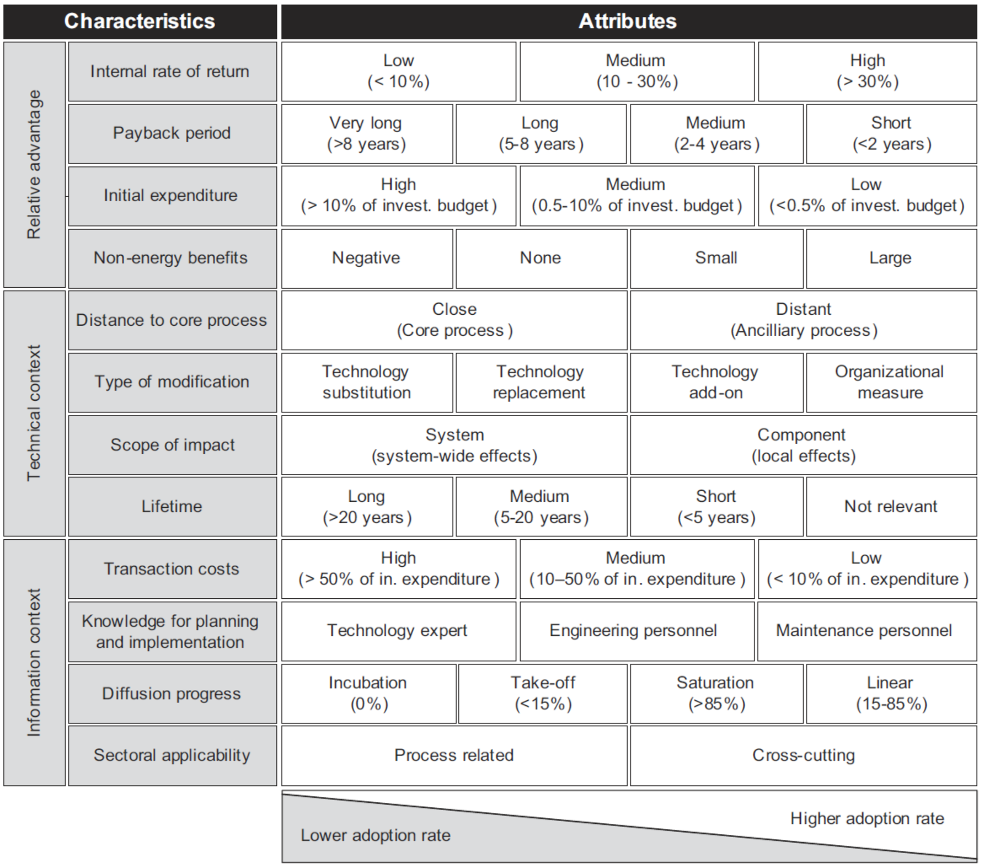
2.2.2 *THE DYNAMICS OF ENERGY EFFICIENCY – THE CHALLENGE OF BARRIERS IN DIFFUSION*

Increased energy efficiency and energy conservation are not new topics (Becker, 1974; Lovins, 1976; Darley, 1977); neither are the technologies involved nor the social and political challenges they pose. Since the 1970s oil crisis, when energy became an increasingly valuable resource, increased energy efficiency has been seen as having unrealised environmental and economic potential.

Despite the interest in energy efficiency after the oil crisis, it was quickly acknowledged that energy efficiency didn't increase as fast as techno-economic studies estimated. So despite the immediate economic, social and environmental benefits, energy-efficient products, services and practices were not readily adopted by households and industry. This challenge, termed the energy efficiency gap (Hirst and Brown, 1990; Reddy, 1991; Jaffe and Stavins, 1994) or paradox (Shama, 1983; Jaffe et al., 1993), illustrates the most difficult aspect of energy efficiency innovation.

The literature on energy efficiency explains this lack of diffusion using the notion of barriers towards energy efficiency. The literature on barriers is vast and wide-reaching, from economics, social science and political science (Hirst and Brown, 1990; Jochem and Gruber, 1990; Reddy, 1991; Sutherland, 1991; Howarth and Andersson, 1993; Weber, 1997; Brown, 2004; Sorrell, 2004; Fleiter et al., 2011; Ryan et al., 2011). Often these barriers are used as input for the development of public policy efforts (Shama, 1983; Lovins, 1992; Golove and Eto, 1996; DeCanio, 1998). In appendix 12.1, a full table provides an overview, dividing barriers into economic, behavioural and organisational. They do not necessarily have the same impact on all types of energy-efficient products and services, but most of them tend to limit diffusion of products across different sectors (Sorrell, 2004) and are, therefore, crucial for the innovation process of any innovation within energy efficiency. The same cannot be said for eco-innovations.

In order to assess the adoption pattern and rate of energy efficiency measures, Fleiter et al. (2012) proposed a classification scheme – see FIGURE 5. The scheme consists of twelve different attributes of energy efficiency measures in terms of their relative advantage, technical context and information context and characterises how these attributes then influence the adoption rate of the measures. This scheme should be seen in addition to a product's more common characteristics such as price, quality, maintenance, functionality, etc., and perfectly illustrates the complexity of products that compete both in their conventional markets as well as the market for energy efficiency and energy savings.



Characteristics		Attributes			
Relative advantage	Internal rate of return	Low (< 10%)	Medium (10 - 30%)	High (> 30%)	
	Payback period	Very long (>8 years)	Long (5-8 years)	Medium (2-4 years)	Short (<2 years)
	Initial expenditure	High (> 10% of invest. budget)	Medium (0.5-10% of invest. budget)	Low (<0.5% of invest. budget)	
	Non-energy benefits	Negative	None	Small	Large
Technical context	Distance to core process	Close (Core process)	Distant (Ancilliary process)		
	Type of modification	Technology substitution	Technology replacement	Technology add-on	Organizational measure
	Scope of impact	System (system-wide effects)	Component (local effects)		
	Lifetime	Long (>20 years)	Medium (5-20 years)	Short (<5 years)	Not relevant
Information context	Transaction costs	High (> 50% of in. expenditure)	Medium (10–50% of in. expenditure)	Low (< 10% of in. expenditure)	
	Knowledge for planning and implementation	Technology expert	Engineering personnel	Maintenance personnel	
	Diffusion progress	Incubation (0%)	Take-off (<15%)	Saturation (>85%)	Linear (15-85%)
	Sectoral applicability	Process related	Cross-cutting		

FIGURE 5 - CLASSIFICATION SCHEME FOR ENERGY EFFICIENCY MEASURES (FLEITER ET AL., 2012)

A market-based perspective on the diffusion challenges has recently gained attention in policy and academia (IEA, 2013b; Lutzenhiser, 2014). It follows the process of achieving energy savings by identifying where barriers are present and where policy efforts are required. FIGURE 6, by Morvaj and Bukarica (2010), illustrates the process from a potential energy-saving project to implementation and delivered savings. Acknowledgement of this process is important as energy efficiency improvement is not merely a question of choosing energy-efficient products or not. It has increasingly become a way of reducing the energy costs in households, or entire industrial production systems. The market-based perspective emphasises that a well-functioning market for energy savings will enable the diffusion of energy-efficient technology and practices.

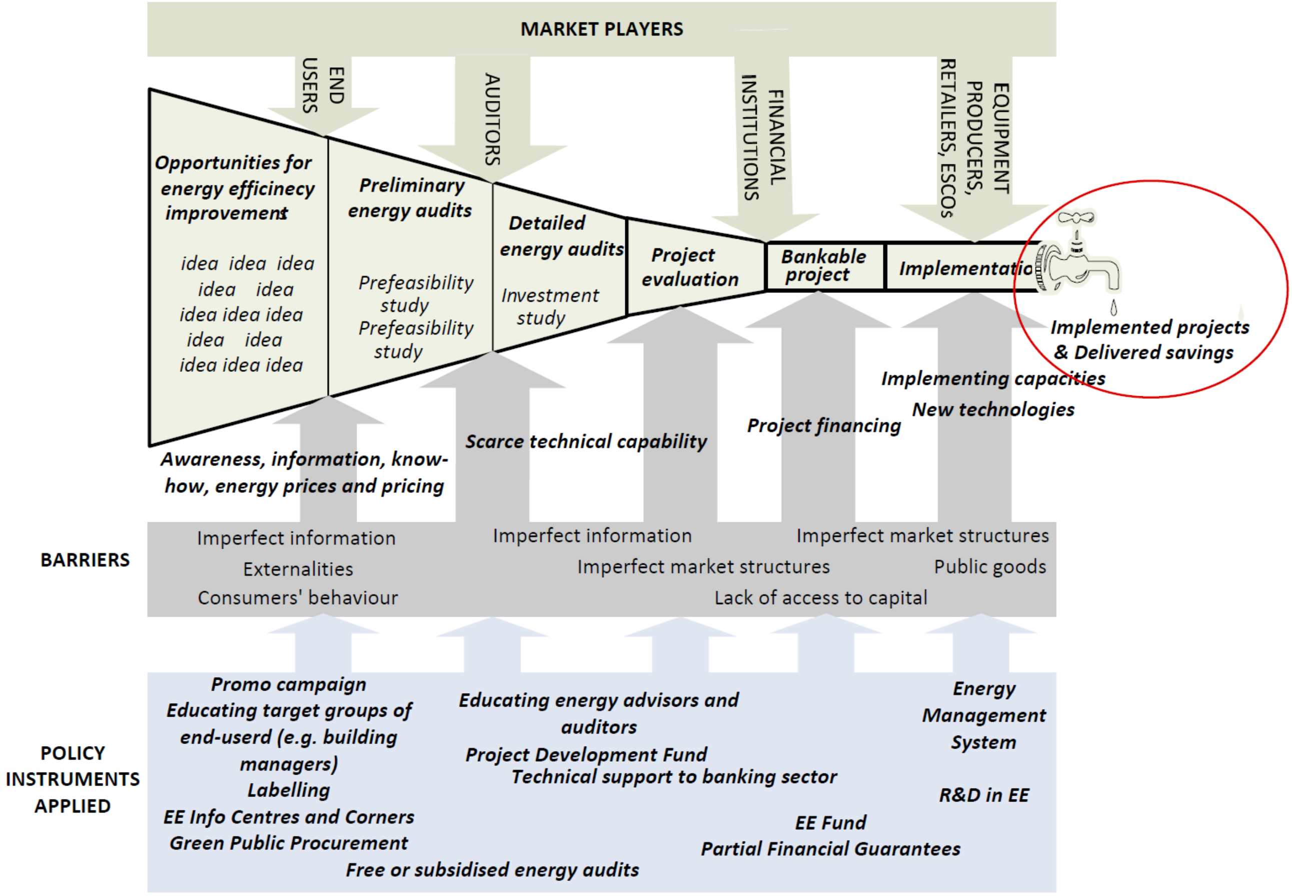


FIGURE 6 –DEFINING ENERGY EFFICIENCY POLICY INSTRUMENTS BASED ON ACTUAL STATUS OF SPECIFIC ENERGY EFFICIENCY MARKET (MORVAJ AND BUKARICA, 2010).

Here it is important to note the emergence of an energy efficiency industry, which Lutzenhiser defines as 'the coordinated actions of utility companies, government agencies, business firms, and non-profit advocacy groups in the process of producing EE as an output' p. 2 (Lutzenhiser, 2014). These are mostly new actors coming from engineering-related industries to utilise business opportunities through delivering energy savings. New policy efforts, like energy-saving obligations for energy companies, utilise this perspective to incentivise the market to deliver energy savings. The diffusion and adoption process of energy-efficient products is therefore becoming increasingly complex and difficult to analyse not to mention relating its success to individual policy efforts.

2.2.3 A GLIMMER OF SUCCESS – THE TRANSFORMATION OF MARKETS

Despite the challenges faced by energy-efficient products in their diffusion phase, there are some good examples of where strategically planned policy efforts have made a difference and a transformation of the market has occurred (Neij, 2001). These examples of market transformation in Europe are typically for appliances, consumer products and components where there have been significant changes in energy efficiency due to the implementation of energy ratings, labels and MEPS (minimum energy performance standards) (Bertoldi et al., 1999, 2012).

Geller and Nadel (1994; 1996) found successful examples market transformation programmes for refrigerators, fluorescent ballasts, compact fluorescent lamps, adjustable speed drives, personal computers, windows and automobiles in the US. They argue for complementary efforts in research and development; demonstration and field tests; commercialisation incentives; marketing and consumer education; grants, loans, and tax incentives; voluntary commitments; bulk purchases; building codes; and equipment efficiency standards. Furthermore, they argue that successful market transformations occur because '*governments, utilities, and the private sector have taken complementary actions (consciously or unconsciously) involving (a) R&D to develop new energy efficiency measures, (b) market-pull or bulk purchase programs to facilitate commercialization, (c) financial incentives to stimulate early adopters, and (d) efficiency codes and standards to eliminate inefficient technologies and practices. These interventions influenced all phases of the diffusion process and resulted in continuous and large-scale efficiency improvements*' p. 336 (Geller and Nadel, 1994). Please see Paper #1 on page 52 for an elaborate case on market transformation in the circulator pump industry.

Ideally the effect of the market transformation policies should resemble FIGURE 7, which shows how the complementary use of labels, technology procurement, rebates and efficiency standards can change market dynamics towards higher efficiency. These are policy types, which are targeted and communicate directly to the consumers to change purchasing behaviour, and thereby have an impact on market dynamics.

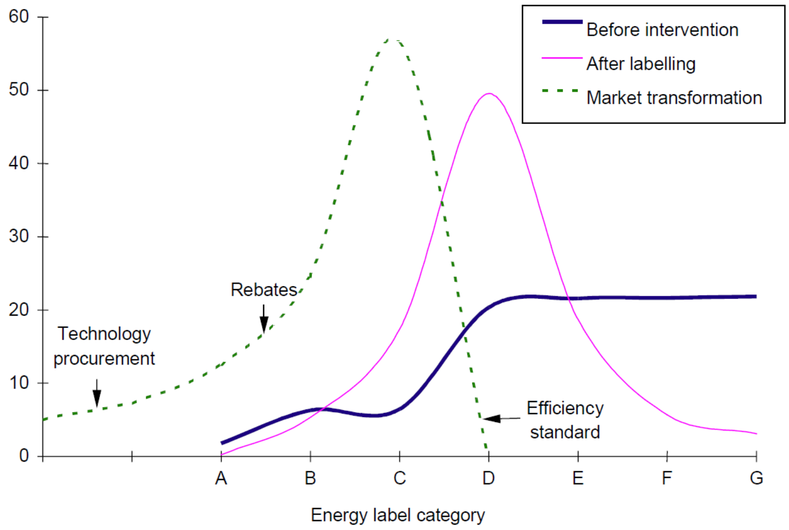


FIGURE 7 - MARKET TRANSFORMATION (PERCENTAGE OF MODELS IN STOCK) (BOARDMAN ET AL., 1997; BOARDMAN, 2004B).

The UK experience with product policies shows similar results to the US (Boardman et al., 1997; Boardman, 2004a, 2004b), although they argue for stricter and more ambitious policies in order to achieve market transformation. '*European market transformation policy is progressing too slowly and needs revitalising: for instance the decisions on the new energy label are weak and very late. The most effective policy—minimum standards—is being replaced with the much weaker industry-promoted voluntary agreements*.' p. 1931 (Boardman, 2004a). Boardman argues that neither market-pull nor technology-push can be relied upon to deliver energy savings without strong policies (Boardman, 2004b). Some argue for even stricter long-term product standards or technology forcing standards (4E - IEA, 2012) to be used for market transformation programmes. These policies go beyond current technologies, and set goals for future technologies in order to push the manufacturers to introduce more-efficient products. These approaches are rarely seen in practice but are very interesting from an innovation perspective to create long-term development trajectories for industry.

These challenges were investigated by Shama (1983) in a diffusion of technology perspective inspired by Everett Roger's work on diffusion curves (2003). This was before market transformation literature gained traction but his findings illustrate well the intended impact of different energy efficiency policy efforts on the diffusion of energy-efficient technology – see figure 8 on the following page. This is one of the best examples in literature of how energy efficiency innovation is struggling with diffusion and how policies assist and impact specific challenges in the diffusion phases. Despite the age of the Shama's work, the potentials, challenges and policies remain the same today.

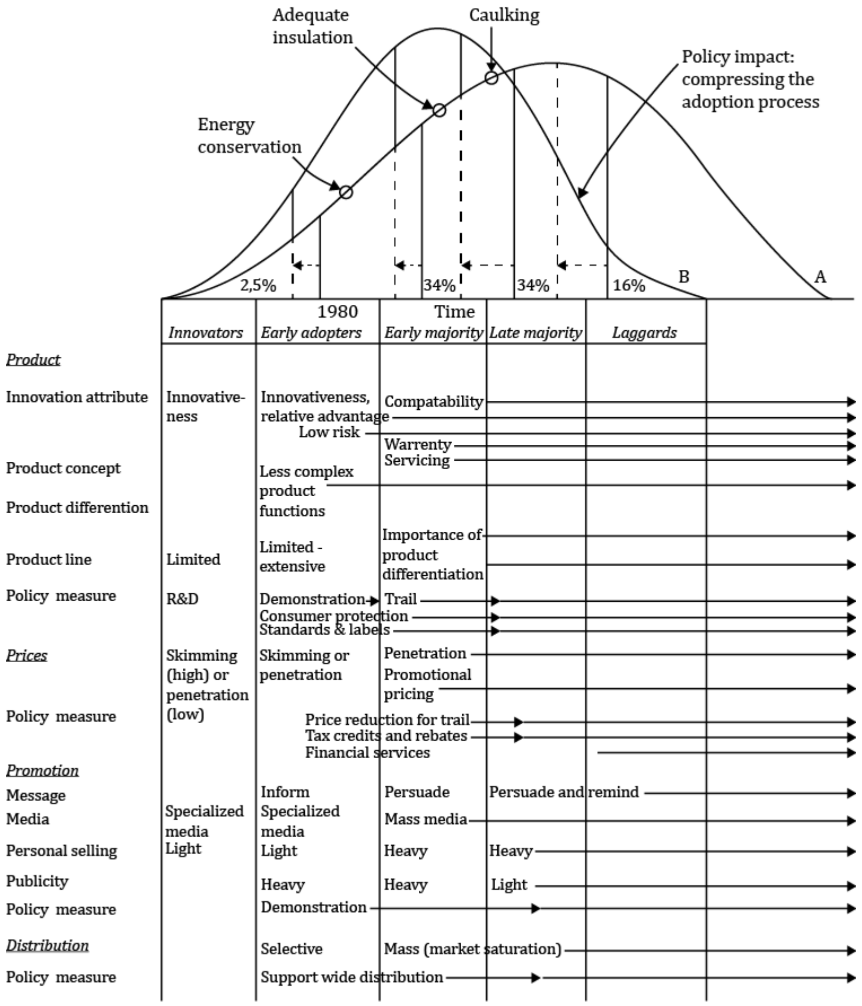


FIGURE 8 –DIFFUSION PATTERNS OF ENERGY EFFICIENT PRODUCTS AND THE ROLE OF POLICY IN MARKET TRANSFORMATION

(SHAMA, 1983)

2.3 ENERGY EFFICIENCY, POLICY AND INNOVATION

When investigating the existing knowledge on energy efficiency policy and its relationship with innovation, the literature is rather scarce. The following review will therefore broaden the scope to also include environmental policies in general.

Michael E. Porter and Claas van der Linde made quite a stir in both business and academia when they proposed that environmental regulation could have a positive influence on the competitiveness of firms and innovation (Porter and Linde, 1995a, 1995b). They argued that properly designed environmental standards could trigger innovation, which would partially or fully offset the cost of complying with them. This was later regarded as Porter's win-win hypothesis, a "phenomenon" that has been tested numerous times by empirical studies (Wagner, 2003; Kriechel and Ziesemer, 2007; Ambec et al., 2011; Lanoie et al., 2011) without fully confirming or disproving the hypothesis (Ambec et al., 2011). This discussion is also framed as whether environmental policy or public policies in general can have innovation-inducing effects.

Empirical studies tend to show varying effects of policy on technological change, depending on the products and their characteristics (Newell et al., 1999; Chappin et al., 2007). A large review of the literature by Jaffe et al. showed conflicting results (Jaffe et al., 2002; Popp et al., 2010) but overall concluded that empirical evidence and theoretical findings indicate that market-based instruments for environmental protection are likely to have significantly greater, positive "innovation-inducing" impacts over time than command-and-control approaches on the invention, innovation, and diffusion of desirable environmentally-friendly technologies. These results do, however, somewhat contradict their own earlier findings (Newell et al., 1999) and empirical studies from the energy- efficiency market transformation literature. In support of the market transformation literature, they also found support for the impact of product labels in conjunction with rising energy prices on the substitution of inefficient products for more efficient ones.

Much of the theoretical literature compares and discusses the effects of market-based policies (taxes, permits, deposit-refund schemes, etc.) relative to direct regulation (technology-based controls, performance standards, input bans, etc.) on technological innovation. Here it is typically argued that market-based policies more efficiently encourage firms to innovate, hence creating a higher rate of technological change (Johnstone, 2005; Chappin et al., 2007; Johnstone et al., 2009). In empirical studies these findings differ, partly because of two elements (Hemmelskamp, 1997). Firstly, the theoretical perspective does not include the environmental policy process, which usually includes interaction between legislators, federations of business enterprises, trade unions, firms, the public, etc. A process is known to have mediating and cost-reducing impacts as knowledge is actively shared (Georg et al., 1992). Secondly, firms must be realistic and do not only consider environmental policies. Their R&D and innovation activities are continuously impacted by factors such as market structure, demand changes and technological opportunities (Hemmelskamp, 1997) as well as other policies. In practice, the theoretical and empirical studies tend to simplify both the policy process and the landscape of policies impacting industries and firms, which is often called the policy mix. These more complex dynamics of policy processes are also found in our own empirical work – see paper #1 on page 52 and the case description of the ventilation case in the appendix.

A recent and comprehensive literature study by Kemp and Pontoglio analysed four strands of literature; theoretical models on incentives for eco-innovation, econometric studies based on observed data, survey analysis based on stated information and technology case studies (2011). They propose five synthesised findings:

1. *'We should not talk about innovation and environmental innovation in an unqualified way,'* meaning that innovation can take different forms. Where econometric studies tend to use patents in innovation analysis, we know that this does a poor job of covering a firm's innovation activities. In energy efficiency in particular, the technologies are typically quite mature and most firms do not patent new products.

2. *'The link between regulator and regulated is not unidirectional and that innovation is affected by multiple policies.'* This finding argues that the stimulus–response model is too simple as it assumes that environmental innovation starts with a regulation or some other policy. In practice these policy processes are interactive and iterative – arguments also posed by Hemmelskamp (1997). Furthermore, the single-policy perspective is not representative of a real-world context, where several policies impact the environmental innovation. For example, Fisher et al. found that environmental and technology policy work best in tandem (2003).

3. *'Impacts of environmental policy instruments on innovation may depend more on design features than on the type of instrument chosen.'* Their third finding emphasises the importance of the different features in environmental policy, e.g. stringency, predictability, timing, enforcement, etc., which has been shown to equally impact the innovation. E.g. there can an anticipation effect of environmental policy known to increase patenting (Taylor et al., 2005a) in response to upcoming policy.

4. *'There is not one single best instrument to foster innovative response to environmental regulations.'* Here the common understanding in theoretical studies is that market-based instruments are more effective, but this might only be the case for incremental innovation. Technology-specific regulation, for instance, has been found in several studies to more efficiently encourage radical innovation (Ashford et al., 1985; Taylor et al., 2005b; Bergek and Berggren, 2014).

5. *'Environmental policy can have both a positive and a negative influence on the development and adoption of particular environmental innovations.'* They argue that the effects of environmental policies are not clear-cut but can impact both positively and negatively. This is an element that has not received much attention in academia.

The cost and outcomes of innovation activities are rather uncertain for firms. So, theoretically, command-and-control policies can reduce the technological uncertainty for firms and thereby reduce their transaction costs when integrating new technologies (Anderson et al., 2006). This hypothesis is neither confirmed nor disregarded in the current literature; it is, however, not always the case that bans and strict regulations clear or "correct" technological trajectories (Gerard and Lave, 2005). What is known is that stringent and ambitious environmental policies in combination with a strong national innovation system on export performance of energy technologies (Costantini and Crespi, 2008) have a positive impact. It has even been proposed that in a situation of global demand or regulatory trends, strict regulation results in the creation of lead markets (Beise and Rennings, 2005). The dynamic of strong policy efforts in combination with a strong national innovation system seems to be behind some of the historical developments in Denmark – more on this aspect will follow in Chapter 4.

At the firm level, a study from Germany finds that firms whose innovation is driven by environmental regulations benefit equally in terms of sales as with other types of innovations (Rennings and Rammer, 2011). The actual impact differs greatly in different sectors, and also depends on the size of the firms (Smith et al., 2002). These findings are complemented by a later study that shows that innovations that increase energy efficiency or lower resource consumption have a positive effect on firm competitiveness, whereas those that lower externalities negatively affect competitiveness (Ghisetti and Rennings, 2014).

When investigating the impact of environmental policy on innovation using a long-term national perspective, Wallace (1995) found through the analysis of policy strategies in Europe, the US and Japan that *'innovation can be successfully harnessed by setting credible, long-term environmental goals and ensuring that regulatory instruments are grounded in flexibility, dialogue and trust*.' This study emphasised the institutional context in countries as the key to their innovative output, much like the innovation systems literature (Freeman, 1987; Lundvall, 1992; Nelson, 1993).

If we look further into specific studies of the influence of energy efficiency policy, there are a few interesting studies concerning the building sector. Gann et al. (2010) discuss whether performance standards at the building level or prescriptive standards at the product-level encourage innovation. They argue that performance standards, which pose demands at the building level but don't choose technologies, are best at encouraging systemic innovation, whereas prescriptive standards encourage product innovation at the building-component level. They furthermore conclude by saying *'it is possible, however, to envisage a new regulatory process in which the order caused by standards can create a stable and supportive environment for focused change. Strict standards could be used to induce market demand for high-performance emerging technologies. This could compel firms to innovate to meet requirements, which are deliberately too strict for current technology. A flexible "performance-based" form of standard would allow firms the freedom, market incentive and institutional framework within which to innovate'* p. 293 (Gann et al., 2010). This quote clearly points to the complexity of a firm's freedom to innovate versus the certainty of a firm's innovation direction.

Kiss et al. found that building codes were important drivers of technological development as well as interaction between actors in the mineral wool innovation system in Germany, UK and Sweden (Kiss et al., 2013). They showed that financial incentives and information was crucial for learning and the development of knowledge in the building sector. Table 1 is their assessment of how multiple policies impacted the development and diffusion of insulation material – which undoubtedly applies for most technologies and products related to energy efficiency and energy savings.

TABLE 1 - THE INFLUENCE OF POLICY INSTRUMENTS ON RELEVANT FACTORS DESCRIBING TECHNOLOGY DEVELOPMENT, AND ACTORS AND NETWORKS (KISS ET AL., 2013).

Development	**Technology**	**Policy instruments**			**Actors and networks**		
	Direction of search	R&D resources	Mgt. of new knowledge	Testing	Sophisticated user group	Form of producer-user interaction	Proximity and mutual interest of actors & networks
R&D		(+)		+			+
EPBD		+					+
Building codes:							
- Early building codes	+	+	(+)				
- EPBD-induced building codes		+				(+)	+
Standards				+		(+)	
Financial incentives					+	+	+
Information					+	+	
Voluntary standards	+	+	(+)	+	+		+
Testing	+			+			+
Education & training					+	(+)	+

+ direct influence; (+) indirect influence.

A recent econometric study also investigated the role of building codes in inducing innovation in the building sector by looking at patents (Noailly and Batrakova, 2010; Noailly, 2011). Here they found that a 10% increase of the insulation demands in the building codes in Austria, Belgium, Denmark, Finland, France, Germany, Ireland, Netherlands and the UK resulted in a 3% increase in patenting. Furthermore, energy prices seemed to have no influence while governmental R&D had a small influence on the patenting. These are quite interesting results as it known that Danish firms seldom patent their innovations but are still highly innovative in energy efficiency (Borup et al., 2009). The danger of these long-term incremental policies is however that it might also hinder the transition to more sustainable building practices (Hagelskjær Lauridsen and Stissing Jensen, 2013)

A recent study furthermore found that the comprehensive European policy efforts in eco-design and energy labelling directives have an positive impact on innovation, illustrated by a correlation between the ambition level and stringency of policy requirements and the innovation impact (Braungardt et al., 2014).

The comprehensive literature on the relationship between environmental policies and innovation is not all coherent. The predominant understanding is however that environmental policy and energy efficiency policy in some cases *can* have a positive impact albeit a small one. The discussion continues on the effectiveness of specific policies. Whether market-based or command-and-control type policies are best for the firms (in terms of cost and flexibility) and the environment is impossible to determine and will depend on multiple factors such as sector, industry, technology, users and market.

3 RESEARCH METHODOLOGY

The research methodology applied in this Ph.D. project is not common in innovation studies. As I have more experience with qualitative research methods (Yin, 2009) through an educational background in Design Research and Engineering Design, the overall approach in the Ph.D. has therefore been a mixed-methods one, combining qualitative and quantitative methods. The Ph.D. project is also seen as learning period, which is why some time has been used on learning new research methods and theories. See an overview of completed Ph.D. courses on p. 139.

The mixed-methods approach refers to a pragmatic use of both quantitative and qualitative research methods and is defined as 'an approach to knowledge (theory and practice) that attempts to consider multiple viewpoints, perspectives, positions, and standpoints (always including the standpoints of qualitative and quantitative research)"'p. 113 (Johnson et al., 2007). The emphasis of the work in the project is on gaining insight into the phenomenon or topic framed through the research questions in Chapter 1. Using a mixed-methods approach is known to increase the understanding, richness and robustness of an analysis (Rossman and Wilson, 1985) and involves a mix of cross-methodological triangulation (Webb et al., 1966; Denzin, 1978; Jick, 2013), a well-known triangulation method for obtaining valid analysis; qualitative research, usually used for theory building; and quantitative research, which is used for theory testing.

The study uses iterations between deductive and inductive approaches, which in practice means that the direction of the research is based on continuous theoretical and empirical insights. This approach is especially useful when insight into a less well-known phenomenon is desired, which was deemed the case in this thesis. Overall the project is very inspired by the longitudinal case study (Yin, 2009) approaches established in recent transitions literature (Geels, 2002; Geels and Kemp, 2007). In particular Geel's approach which builds on the history of technology studies and science and technology studies, with emphasis on strong and detailed narratives has been an importance source of inspiration. The inspiration is explicitly seen paper #1 (Ruby 2015).

The following two sections will present an overview of the qualitative and quantitative research methods applied in this Ph.D. project.

3.1 QUALITATIVE RESEARCH METHODS

Qualitative research methods are well used in social science and management studies (Eisenhardt, 1989; Brown and Eisenhardt, 1995). As mentioned, qualitative research methods are desirable when there is little theoretical knowledge concerning a topic or phenomenon. Throughout this Ph.D. project, qualitative research methods have contributed insights concerning the phenomena of energy efficiency innovation and policy.

In this thesis, the following qualitative research methods have been used.

> Semi-structured interviews

The project has used empirical data collected through interviews to gain insights into the reality of the phenomena as defined by those actors involved in it. Semi-structured interviews have been carried out with businesses, institutions and civil workers in governmental agencies. These interviews have been used for input into almost all other research activities. See full list of interviewees on p. 136.

> Industry magazine analysis

To gain insight into the project-related industries, national and international industry magazines and technical magazines have been systematically read. These have given both an historical and contemporary understanding of the industries. The following magazines have been systematically analysed: ***World Pumps*** (Elsevier), ***Pump Industry Analyst*** (Elsevier) and ***HVAC Magasinet*** (in Danish). Furthermore, participation in industry fairs and exhibitions has also been carried out in order to meet and informally interview industry actors.

> Relevant reports and studies from policy or industry actors.

The data and information in relevant policy and industry reports have been used as empirical data in the project. This is especially helpful in defining historical events and building narratives. See the second paper – p. 52.

> Case study methodology

The framing of the qualitative data has been done through a longitudinal case study setup (Yin, 2009), where an historical or event-based narrative is constructed from several data sources. In the case study setup, both qualitative and quantitative data sources are used to support the narrative (e.g. descriptive statistics).

3.2 QUANTITATIVE RESEARCH METHODS

The use of quantitative research methods has the clear advantage of giving clear and concise results in the analysis of complex problems. In this thesis, quantitative methods are used to create insights into meso- and macro-level dynamics; for instance, in collaborative processes in public research and developments projects. Here the quantitative research methods ability to provide generalizable results is of great importance. Quantitative methods are, however, only as good as the data permits, which is why a significant amount of time in the project has been used on data collection and data organising.

In this thesis the following quantitative research methods have been used.

> Social network analysis

Social network analysis (Burt, 1976, 1980; Wasserman and Faust, 1994; Scott, 2000) is a way of quantifying relational networks and is mostly used in the social sciences. In this thesis it is used in an explorative manner on public RD&D projects in energy efficiency to investigate *who* and *how* actors are collaborating. This gives tremendous insight into the structures of collaboration and how knowledge is flowing in the innovation system. See paper #4 for more on the application of social network analysis.
For an overview of the little used social network analysis in innovation research, see Coulon (2005).

> Keyword analysis

The substantial amount of empirical data found in industry magazines was also used to make a simple keyword analysis in order to investigate how certain topics had increased or decreased in interest in the industry media.

> Online questionnaire

Initially in combination with social network analysis and research project data, an online questionnaire was made for the project managers of the ELFORSK funding programme. The questionnaire was made using the open source software LimeSurvey based on a simple setup of one page per project. This led to interesting questionnaire data of which a small part was used in the econometric study – see paper #3. Descriptive statistics based on the questionnaire will also be presented in Chapter 5.2 on page 39.

> Statistics and econometrics

To analyse the determinants of a successful project output from public RD&D projects, a binary logistic regression was completed in the IBM SPSS software. The database from public research project records was combined with the online questionnaire to analyse how different diversity and collaboration patterns had an impact on the output of the projects. See paper #3.

The study uses the ELFORSK public RD&D programme in two of the included papers. This is primarily done in order to keep a consistent framing of the innovation activities which is a challenge when dealing with energy efficiency efforts. Please see paper #2 and #3 for elaboration of the funding programme and how its application has advantages and disadvantages.

4 POLICIES FOR INCREASING ENERGY EFFICIENCY

Attention to energy efficiency and energy savings essentially began with the global energy crisis in the 1970s; before this there was no broad interest in lowering the demand for energy. The economic and social shock to the system meant an instant shift in energy policy towards energy security, self-sufficiency and grid stability. In terms of policy, this led to the implementation of building codes in Denmark, UK, France and Germany, among other European countries, to set energy efficiency demands for new buildings. In the case of Denmark, this also led to exploration of oil and gas in the North Sea as well as research, development and demonstrations in favour of renewable energy and energy efficiency.

In the 1990s, resource depletion and climate change began to have some impact on energy policy. With the 1992 United Nations Conference on Environment and Development in Rio and the annual United Nations Climate Change Conference, from 1995, some of these issues started to attract attention at the top political level, although without making a major impact on policy, consumption or emissions. The 1997 UN Climate Change Conference in Kyoto, Japan, did lead to the Kyoto Protocol, which gave binding targets for greenhouse gas emissions and introduced mechanisms such as emissions trading.

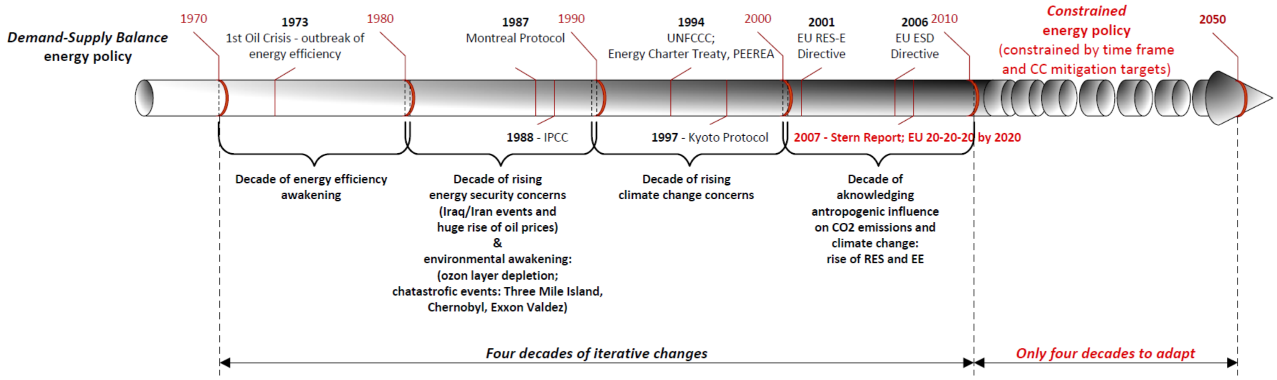


FIGURE 9 - GRADUAL CHANGES OF ENERGY POLICY ACCENTS DUE TO VARIOUS DRIVERS (MORVAJ AND BUKARICA, 2010)

Since the 1990s, none of these environmental challenges have been resolved and they are ever higher on the political agenda. In the last decade, the approach has changed from acknowledgement of environmental issues to taking action, which is focusing political, economic and societal attention on renewable energy and energy efficiency. The current drivers of energy efficiency policy therefore are energy security, economic development and competitiveness, climate change and public health (IEA, 2010).

4.1 CHARACTERISTICS OF ENERGY EFFICIENCY POLICY

Since the 1970s, energy efficiency improvements have been known to lower the consumption of energy (Shama, 1983; Lovins, 1992). For instance, insulating and tightening your house has long been known to be a proven energy efficiency measure. But energy efficiency improvements do not happen automatically. According to the energy efficiency literature, barriers either slow or halt their diffusion, and overcoming these barriers is generally seen as a challenge for public policy. See Chapter 2.2 for an overview on the literature on energy efficiency barriers.

Energy efficiency policies are goal-orientated by nature, with the main policy aim the achievement of energy savings. Typically, efforts are directed at focus areas where energy consumption is high or where energy savings are easily addressed through policy.

When characterising energy efficiency policies, there are five dimensions deemed important in this thesis: policy focus, refers to the focus area where the energy savings are desired; policy type, refers to the type of policy – whether economic (e.g. taxation, rebates, etc.), normative (e.g. regulation, appliance standards, etc.) or informative (e.g. information campaigns, labels, etc.) (Togeby et al., 2009a, 2011); policy level, refers to whether the influence is at the system-, product- or component-level; policy aim, which is not always obvious but whether policies are directed towards new technological development or whether they are more directed towards the market and diffusion of existing products is relevant; and, finally, policy strength, as it is important to distinguish between voluntary and mandatory agreements. These dimensions are useful for characterising single energy efficiency policies. In practice, however, there is more of a mix of policies impacting at different levels on energy efficiency innovation.

TABLE 2 – SIMPLIFIED CHARACTERISTICS OR DIMENSIONS OF ENERGY EFFICIENCY POLICY EFFORTS (AUTHORS INTERPRETATION)

Policy focus:	**Policy type:**	**Policy level:**	**Policy aim:**	**Policy strength:**
Households	Economic	System-level	New technology focus – R&D and innovation	Voluntary
Industry	Normative	Product-level	Market focus - Diffusion of existing products	Mandatory
Transport	Informative	Component-level		
Cross-sectoral	Public RD&D funding			

4.2 NATIONAL, EUROPEAN AND INTERNATIONAL POLICY EFFORTS

The following will provide an introduction to current energy efficiency policies at different institutional and government levels. It will not be an exhaustive list, but merely an overview to aid understanding in the thesis – for a complete review, see the IEA Energy efficiency Policy database (IEA, 2014a) and selected reports (Jochem and Gruber, 1990; Geller et al., 2006; Gillingham et al., 2006; Doucet, 2008; Bertoldi et al., 2012). For reviews at the industry level, see (Tanaka, 2011; Thollander and Palm, 2013); and for household level, see (Gillingham et al., 2006).

Table 3 contains an overview of the current policies for the European Union, Japan and the United States. Other countries have implemented similar energy efficiency policies, but those in the table represent the most ambitious policy strategies. The specific Danish policy efforts will be presented more in-depth in Chapter 5.

TABLE 3 – OVERVIEW OF KEY ENERGY EFFICIENCY POLICIES THAT ARE CURRENTLY IN PLACE BY REGION AND SECTOR – ADAPTED FROM (IEA, 2012)

	European Union	Japan	United States
Cross-sectoral			
Energy efficiency strategy or target	EU Energy efficiency Directive agreed; National Energy efficiency Action Plans required; EU-level target to reduce primary energy consumption by 20% in 2020; EU ETS; White certificates schemes in Italy, UK, Denmark and other member states.	None	None
Buildings, appliances, equipment and lighting			
Building energy performance requirements	Building energy performance requirements for new buildings (zero-energy buildings by 2021) and for existing buildings when extensively renovated; 3% renovation rate of central government buildings.	Voluntary guidelines in place.	Mandatory energy requirements in building codes in some states.
Energy labelling	Labelling mandatory for sale or rental of all buildings and some appliances, lighting and equipment.	Voluntary buildings labelling; national voluntary equipment labelling programmes.	Voluntary buildings labelling; mandatory and voluntary labelling for some appliances and equipment.
Equipment energy performance requirements	15 product groups in EcoDesign Directive, further product groups planned; phase-out of incandescent light bulbs.	Top Runner programme: 23 products covered.	45 products covered.
Industry			
Energy management programmes	Voluntary agreements in place or planned in many countries.	Periodic energy audits and nationally certified energy managers for large industries.	Voluntary energy management programme for the implementation of ISO-50001.
MEPs for electric motors	IE3 for 3-phase induction motors < 7.5 kW by 2015; all IE3 (IE2 + variable speed drive) in 2017.	Adding 3-phase induction MEPs to Top Runner programme.	Premium efficiency (IE3) MEPs for 3-phase induction motors.

The IEA recommend and evaluate the efforts of member states (IEA, 2011; Pasquier and Saussay, 2012) based on 25 policy recommendations within the following seven focus areas; cross-sectoral, buildings, appliances and equipment, lighting, transport, industry, energy utilities. In the recent years, an increasing number of policies have been implemented but there are still many recommendations that have not been followed up on. Policy efforts do of course differ significantly from country to country, which also applies to within the European Union.

Energy efficiency policies tend to be incremental. An example of the incremental change for energy efficiency requirements since the 1970s is seen in the national building codes - see FIGURE 10.

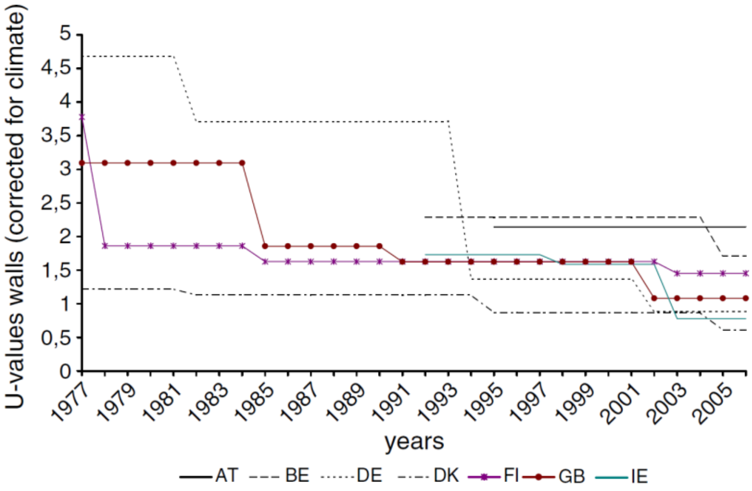


FIGURE 10 - THERMAL INSULATION STANDARDS, U-VALUES WALLS, CORRECTED FOR CLIMATE (NOAILLY, 2011).

Several countries implemented insulation requirements in the 1970s and have since adjusted them. Besides the mandatory standards, several voluntary standards have also appeared, e.g. the Passive House standard in Germany. Building codes have changed significantly. From being mostly about insulation and windows, they now address a more complex system of several heating sources, solar panels, mechanical ventilation, etc. (Guerra-Santin and Itard, 2012).

Recently the policy efforts in energy efficiency have been more strategic, integrated and comprehensive. An example of this is the Eco-Design Directive for energy-using products and energy-related products, which is a framework that allows for design and efficiency requirements for more than 40 product categories. This level of integration is also present in broader climate and energy agendas, as is the case with the recent Danish Energy Agreement 2012-2020, which covers both production and consumption of energy in relation with greenhouse gas emissions. This is in line with the recently published report on energy efficiency governance by the IEA, which recommends a more comprehensive and strategic approach to energy efficiency policymaking. See Table 4 below for a checklist on energy efficiency governance strategy.

Checklist for an Energy efficiency strategy
Take a long-term, high-level view, but supplement with shorter-term and more pragmatic action plans
Have a strong analytic foundation
Articulate purpose, goals and objectives
Incorporate quantitative time-bound targets, both long-term and short-term
Identify internal and external factors affecting success
Be comprehensive and cross-sectoral
Ensure integration with other policy areas
Identify the resources needed to turn strategy into action
Prioritise consuming sectors and policy measures
Identify actions and assign responsibility
Provide for results monitoring, updating and revisions
Facilitate stakeholder engagement and build political consensus

TABLE 4 - CHECKLIST FOR AN ENERGY EFFICIENCY STRATEGY (IEA, 2010)

Besides the policy efforts becoming more integrated, there is also increasing attention towards market-based approaches, as, for example, with ESCO programmes, energy-saving obligations for energy companies (white certificates) and energy audits (Anderson and Newell, 2004). These approaches apply the market perspective on energy efficiency improvements with the aim of creating policies to support well-functioning markets for “selling” energy savings (IEA, 2013b; Lutzenhiser, 2014). These efforts are complementary with the existing policy mix, and draw increasing attention to the removal of barriers to energy efficiency.

4.3 IMPACTS AND FUTURE POTENTIALS OF ENERGY EFFICIENCY POLICY ON ENERGY CONSUMPTION

The main goal of energy efficiency policy is to reduce overall energy consumption. It is estimated that energy efficiency policies since the 1970s have reduced 63% of the hypothetical consumption in IEA member countries (Pasquier and Saussay, 2012). These figures are quite substantial, but are attributed to energy policy efforts only and should not be taken for actual savings. Globalisation has also had a major impact on the energy intensity of industrialised nations.

Actual studies of individual policy efforts, for instance, on building performance, do not give a clear picture (Guerra-Santin and Itard, 2012; Jacobsen and Kotchen, 2013), primarily due to the complexity of the building systems and variances due to behavioural change.

In terms of appliances, products and components, there have been significant changes due to the use of energy ratings, labels and MEPS (Bertoldi et al., 2012). The success of using energy labels is often assessed by its ability to transform a market towards more energy-efficient-product purchasing (Geller and Nadel, 1994; Nadel and Geller, 1996). Using energy labels and ratings has proven successful for different types of products and appliances (Boardman et al., 1997; Bertoldi et al., 1999; Boardman, 2004b), and is the subject of paper #1.

One of the more recent cross-sectoral policy efforts is the white certificates scheme, or energy-saving obligations for energy companies. Denmark introduced this policy in 2006 and has since increased the yearly targets to 10.7 PJ from 2013. The realised savings from 2010 and 2011 in different focus areas can be seen in FIGURE 11. This policy is designed to use market principles to find the cheapest energy savings.

A significant challenge for realising energy savings through increased energy efficiency is the rebound effect (Greening et al., 2000; Herring and Roy, 2007). Rebound effects propose that energy efficiency gains are more or less counteracted by increasing consumption, which is primarily based on a behavioural response. Direct rebound effects refer to the way a change in the implicit price of using an energy-consuming good or service leads to more use (Gillingham et al., 2013). Indirect rebound effects might also influence the achieved energy savings through the increased income that results from it being used on another energy consuming good or service. It is therefore a challenge to evaluate the actual energy savings from implementing energy efficiency improvements. Rebound effects do however tend to be over exaggerated and are used to oppose energy efficiency policy (Laitner, 2000; Sorrell, 2007; Gillingham et al., 2013). This thesis acknowledges the issue of rebound effects, but does not go deeper into the issues because it does not have direct relevance for the subject of the thesis.

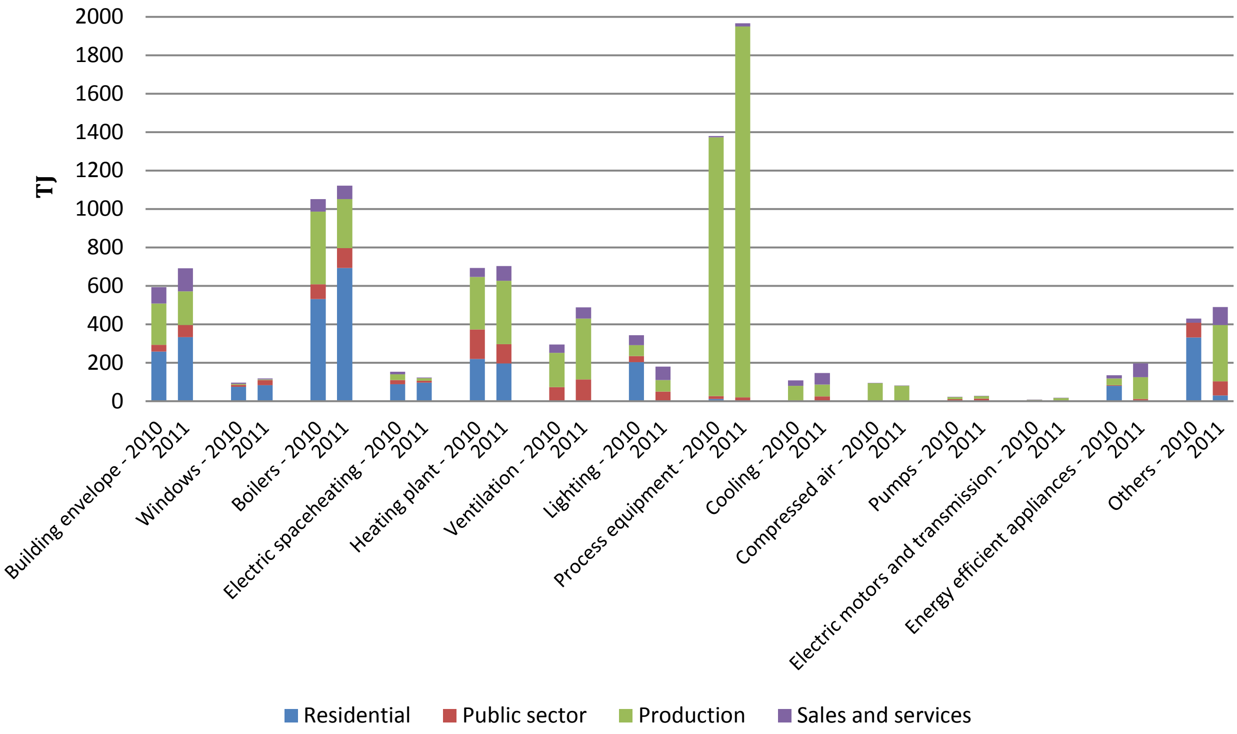


FIGURE 11 – REPORTED ENERGY SAVINGS FROM WHITE CERTIFICATES IN DENMARK 2010 AND 2011 IN TJ (DANISH ENERGY AGENCY, 2011).

The increase in attention towards energy efficiency improvements is not merely because of the direct impact on energy consumption. A recent IEA study looked at the multiple benefits of energy efficiency improvements, which have gained attention recently because of economic and employment issues. There were more than 16 benefits found in the categories of social, economic and environmental benefits (Ryan and Campbell, 2012). The study did not account for the impact on innovation, however.

Despite almost five decades of efforts to increase energy efficiency, there are still plenty of cost-effective savings available for implementation. The potential for energy efficiency improvements continues to be high, as indicated in several studies (IEA, 2012, 2013b; Laitner, 2013). Similarly, the potential for cost-effective energy efficiency improvements in the United States has been illustrated in a study by consulting firm McKinsey (Granade et al., 2009). It is therefore not a “market” that will soon run out of “demand”.

5 THE EMPIRICAL CONTEXT OF ENERGY EFFICIENCY, POLICY AND INNOVATION IN DENMARK

This section will serve as an introduction to the context of Denmark and present its energy and innovation system-related dynamics using additional empirical data collected from interviews, reports, questionnaires and RD&D project data.

Denmark's tradition of striving for renewable energy and energy efficiency can be traced primarily back to the global oil crisis in 1973. At the time, Denmark was highly dependent on the import of oil and coal for electricity and heat, so the crisis had a severe impact on the country. This led to a fundamental shift towards the development and use of renewable energy, as well as energy efficiency. Since then, Denmark has been a progressive country when it comes to energy (Lipp, 2007; Mendonça et al., 2009) and environmental (Wallace, 1995; Klok et al., 2006; Christensen et al., 2007) policy and the on-going transitions towards sustainability.

On an international scale, the most attention has been focused on wind energy (Garud and Karnøe, 2003; Meyer, 2004; Buen, 2006; Lewis and Wiser, 2007), which Denmark has been key in developing and utilising in its energy systems. Denmark has also been key in developing CHP systems (combined heat and power), district heating systems, and, of cause, increasing energy efficiency in many sectors. These advances are the result of tremendous research and development efforts in energy technology in Denmark (Borup et al., 2009), which are deeply embedded in the national energy and industry policy. As a testament to these efforts, Denmark has been able to decouple its energy consumption from its economic growth.

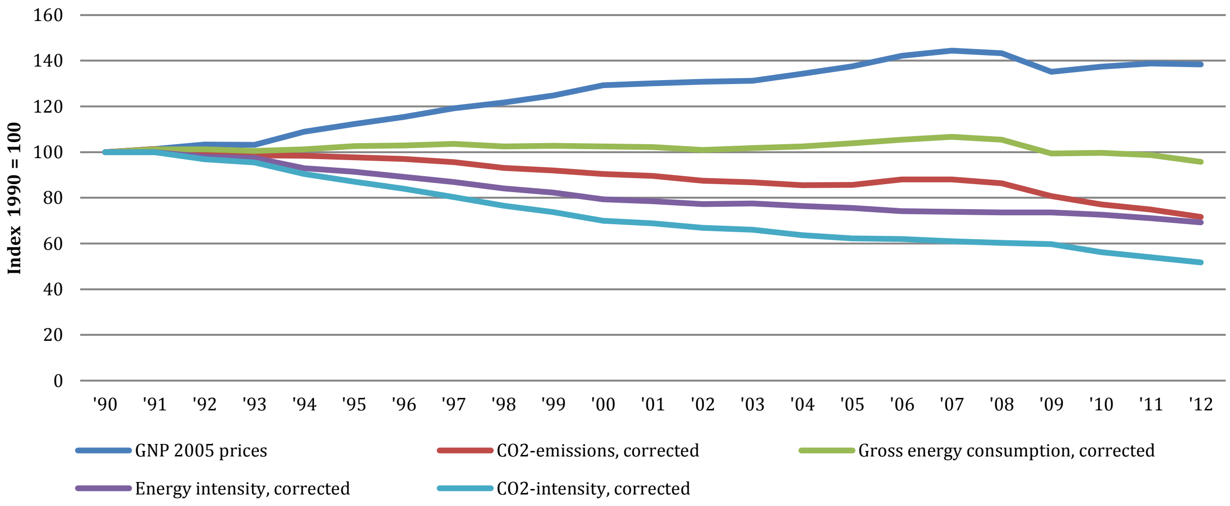


FIGURE 12 – THE DECOUPLING OF ENERGY CONSUMPTION, GROWTH AND CO_2 EMISSIONS (ENERGISTYRELSEN, 2012)

Denmark has continued to set some of the world's most ambitious energy policy with a recent long-term strategy for becoming completely fossil fuel-free in 2050 (Danish Government, 2011). Also, there is a new target of 50% of electricity coming from wind turbines (onshore and offshore) in 2020 – up from 33,2% in 2013 (Energinet.dk, 2013). In general, there is a high integration between energy, climate and science, which leads to comprehensive and integrative policy efforts (Danish Government, 2012). Denmark is also highly influential in energy and climate policy development on the international stage. Recently they pushed for legally-binding energy-saving goals in Europe for 20% by 2020, and 30% by 2030, which, however, are still under negation.

Overall, Denmark represents a unique empirical context in terms of its historical development and ambitious policies, which has had a distinct impact on the characteristics of its energy efficiency innovation system.

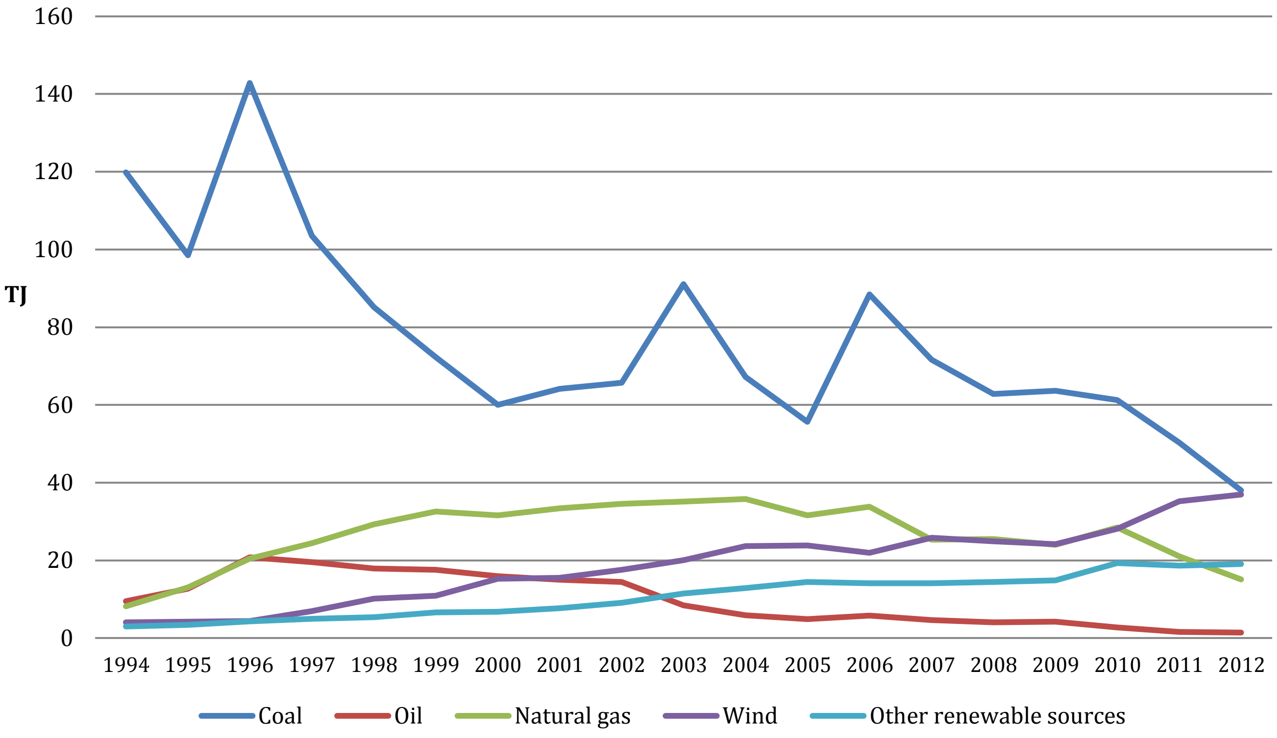


FIGURE 13 –ELECTRICITY PRODUCTION IN DENMARK ACROSS ENERGY SOURCES IN TERAJOULE (ENERGISTYRELSEN, 2012)

5.1 ENERGY SYSTEMS AND ENERGY EFFICIENCY IN DENMARK

As a result of policy and strategic efforts, the Danish energy system has undergone major changes since the 1970s in terms of both supply and consumption. Electricity supply has changed significantly since the mid-1990s when wind energy started to be integrated into the energy system. At the same time, coal has been significantly reduced and oil completely phased-out – see FIGURE 13. The heating system is built primarily around a district heating system, which supplies more than 63% of all households. The heat is supplied mostly by centralised and decentralised CHP plants that have increasingly changed from oil and coal towards gas and renewable energy in the form of biomass and waste.

On the consumption side, the primary trends are decreasing energy consumption in households and the manufacturing industry because of energy efficiency and conservation policies. Globalisation and the outsourcing of manufacturing also add positively to this development in the manufacturing industry. Overall the energy consumption of the transport sector has increased because of an increase in the number of cars and in the length of journeys, which have overcome the increases in efficiency.

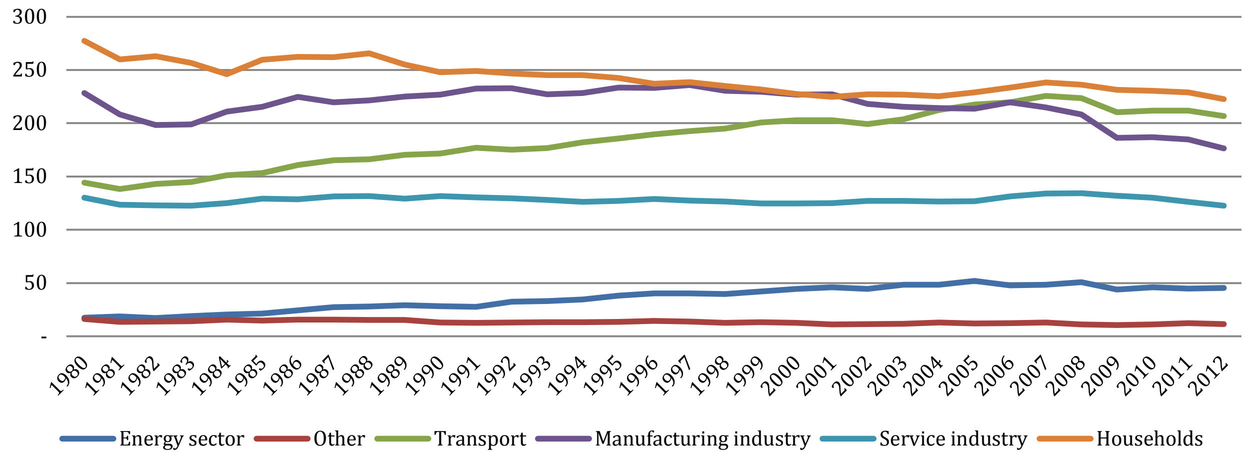


FIGURE 14 – HISTORICAL DEVELOPMENT OF ENERGY CONSUMPTION ACROSS USES – [PJ] (ENERGISTYRELSEN, 2012)

Public funding for research, development and demonstration efforts in energy and energy efficiency has been a crucial part of energy and technology policy in Denmark since the 1970s. Since 1990, the biggest share of public funding has gone to renewable energy sources, but energy efficiency has also received a significant amount.

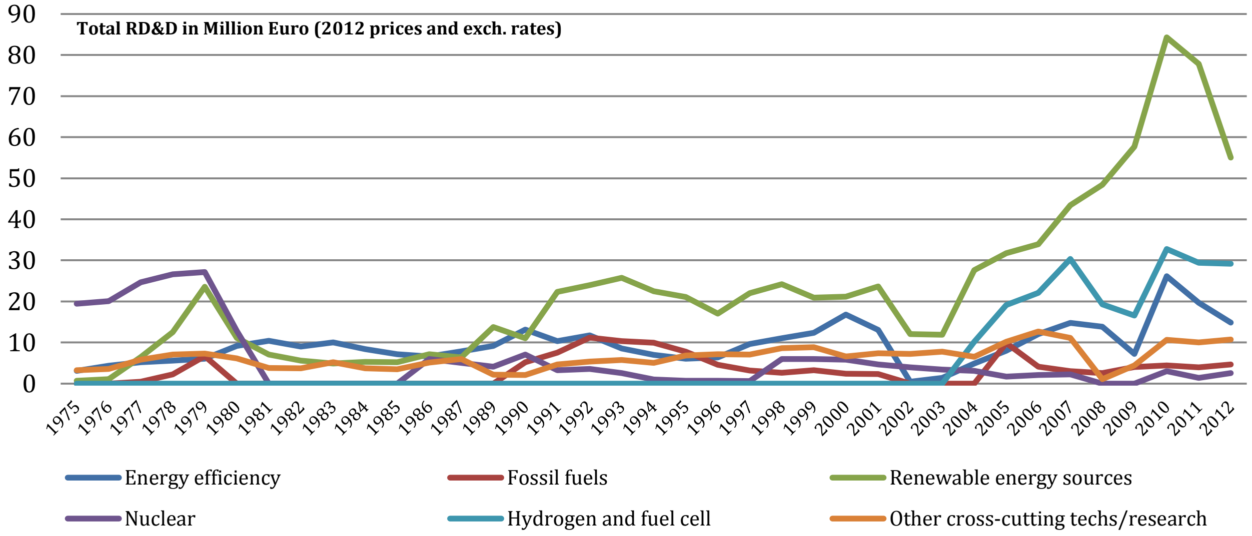


FIGURE 15 – RD&D SPENDING ON ENERGY TECHNOLOGY IN MILLION EURO (2012 PRICES AND EXCH. RATES) IN DENMARK (IEA, 2014B)

Along with the specific efforts in developing and diffusing new technologies, there has also been an industry and institutional built-up in Denmark as can be seen, for instance, in the successful wind turbine industry and in the companies exporting energy-efficient products (e.g. circulating pumps, windows, insulation, ventilation, etc.).

The current national and cross-sectoral policy efforts in energy efficiency (Togeby et al., 2009b, 2011) cover multiple stages of the innovation process, meaning that there are policies directed at developing new technologies and processes as well as policies aimed at the diffusion of products (e.g. national information campaigns, energy-saving obligations for energy companies, etc.) - see for an overview.

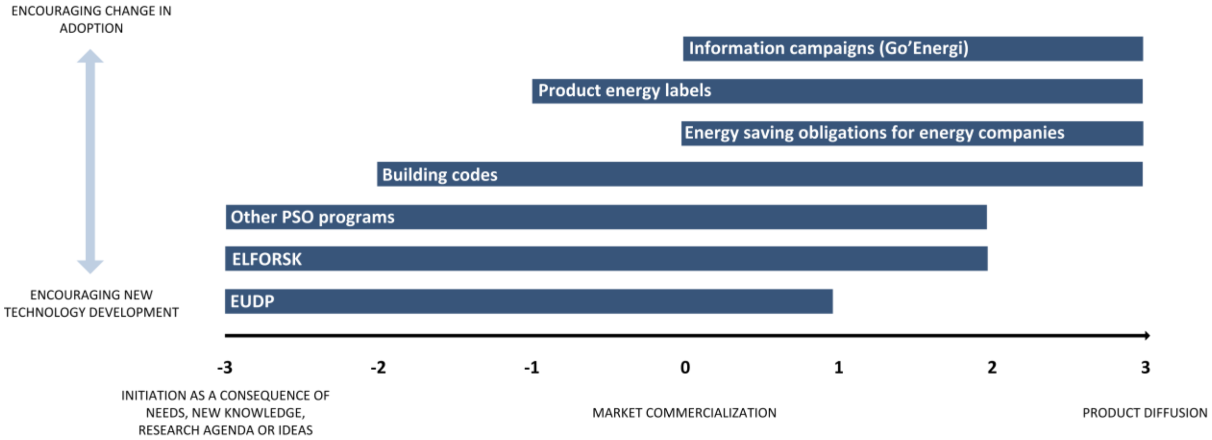


FIGURE 16 16 for an overview.

FIGURE 16 - ENERGY EFFICIENCY POLICY AND THE INFLUENCE ON INNOVATION PROCESSES IN DENMARK – (AUTHORS INTERPRETATION)

5.2 ENERGY EFFICIENCY R&D AND INNOVATION SYSTEMS IN DENMARK

Christopher Freeman defined the innovation system as 'the network of institutions in the public and private sectors whose activities and interactions initiate, import, modify and diffuse new technologies' (Freeman, 1987). The following section will be an analysis of these innovation networks by looking at collaboration patterns in publically funded research, development and demonstration projects in energy efficiency in Denmark. Here the emphasis is on investigating who is collaborating and to which extent collaboration differs across different technology focus areas. For a thorough analysis of the collaboration structures in different focus areas, please see paper #4 in the appendix. This analysis does by no means cover all the innovation activities in energy efficiency, but it provides a platform to approach the diffuse area of energy efficiency innovation activities.

The RD&D project data comes from the ELFORSK funding agency, a part of the Danish Energy Association that supports the research, development and demonstration into efficient end-use of electricity. The programme supports about twenty projects each year, with a total expenditure of 3,35 million Euro within seven focus areas. See Table 5 below.

Focus area:	**Behaviour**	**Buildings**	**Cooling**	**Industrial processes**	**Lighting**	**Power electronics**	**Ventilation**
***N* projects**	57	36	25	25	30	10	21
% covered in survey	49,1	61,1	60	52	56,7	50	52,4
***N* organisations involved**	143	73	83	72	73	29	55

TABLE 5 – OVERVIEW OF R&D IN THE ELFORSK PROGRAMME.

The data about the individual RD&D projects include names of participants, organisations, type of organisation (producer, consultant, user, university, energy company, technological institute), funding grant, project duration and more. This data was then combined with an online survey, which was made with the project managers of each project. Here complete or partially complete data was collected for a total of 111 projects (57%) out of 194 projects concerning the activities and outcomes of the project. The focus area of power electronics is left out in the survey results, because the low number of respondents makes it incomparable with the other focus areas.

In general, the projects are very diverse in terms of their composition of different actor types. FIGURE 17 shows the average composition of actors in each of the focus areas. It is clear that the projects are quite diverse across different organisations, but also that this differs between focus areas. Where, for instance, the *universities* are represented well in the *lighting* area, they are not so present in the more application-focused area of *industrial processes*. For a thorough analysis of the actor composition, actor diversity and innovation outputs, please see paper #3.

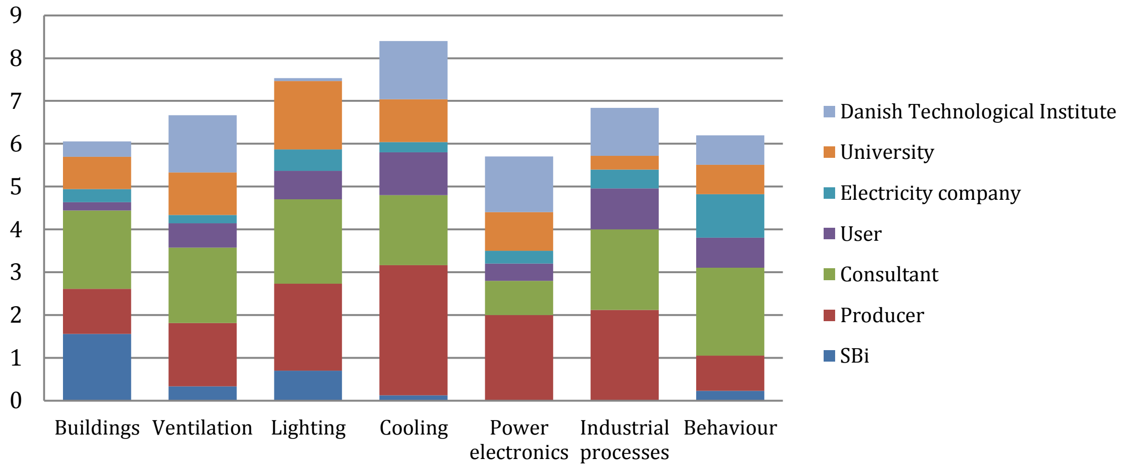


FIGURE 17 - ACTOR OVERVIEW AND DISTRIBUTION - PER PROJECT (ELFORSK 2002 - 2012)

As previously mentioned, energy efficiency innovation is not something that occurs within one specific sector or industry but goes across different sectors. This is illustrated in the RD&D project data when looking at the shared organisations across different focus areas (Table 6). Here it can be seen how several focus areas share a high percentage of organisations, for instance, between *industrial processes* and *ventilation*. This points to how innovation activities are organised around technical sector-specific organisations and cross-sectoral organisations such as universities, research institutions and technical consultants.

	Industrial processes	**Lighting**	**Buildings**	**Cooling**	**Ventilation**	**Behaviour**	**Power Elec.**
Industrial processes	-	8,2	6,6	15,1	24,6	12,5	27,6
Lighting	8,3	-	17,1	8,1	14,0	13,9	31,0
Buildings	6,9	17,8	-	14,0	21,1	15,3	20,7
Cooling	18,1	9,6	15,8	-	17,5	12,5	13,8
Ventilation	19,4	11,0	15,8	11,6	-	9,7	34,5
Behaviour	25,0	27,4	28,9	20,9	24,6	-	37,9
Power Elec.	11,1	12,3	7,9	4,7	17,5	7,6	-

TABLE 6 – PERCENTAGE OF SHARED ORGANISATIONS BETWEEN FOCUS AREAS.

Innovation activities in energy efficiency mostly involve the use of mature technologies. In the survey, the project managers were asked to assess what kind of activities they had carried out in projects across *Research*, *Development*, *Demonstration* and *Dissemination*. FIGURE 18 below shows the average distribution of activities across the seven focus areas. In general, less than a quarter of the activities were characterised as research, which indicates the use of known technologies and a tendency to emphasise development and demonstration activities. There are also differences across focus areas, with, for example, the *cooling* area relying less on research activities whereas the *lighting* area is more research orientated.

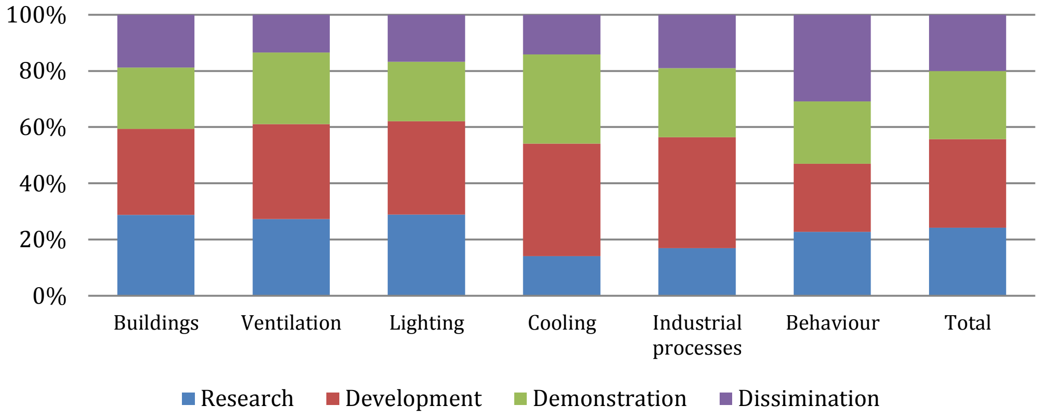


FIGURE 18 –THE DISTRIBUTION OF ACTIVITIES IN THE PUBLIC RD&D PROJECTS (ELFORSK 2002 - 2012)

In order to get an overview of the entire network, social network analysis (Wasserman and Faust, 1994; Scott, 2000) tools are used. Here the RD&D project data are used as network relations and aggregated across organisations. This makes it possible to get an overview of the central type of organisations in the innovation system. See the network diagram on the following page, FIGURE 19.

In the network illustration, it is clear that research institutions (light blue colour) and universities (grey colour) take the central position in the network. In particular, the applied research institution DTI has a very central position, which points to the “applied” nature of innovation activities in energy efficiency. The energy companies (green) are also quite centrally positioned, typically as collaborators with all of the research institutions. At the periphery of the network, most of the “user” organisations are positioned, which indicates their single time appearance on projects. Lastly, it is important to point out the scatteredness of the consultants (blue); very few are positioned centrally in the network despite being the most frequent type of organisation participating in the projects.

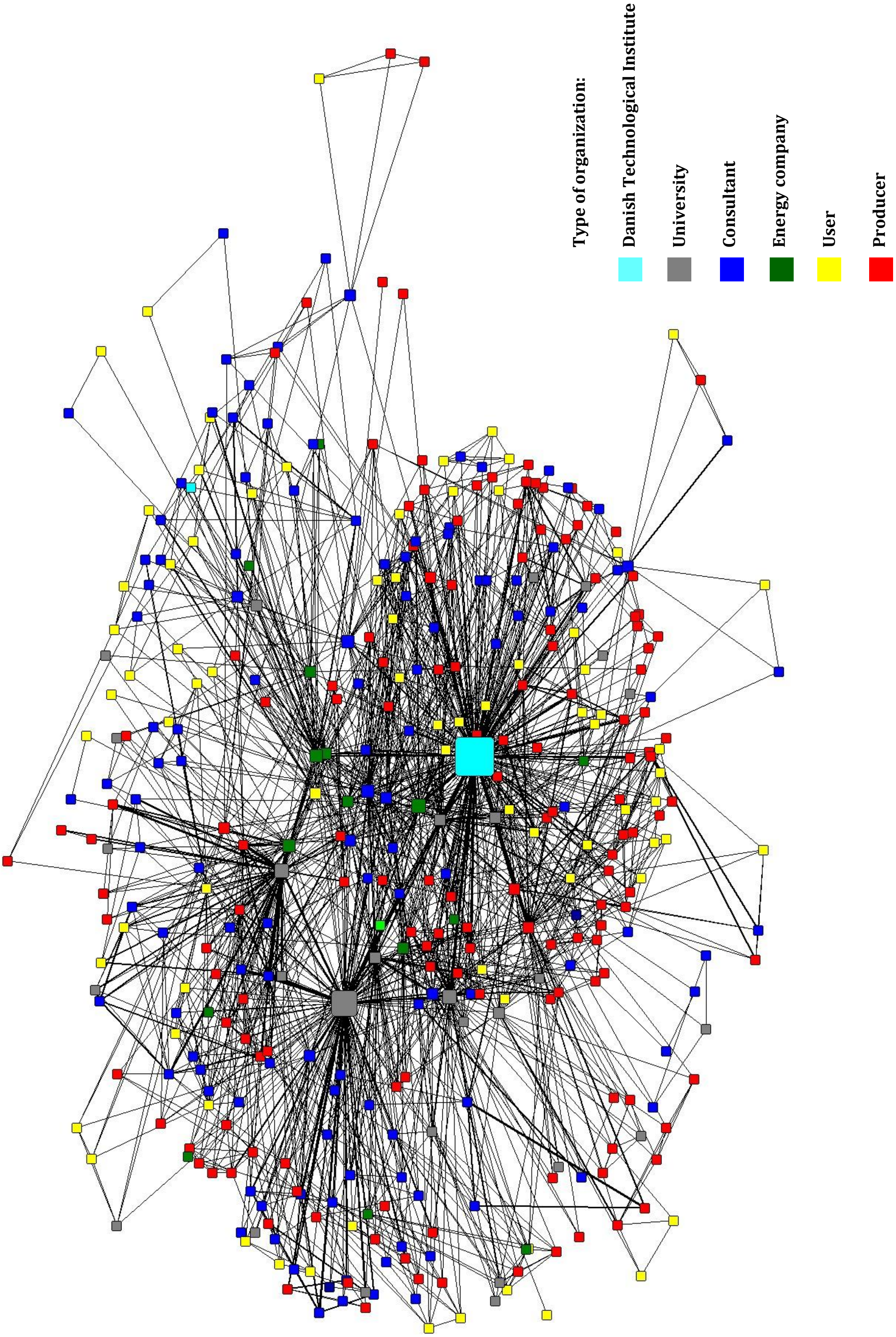


FIGURE 19 – NETWORK REPRESENTATION OF COLLABORATION IN THE ENERGY EFFICIENCY RD&D (NODE SIZE INDICATES THE INBETWEENESS CENTRALITY AND LINE TICKNESS THE TIE STRENGTH)

At the level of the individual networks for each focus area, there are some important differences between them – see FIGURE 20. The density of a network is a measure based on how well everyone is connected, and here it is clear that the focus area of *behaviour* is the least dense. This very low density points out the very diffuse nature of activities and approaches in the projects in this focus area. At the opposite end are the focus areas of *ventilation* and *power electronics*, which have very dense networks. This high density means that there is a great coherence in the network and it is more likely that more organisations have a relationship with others. These networks probably have higher densities because of their more single-sector focus; e.g. the ventilation area is a sub-sector of the construction industry with its own institutions, sub-suppliers, etc.

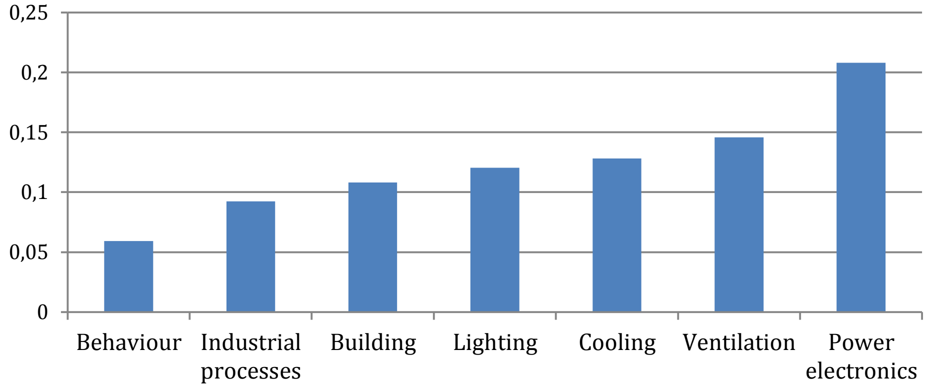


FIGURE 20 - NETWORK DENSITY ACROSS THE SEVEN FOCUS AREAS

5.2.1 *INNOVATION OUTPUT OF ENERGY EFFICIENCY RD&D IN DENMARK*

The Danish energy technology sector has seen significant success in terms of exports, and, recently, the green energy technologies (primarily renewable energy sources and energy efficiency) have become the biggest contributors to these rising exports. This indicator of success is supported by a recent study that found Danish companies were particularly innovative in terms of bringing new energy-efficient products to the market (Borup et al., 2009).

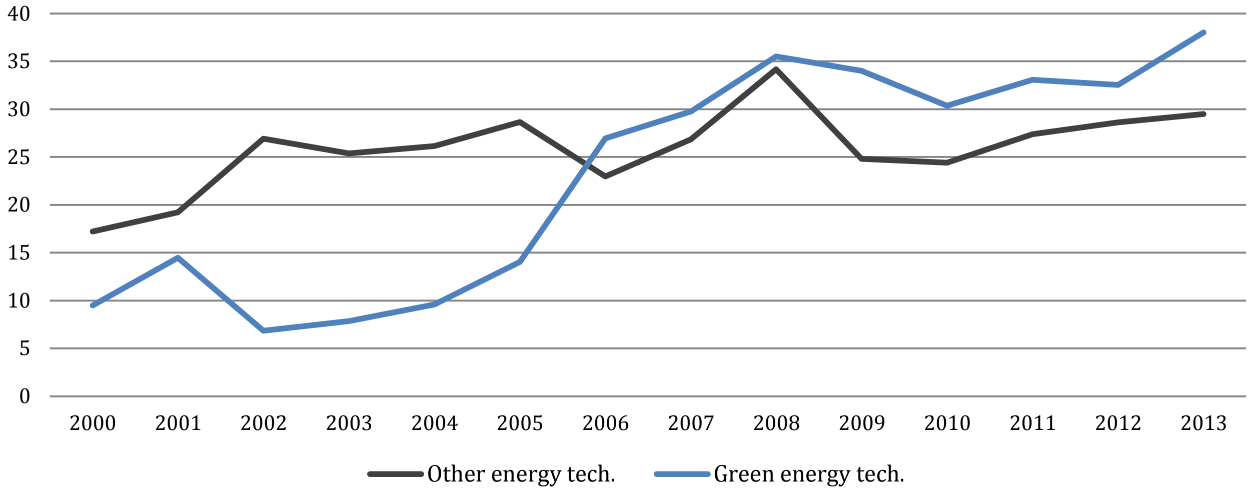


FIGURE 21 – ANNUAL ENERGY TECHNOLOGY DANISH EXPORT IN BILLION DKK .

In the survey, the project managers were asked about the kind of output from the RD&D projects, which is here used as an indicator of innovations. The project managers indicated that, on average, 23,4% of projects had a product innovation, meaning that the project has contributed primarily to the commercialisation of one or more new products – see Table 7. In 64% of the projects with a product innovation, it was indicated that these were radically new products not known to the market. Furthermore, an additional 15% of the project managers indicated that processes, new business models, positive lists, etc. These responses indicate a high innovation output in terms of new product introduction and commercialisation from RD&D projects in energy efficiency but also that innovation activity in energy efficiency is not merely about technological innovation. These indicators of innovation are used as performance variables in paper #3.

TABLE 8 – SURVEY RESPONSES REGARDING PROJECT OUTPUTS.

	Buildings	**Ventilation**	**Lighting**	**Cooling**	**Power Electronics**	**Industrial Processes**	**Behaviour**
N projects total	22	11	17	15	5	13	28
Product innovation outcome	32%	27%	29%	27%	0%	8%	21%

In order to understand if public policy influenced these innovation activities, the project managers were asked about which public policies were positively driving their activities (FIGURE 22). With, for example, more than 50% of projects being positively influenced by information campaigns, it is clear that public policies influence innovation activities positively. These responses also illustrate how different policies impact differently across focus areas. Rather obviously, building codes make a tremendous impact on the *buildings* area but no impact on *industrial processes*. This also rejects the single-policy focus, which a number of scientific studies apply. It is necessary, from a systemic innovation perspective, to acknowledge the reality of heterogeneous types of policies and their impact on the innovation processes. These results are covered in-depth in paper #2.

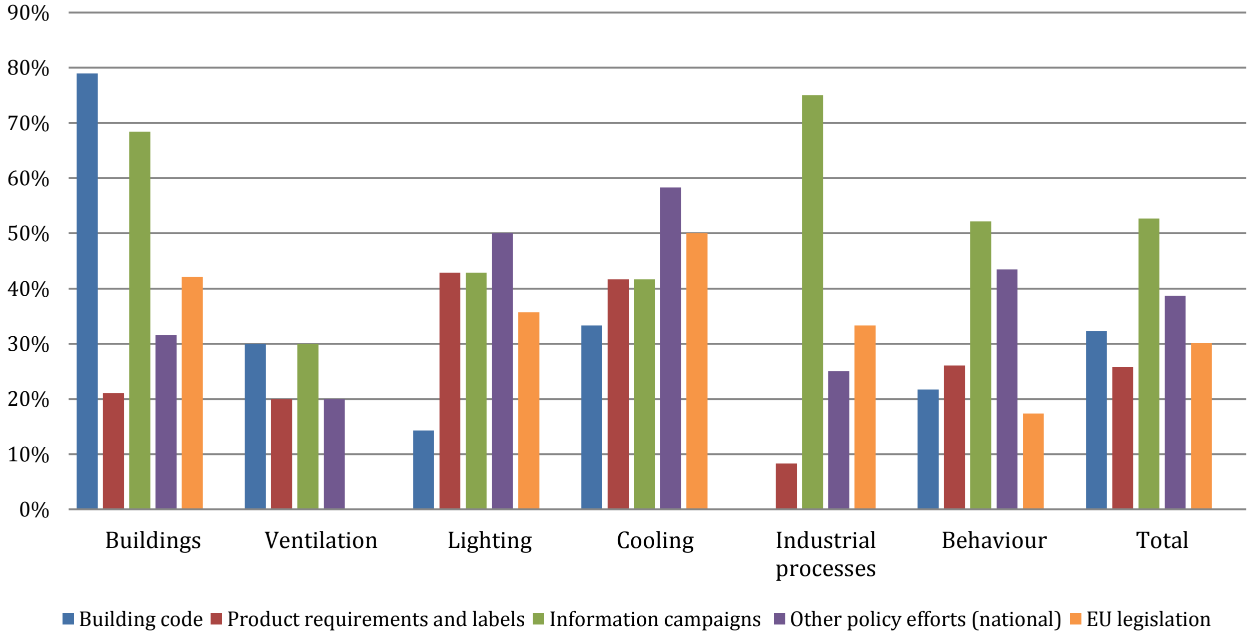


FIGURE 22 – POLICY DRIVERS IN ENERGY EFFICIENCY RD&D

If we then return to Christopher Freeman's definition of a innovation system *'the network of institutions in the public and private sectors whose activities and interactions initiate, import, modify and diffuse new technologies'* (Freeman, 1987), it is clear that these elements certainly exist for energy efficiency activities in Denmark. Furthermore, these activities seem to be very coordinated and successful in terms of their ability to support the creation, flow and application of knowledge (Borup et al., 2009).

6 PUBLICATION OVERVIEW AND SUMMARIES

The article contributions revolve around the main phenomena of *policy efforts and energy efficiency innovation,* which are approached using different research methods and data. The work accomplished during the Ph.D. therefore consists of the three following scientific contributions – see summaries on the following pages and full papers in Chapter 7 and in the appendix.

#	Title	Research method & data	Status
1	*Innovation-enabling policy and regime transformation towards increased energy efficiency: the case of the circulator pump industry in Europe*	In-depth case study using a mixed-methods approach	Accepted for publication in *Journal of Cleaner Production* – in press.
2	*Public Policy As Driver Of Energy Efficiency Innovation - Actor-Level Evidence From Public R&D Projects In Denmark* *Co-authored by Mads Borup.*	Descriptive survey data	Planned for journal submission, in *Energy Policy* – Spring 2015.
3	*Open innovation and collaborative public RD&D projects in energy efficiency – a look into project participants and participant diversity*	R&D project database, survey, logistic regression	Revise and resubmit to journal *Industry & Innovation* – Spring 2015.
	Supplementary conference paper in appendix:		
4	*Characteristics of networks in energy efficiency research, development and demonstration – a comparison of actors, technological domains and network structure in seven applied research areas.*	R&D project database, qualitative interviews and reports	Conference: EU-SPRI Early Researchers Conference - Science Dynamics 2013 (Peer-reviewed).

6.1 PAPER #1 SUMMARY: INNOVATION-ENABLING POLICY AND REGIME TRANSFORMATION TOWARDS INCREASED ENERGY EFFICIENCY: THE CASE OF THE CIRCULATOR PUMP INDUSTRY IN EUROPE

The relationship between environmental regulation and innovation has been studied numerous times, mostly with mixed results. These studies tend to simplify the dynamics of regulation and innovation by, for instance, including only single policies or generalising across sectors and product types. From the energy efficiency literature, however, we know that public policies are needed in order to overcome economic, behavioural and organisational barriers towards energy efficiency. Some even take it further and argue for integrated and systematic policies in order to transform the existing market.

This paper uses a longitudinal case study of the circulator pump industry in Europe to analyse the complexities of energy efficiency innovation. The empirical data consists of a mix of interviews, policy documents, reports, industry magazines and patents to create a strong descriptive, but explanatory, narrative. This narrative is combined with a theoretical framework on change dynamics in sociotechnical regimes to explain the complex energy efficiency transformation of the circulator market.

The case study presents a unique example of industry-driven policy efforts which creates a transformation of the existing sociotechnical system in the form of endogenous renewal. The introduction of a voluntary energy labelling scheme for circulators sparked R&D and business development in the industry, which reduces the market barriers for energy-efficient circulator pumps. This creates competitiveness, and changes the dynamics of the industry towards increased energy efficiency. The study illustrates the complexity of innovation processes, especially for energy-efficient products, which have difficulty diffusing into the market.

6.2 PAPER #2 SUMMARY: PUBLIC POLICY AS DRIVER OF ENERGY EFFICIENCY INNOVATION - ACTOR-LEVEL EVIDENCE FROM PUBLIC R&D PROJECTS IN DENMARK

The literature on barriers towards energy efficiency is comprehensive, but little is known about what elements are acting as drivers of energy efficiency innovation. This paper specifically looks at how different energy efficiency policies are impacting the innovation activities in energy efficiency. Differently from most studies in the energy efficiency literature this study is done at the actor-level with actors embedded in public R&D activities and covers six different sub-areas of energy efficiency. This paper uses descriptive statistics from a survey with the projects managers of publically funded RD&D projects in energy efficiency in Denmark to gain insight into the drivers of energy efficiency innovation activities.

From the perspective of project managers in charge of public RD&D projects it is clear that energy efficiency policy efforts frequently are driving innovation activities. In detail the study finds that information campaigns are the most frequent driver of innovation activities, although the actual impact is unknown. There are also differences across the seven different focus areas with respect to the impact of different policies. As was expected were building codes a frequent driver of innovation in the building area whereas it had no impact on industrial processes. In general national policy efforts seemed to make the biggest impact although influence from policies at the European Union level also was quite frequent.

Single policies or mix of policies do however not stand alone, but should be seen in the context of the entire sociotechnical system where it coexists with other drivers as well as barriers. The analysis here provides new insights into the importance of relations between market development, technology development and policy drivers in certain sectors and industries, something which is often overlooked in broader studies of for instance products and appliances. Overall the study therefore adds to the existing studies of the innovation impact of energy efficiency and environmental policies with a deeper level of complexity and cross-area insights distinctive for energy efficiency innovation efforts.

6.3 PAPER #3 SUMMARY: OPEN INNOVATION AND COLLABORATIVE PUBLIC RD&D PROJECTS IN ENERGY EFFICIENCY – A LOOK INTO PROJECT PARTICIPANTS AND PARTICIPANT DIVERSITY

Open innovation activities and in particular collaborative RD&D activities between industry and the public sector are crucial in a well-functioning innovation system. The determinants of innovation in these public RD&D projects are, however, not well known, despite the significant funding allocated for these activities. The open innovation theory as well as evolutionary theory would argue that collaboration between diverse actors would provide the firm with access to diverse sources of knowledge and thus increase the likelihood of innovation. These positive effects have been studied and acknowledged several times. Furthermore it has been found that increasing diversity among partners has a strong positive influence on innovation. There are also challenges in public and private R&D collaborations, specifically the "valley of death" problem. This can occur when commercial and academic interests are not aligned and the innovation doesn't reach commercialisation. This paper, therefore, investigates how the innovation outputs of the projects are influenced by the diversity and characteristics of the participants.

The paper combines a unique database of public RD&D projects (ELFORSK) with a questionnaire conducted with the project managers on public RD&D projects in energy efficiency in Denmark. In the questionnaire, the project managers are asked to specify the outputs from the projects as well as other controlling factors. Using a binary logistic regression, the analysis determined the significant factors that increase the likelihood of a product innovation resulting from the projects.

Initially the paper was intended as a network analysis paper to determine whether the central actors and projects could be linked to the projects with product innovation, but this did not show significant results and so the direction of the analysis changed.

The paper shows that public RD&D efforts in energy efficiency have a strong innovation output. The regression analysis finds a significant relation between the increasing diversity of the actors on the projects and the likelihood of a product innovation – the higher diversity among participants, the better. Furthermore, it shows that there are certain combinations of actor types that benefit projects and a single combination that has a negative impact.

These findings support the existing literature on open innovation and collaborative R&D activities and contribute the added complexity of actor diversity and actor characteristics. The higher diversity of actors could ensure ownership during the innovation process, which reduces the number of "valley of death" projects where the innovation gets dropped along the way. For the empirical context, it is shown that public RD&D activities in energy efficiency are highly innovative and that the actors involved are highly diverse.

7 THESIS PUBLICATIONS

51

7.1 PAPER #1 – INNOVATION-ENABLING POLICY AND REGIME TRANSFORMATION TOWARDS INCREASED ENERGY EFFICIENCY: THE CASE OF THE CIRCULATOR PUMP INDUSTRY IN EUROPE

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Innovation-enabling policy and regime transformation towards increased energy efficiency: the case of the circulator pump industry in Europe

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A B S T R A C T

When new energy efficient products are struggling with their commercialisation and diffusion into widespread applications you would typically expect policy-makers and green lead-users to guide the way. This paper examines the case of the hot water circulator pump industry in Europe, where parts of the industry envisioned and worked for a voluntary energy label, bringing technological innovation, new business and energy savings of approx. 85% for each new circulator pump. The case study explores the complexities of innovation processes where technology, market, actors and policy co-evolve over time to transform an existing socio-technical regime. The paper highlights the importance of policies to reduce barriers towards innovation and energy efficiency and shows that it is not always policy-makers that establish the crucial policies that change the innovation dynamics for the benefit of the environment and the industry.

1. Introduction

Sustainable energy systems in the future will require change in the way energy is both produced and used. On the consumption side the load on the energy system must be lowered either through energy conservation or through increased energy efficiency (IEA, 2012).

Achieving energy savings through increased energy efficiency is, however, difficult. There are in practice multiple barriers towards energy efficiency (Hirst and Brown, 1990; Reddy, 1991; Weber, 1997; Sorrell, 2004) whether related to institutional (Lovins, 1992), market and economic (Jaffe and Stavins, 1994) or organisational aspects. These barriers seem present in some way or another for any kind of energy efficient product, reducing the likelihood of the product actually leading to energy savings (Sorrell, 2004). The literature does, however, also provide a few examples of how these barriers are overcome, primarily through various forms of public policy instruments (Sorrell, 2004; Farinelli et al., 2005). What are not present in the current literature are elaborate empirical accounts of how energy efficient products are developed and diffused while among other things are being influenced by public policy. This paper will cover a complete innovation process through the case of the energy efficient circulator pump[1] in Europe — see a typical hot water circulator pump in Fig. 1.

In Europe alone, hot water circulator pumps for heating systems are estimated to use approx. 53.2 TWh electricity per year (AEA Energy and Environment, 2008) for an estimated stock of 140 million including both standalone and boiler-integrated circulators.[2] Even though these figures are quite substantial there has been little awareness of the energy consumption and related potential savings for circulators among house owners, tenants, professionals and policy-makers. As circulators are somewhat hidden in homes and apartment blocks most house owners or tenants are not aware of having one. The barriers towards energy efficiency are therefore well established for this type of product (Sorrell, 2004).

Technological development has however led to breakthroughs in electric motor efficiency, motor control systems and circulator housing through the 1980s and 1990s. Combined, these developments have had tremendous impact on the overall energy

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[1] The terms notation pump, circulator and circulator pump will be used interchangeably and refer to the same product.

[2] The circulator manufacturers see themselves as part of the overall pump industry and suppliers to the heater/boiler manufacturers.

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Fig. 1. A typical household circulation pump (Smedegaard).

efficiency of the circulators. Typically switching from a "conventional" circulator (D-rated or worse) to a state-of-the-art circulator (A-rated or better) means an approx. 85% reduction in yearly energy use (AEA Energy and Environment, 2008). In this innovation journey, technological development, economic growth and energy conservation efforts co-occur. The development is by no means a linear innovation process where one activity inevitably leads to the next (Garud et al., 2013), which is why this paper uses an evolutionary perspective on innovation processes and systemic change (Nelson and Winter, 1982; Kline and Rosenberg, 1986). The paper will untangle these complex processes and describe how the co-evolution of energy efficiency, technological development, policy and innovation actually occurred – something that is rarely studied in depth in the current scientific literature.

The paper is structured as follows. A short literature review will highlight the characteristics of energy efficiency and innovation to identify gaps in the current knowledge. Following, there is a brief section on the theory of innovation and socio-technical systems to establish the paper's theoretical foundations. The research methodology applied in the paper will then be explained. The main emphasis of the paper is on the comprehensive empirical case study after which the paper will end with discussion, conclusion and policy implications.

2. Challenges of energy efficiency innovation and the role of policy

The commercialisation and diffusion (Shama, 1983; Rogers, 2003) of energy efficient versions of existing products is a challenge. Despite the direct economic and environmental benefits of energy efficiency, new energy efficient products are struggling on the market. This challenge is attributed to a series of economic, behavioural and organisational barriers that are hindering the diffusion and use of energy saving technologies (Hirst and Brown, 1990; Reddy, 1991; Weber, 1997; Sorrell, 2004).

Most of the literature on barriers towards energy efficiency has its focus on market failures owing to the products' inability to compete with conventional products on the market, owing to higher capital cost and inability to value lower lifecycle cost (DeCanio, 1998; Sorrell, 2004). The consensus is that public policies are needed to overcome these barriers in order to achieve market transformation (Birner and Martinot, 2005; Foxon and Pearson, 2008; Montalvo, 2008).

2.1. Policy instruments and their impact

Three generic types of specific policy instrument are usually put in place to overcome barriers towards energy efficiency (Sorrell, 2004; Farinelli et al., 2005). Through normative, informative and economic policies (Togeby et al., 2009) or a combination of all three, energy efficient products are to some extent able to succeed on the market, overcoming barriers such as risk, hidden cost, access to capital, split incentives, imperfect information and bounded rationality (Sorrell, 2004; Foxon and Pearson, 2008). These policies are often designed to target where the barriers are located, so it could be with the producers, the consumers or elsewhere.

As increasing energy efficiency in most cases is a directed action towards saving energy, there is often a strong emphasis on focus areas or impact areas when developing policies. These areas are typically chosen because their consumption is high or because the savings are relatively easy and cost-effective. This is for instance seen in IEA's policy recommendations with the focus areas of cross-sectoral, buildings, appliances and equipment, lighting, transport, industry and energy utilities (IEA, 2014).

This paper will primarily focus on product-level policies although these should be seen in relation to cross-sectoral energy saving policies and taxes. A complete overview of policy options can be found in existing literature (Hirst and Brown, 1990; Thiruchelvam et al., 2003; Sorrell, 2004).

Energy labels are seen as one of the primary ways of supporting energy efficiency directly at the product level. Using product energy labels is a way of supporting rational consumer choice and overcoming the barriers of imperfect information and bounded rationality. These efforts are often mandatory but can also be voluntary (Krarup and Ramesohl, 2002).

Energy labels are usually directed at changing end-user behaviour and were first seen in use in domestic goods and white goods in the early 1990s (Bertoldi et al., 1999). Within these product categories certain successes have been seen owing to the implementation of product energy labels, but these cannot be seen as isolated policies as markets, areas and countries differ greatly (Boardman, 2004).

Product labels are not necessarily a sure path to the diffusion of more energy efficient products so stricter regulation forms could be more efficient in some cases (Colombier and Menanteau, 1997). These typically come in the form of Minimum Energy Performance Standards (MEPS) or appliance standards (Gillingham et al., 2006) which accelerate the market process by demanding a certain level of efficiency (4E – IEA, 2012). The use of stricter regulation types such as MEPS in combination with other policies is regarded as necessary to support the transformation of existing markets (Geller and Nadel, 1994; Nadel and Geller, 1996; Bertoldi et al., 1999; Birner and Martinot, 2005). When implementing energy savings through increased energy efficiency direct and in-direct rebound effects can have an impact on the actual reduction of the consumption (Greening et al., 2000; Herring and Roy, 2007; Sorrell, 2007). These effects are, however, often overestimated (Gillingham et al., 2013) and in this particular case do not seem to play a large role.

The experiences in OECD countries have been summarized by Geller et al. (2006) and they concluded in their cross-going analysis that policies can lead to substantial energy savings. Minimum efficiency and strict regulation programmes can be effective especially if they are continuously updated to fit the product and its development pace. Furthermore, the authors found that government funded R&D can help lower the risks and accelerate the innovation pace. Recent work (Gillingham et al., 2009) supports the majority of these findings, but adds a crucial point concerning the lack of empirical data that in general limits this kind of analysis.

Gann et al. (2010) discuss whether performance standards at the buildings level or prescriptive standards at the product level are encouraging innovation. They argue that performance standards, which pose demands at the building level but don't choose technologies, are best at encouraging systemic innovation, whereas prescriptive standards encourage product innovation at the building component level. Their work clearly point to the complexity of

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Table 1
Framework for assessing the role of policy instruments supporting the development of technology and actor-networks as well as four learning processes (Kiss et al., 2013).

Policy instruments: ↓	R&D/↓	EPBD/↓	Building codes/↓	Labels/↓	Financial incentives/↓	Information/↓	Voluntary standards/↓	Testing/↓	Education & training/↓
Technology development	a) Direction of search and development			For example technological guideposts and/or paradigms, scientific theories and standards				Learning-by-searching	
	b) R&D resources			Resources assigned for research and development				Learning-by-searching	
	c) Management of new knowledge			For example the use of patents				Learning-by-searching	
	d) Testing			The frequency and outcome of testing				Learning-by-doing	
Actors and networks development	a) Sophisticated user group			The degree of sophistication of the user group, i.e. what is the nature of the group and what are its demands				Learning-by-using	
	b) Form of producer–user interaction			With a special focus on education, training and user feedback				Learning-by-using	
	c) Proximity & mutual interest of actors and networks							Learning-by-interacting	

the firm's freedom to innovate versus the certainty of a firm's innovation direction.

Evaluating the influence of single or multiple policies on innovation is very difficult. Several studies therefore focus on technological change over time and come to the conclusion that the effects of policies differ greatly. A study of air conditioners and gas heaters in the US (Newell et al., 1999) showed how energy efficiency was influenced by the 1970s oil crises, energy prices and especial synergy between energy price and product labels. In their 2002 paper they furthermore conclude that "[t]he empirical evidence is generally consistent with theoretical findings that market-based instruments for environmental protection are likely to have significantly greater, positive impacts over time than command and control approaches on the invention, innovation, and diffusion of desirable, environmentally-friendly technologies" (Jaffe et al., 2002, p. 61).

A recent econometric study also investigated the role of building codes in inducing innovation in the building sector by looking at patents (Noailly and Batrakova, 2010; Noailly, 2011). Here they found that a 10% increase of the insulation demands in the building codes in Austria, Belgium, Denmark, Finland, France, Germany, Ireland, the Netherlands and the UK would result in a 3% increase in patenting. Furthermore, energy prices seemed to have no influence while governmental R&D had a small influence on the patenting. In a descriptive and holistic comparative study Kiss et al. (2013) analysed the role of different policy instruments at different phases of innovation processes for the case of insulation materials in Germany, Sweden and the UK.

The study by Kiss et al. (2013) presents a framework (Table 1) for assessing the policy instruments supporting the development of the technology and the surrounding actors and networks. Their framework provides an overview and insight into the specific policy efforts and how they influence different activities and learning processes involved in complex innovation processes specifically for energy efficiency-related technologies.

The need for policies to support innovation and energy efficiency is well established, but how they should be designed and how they interact with the innovation process is quite unknown. This paper looks at the innovation process in high detail to investigate the co-evolution between technology, industry structure and policy institutions (Nelson, 1994; Rosenkopf and Tushman, 1994; Van de Ven and Garud, 1994; Lynn et al., 1996).

3. Change dynamics in socio-technical regimes

In this empirically-focused study theory is used in two ways. First of all it is used to establish a general perspective of how innovation and change processes occur in complex socio-technical systems and regimes. Secondly, theoretical frameworks contain concepts and terminologies that are useful for describing and understanding complex processes.

Understanding complex innovation dynamics requires a systemic perspective of innovation as proposed by early evolutionary economists (Nelson and Winter, 1982) developing on the novel works by Joseph Schumpeter (Schumpeter, 1942). This led to the systemic and non-linear understanding of innovation, entitled innovation systems (Freeman, 1987; Lundvall, 1992; Nelson, 1993). This string of literature applies an understanding of innovation that assumes non-linear processes and moves away from a firm focus to the system level where firms are interacting with other firms, users, institutions, policy, etc. In order to understand the case presented in this paper where there is a co-evolution of firms, institutions, technologies, policies and users, an evolutionary and systemic innovation perspective is beneficial (Garud et al., 2013). Although innovation systems theory contains micro-level elements such as technology users it is rarely the focus in current research (Geels, 2004). Geels points to the use of the *sociotechnical system*[3] concept when describing the system in which innovation is taking place. His use of the concept emphasises both the *production* of new technologies as well as the *application* of them. Using the concept of socio-technical systems enables a better understanding of the diffusion and application dynamics of new technologies while still acknowledging the processes of new technology development.

Both innovation systems theory and socio-technical systems theory put emphasis on dynamics and change. To understand these changes in socio-technical systems there must be an understanding of what keeps the system as it is and how it might be altered or influenced (Kemp et al., 1998; Rip and Kemp, 1998).

Socio-technical systems are dominated by regimes that determine the structure and direction of activities (Dosi, 1982). Smith et al. define socio-technical regimes as "[…] relatively stable configurations of institutions, techniques and artefacts, as well as rules, practices and networks that determine the 'normal' development and use of technologies" p. 1493 (Rip and Kemp, 1998; Smith et al., 2005). Geels furthermore argues that socio-technical regimes consist of a series of sub-regimes: Technological regime, Science regime, Policy regime, Socio-cultural regime, User and market regime (Geels, 2004). Another dimension to characterise regimes is whether they are a *nested* regime or a *spanning* regime (Berkhout et al., 2004; Smith et al., 2005). Nested regimes are established

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[3] The concept of the socio-technical system is well known in the STS (Science and Technology Studies) community coming mainly from the earlier works on the social construction of technology and actor network theory (Callon, 1986; Bijker, 1997).

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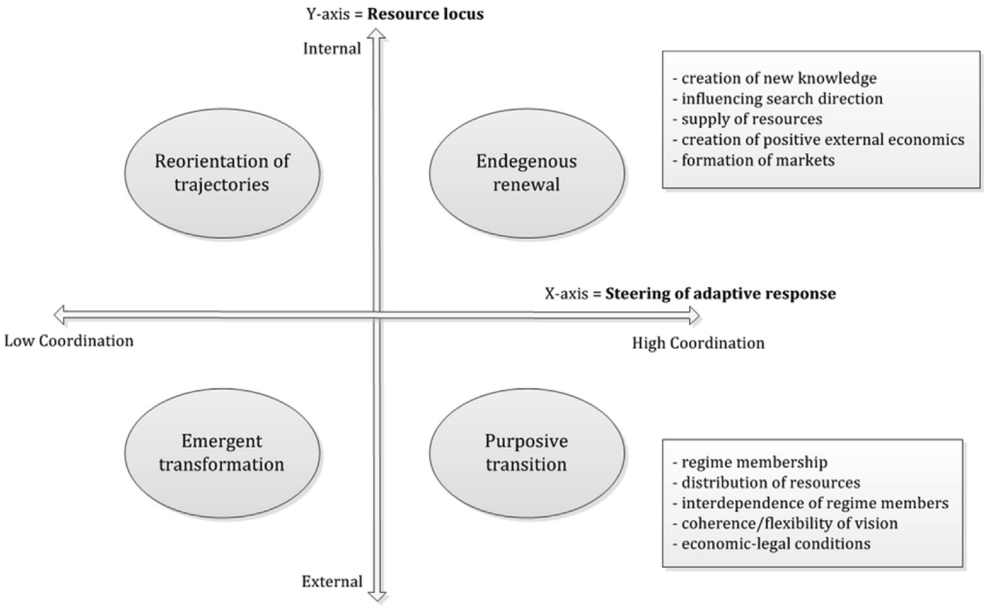

Fig. 2. Transition contexts as a function of degree of coordination to selection pressures and the locus of adaptive resources (Smith et al., 2005).

vertically across levels, whereas spanning regimes are horizontally established.

The change dynamics of established regimes can take several shapes and forms. Geels proposes four transition pathways to characterise change dynamics. These are *transformation*, *reconfiguration*, *technological substitution*, and *de-alignment and re-alignment* (Geels and Kemp, 2007; Geels and Schot, 2007). Despite differences between the four they primarily emphasise the role of technological niches in socio-technical change. This paper is mostly interested in the transformation of existing regimes as energy efficiency is a secondary parameter that is integrated into existing industries, markets and user practices.

Van de Poel proposes four innovation patterns for change in technological regimes. These different patterns are entitled *supplier-dependent*, *user-driven*, *mission-orientated* and *R&D-dependent* (2003). These are well-known influencing factors on the direction of firm strategy, but the patterns from Van de Poel seem to attribute little agency or power to the existing regimes or their members.

This paper will, however, use a third framework as proposed by Smith et al. (2005), which has its intention of governing sustainable transitions. They look specifically at the transformation of existing regimes and propose two dimensions to map transition contexts. The first dimension measures whether change is actively engaged and coordinated in the regime and is used to identify whether the change is intended and purposively governed or a result of random historical events. The second dimension distinguishes between the application of internal or external capabilities and resources in the change processes.

These two dimensions form four stylised types of transition context: *re-orientation of trajectories*, *endogenous renewal*, *emergent transformation*, and *purposive transitions* as seen in Fig. 2. These four will now be described in more detail.

Low co-ordination, unintentional behaviour and the application of internal resources are termed *re-orientation of trajectories*. This is characterised by an exogenous or endogenous shock to the regime unintended by the regime actors, which leads to radical transformation. High coordination and the application of internal resources are termed *endogenous renewal.* This is characterised by action taken by conscious coalitions within the regime as a result of perceived threats to the regime. These are transformation processes that are incremental and path following. Retrospectively they might appear radical but it has come about through the alignment of smaller changes shaped by existing capabilities. Low coordination, autonomous behaviour and external use of resources and capabilities are termed *emergent transformation*. This is typically characterised by new capabilities and technologies external to the regime, which has unintended major impact on the regime. A high degree of coordination and external use of capabilities is termed a *purposive transition*. These transitions draw on external resources and deliberately pursue an explicit set of societal expectations or interests. These four typologies cover the transformation dynamics of regimes well, with specific attention towards agency, coordination, and internal/external use of capabilities. These typologies and associated terminology by Smith et al. (2005) will be used on the empirical case in this paper to explain the context of energy efficiency, policy and innovation.

4. Research methodology and data analysis

The research methodology applied in this paper builds on a generic case study methodology (Yin, 2009) but expands using a mixed methods approach to provide a detailed empirical account of the case narrative.[4] The study draws primarily on qualitative data from semi-structured interviews with key actors (circulator manufacturers, technology consultants, policy-makers and researchers) but it also ties in with several types of additional data. The additional data comes from different sources among others the European Association of Pump Manufactures (EUROPUMP), several technical reports, policy documents, industrial magazines (World Pumps, Pump Industry Analyst) and patent databases (Derwent). These complementary data sources are combined to create a coherent case narrative based on sequential, historical events, which allows for a rich understanding of the complex dynamics of the case. In a few cases a simple count-based keyword method is used to support events identified through qualitative data — for example to point out the attention on certain concepts in the industry by looking at industry magazines.

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[4] Inspired by Geels (2002).

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Using a mixed methods approach minimises historical or company bias. The study will, however, mention some manufacturers more frequently than others owing to their relative size in the industry and their importance in steering socio-technical change.

5. The circulator industry transformation in Europe

Pumps have been produced and used for more than four thousand years. This paper, however, focuses on a specific type of standardised pump – the hot water circulator (see the image on p. 2). Compared to other types of pump they are small in size and power but they are very widespread in application. According to the EUP Lot 11 study the total installed stock of circulators was approx. 140 million in 2008 (AEA Energy and Environment, 2008).

Different from the average pump, a circulator is a more integrated and standalone device and it is more of a mass-market product. The market for standalone circulators is, however, connected to the overall market for oil and gas boilers with approximately half of all circulators ending up in a boiler. This case will focus on the standalone circulators where the pump manufacturers have direct interaction with the entire value-chain. Furthermore, the boiler-integrated pumps were left out of the initial policy efforts because of a conservative and reluctant boiler industry.

Typical homeowners are not aware of having a circulator pump or of its high energy consumption. The pumps are usually hidden away in houses and are only thought of when they fail. When purchasing a new circulator pump it is typically the plumber who decides the size and make of the circulator based on their skill, experience and preference. Therefore the market parameters have always been the upfront cost of the circulator and its reliability (i.e. operating lifetime and serviceability).

A socio-technical transformation is usually a long and gradual change process (Geels, 2002). The case of the circulator pump industry is no different and therefore the case narrative is divided into six chronological periods. Periods 1 and 2 will serve mainly as a background introduction to how the circulator industry originally emerged and how it can be characterised. Period 3 will describe a period of technological innovation and subsequent market failures. Period 4 contains the process of industry alignment and the characterising of energy efficiency for circulator pumps. And lastly Periods 5 and 6 show the implementation of policies leading to innovation and actual market transformation.

5.1. An emerging industry, 1940s–1975

With the move towards waterborne heating systems, a need for smaller hot water pumps emerged. New and existing companies, primarily related to the machine industry, started making specific pumps for hot water circulation in houses and apartment blocks. The majority of the companies in the industry today were created in the 1940s, 1950s and 1960s. Very few new entrants into the market have appeared, making the industry quite stable and consolidated, with Grundfos (Denmark) and Wilo (Germany) accounting for approx. 80% of the market in 2008 (AEA Energy and Environment, 2008).[5]

At this time, circulators were simple one-speed electric motors combined with mechanical pump components in a small enclosure, whereas earlier the motor and pump components were separate from each other. In the 1960s manual variable speed pumps were introduced, which meant that the circulator could be adjusted for multiple purposes thus removing the need for several different circulator sizes. This adjustment was, however, not widely used as most circulators were unnecessarily left on the highest setting, thus consuming the most energy. At this time the functionality was not seen as a matter of saving energy but only as an extra functionality that increased the convenience for professional users.

5.2. The influence of modern electronics, 1976–1986

Modern electronics, i.e. transistors, integrated circuits and microprocessors, started appearing in the 1960s and 1970s. This meant a radical miniaturisation of electronic components and enabled the introduction of electronics in circulators.

In the late 1980s the circulator industry started looking at the use of electronic frequency converters to control the speed of their motors. This was previously done manually by simpler and more inefficient electronics, so using the new frequency converters would make the circulators smarter and more efficient. The circulator companies worked to develop smaller frequency converters than were available, as they had to have in integrated into a product similar to what was on the market. This meant increased patenting behaviour of the biggest companies in the late 1970s and early 1980s (Derwent World Patents Index|Thomson Reuters, 2014).

At this point energy efficiency was still not on the agenda of motor or pump research in general, but some did start to acknowledge the widespread savings potential of variable speed motors (Becker, 1974; Hickok, 1985), undoubtedly owing to the energy crises at the beginning of the 1970s.

5.3. Failed new functionality, 1987–1997

Following the recent development in electronics, manufacturers began introducing more advanced electronics into their circulators. This was primarily the use of frequency converters in the pump housing to enable variable speed drives.

The first pump on the market with continuous variable speed was the Wilo Star-E in 1988. Besides being able to vary the speed of the motor it was also able to sense how much hot water was needed. This combination of technologies was vital in enabling energy savings for circulators and defined the functionality of all circulators that were to come. In 1992 Grundfos ran an internal technical energy project, supported by public funding, which identified the technical aspects of an energy-efficient pump (Thiesen and Remmen, 2008).

These developments were happening in most of the industry. Grundfos especially patented technologies in the late 1980s and early 1990s according to when it was introducing new products with frequency converters (see Fig. 3).

The introduction of advanced electronics in circulators primarily meant increased functionality for professional users. But it also meant that the cost of production rose and subsequently the sales price increased up to four times compared to the previous generation of circulators.

As neither the homeowner nor the plumber was interested in paying more for the circulators upfront, the new technologically advanced pumps were largely ignored on the market. At this time the technologies were acknowledged within the industry and a clear niche of advanced circulators was formed. But they were viewed only as added functionality for the users and not as energy saving measures.

5.4. Alignment on increasing energy efficiency, 1998–2003

To maintain its leading role in the industry Grundfos, which had been developing advanced pumps for many years, was by the late

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[5] Other manufacturers include Smedegaard (Denmark), KSB (Germany), Circulating Pumps (UK), Biral (Switzerland) and Calpeda (Italy) (AEA Energy and Environment, 2008).

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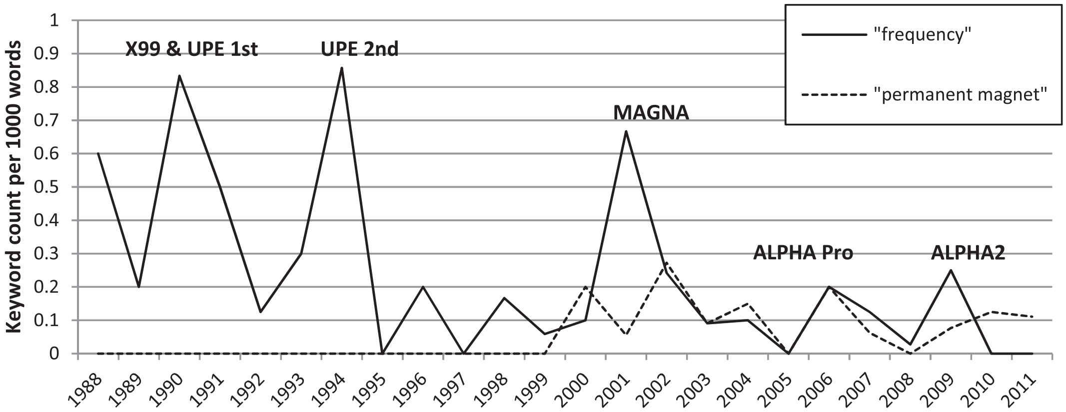

Fig. 3. Keyword analysis in the Grundfos patent portfolio combined with major product launches [Derwent database 1988–2011, Grundfos as patent applicant].

1990s thinking of ways to better market its new, more efficient pumps. Key employees within the Grundfos management sought inspiration from the energy labelling schemes for refrigerators and how their implementation was transforming the market by making energy efficiency a competitive parameter (Bertoldi et al., 1999).

As a part of the EU SAVE II programme (Specific Actions for Vigorous Energy Efficiency) Grundfos pushed to initiate a study together with a few other circulator producers and technical consultants. The study was entitled “Promotion of Energy Efficiency in Circulation Pumps, especially in Domestic Heating Systems” (Bidstrup et al., 2001) and ran from 1999 to 2001.

This study was fundamental in defining energy efficiency for circulators, its efficiency enabling technologies and the prospective policy measures. The study took inspiration for the energy efficiency index or EEI from an earlier but largely unused scheme that was a part of the “Blauen Engel” programme in Germany. This defined the load profile and calculation methodology that were combined with a classic A–G rating scheme.

As well as defining energy efficiency levels, the study also stated the following technologies as the technological options that were plausible for the whole industry to implement in order to radically lower the energy consumption of the circulators (Table 2).

These technologies were at this time not seen as radically new, as most of the manufacturers had some experience with them. It was more the case that there were perceived barriers in the market that were holding these technologies back from wide diffusion.

At the end of the EU SAVE II programme it was on the European Commission's table whether policy should be introduced based on the finished circulator study. Even though the report concluded that several policy measures were available, nothing was done, to much dismay from some circulator producers. As no European policy was implemented based on the study Grundfos made efforts to set up an industry working group through the European Pump Association or EUROPUMP, which would work to get a voluntary agreement into place through the association.

The working group decided on a final classification of the circulators in 2003 based on the earlier EU SAVE II study. Grundfos (DK), KSB (DE), Wilo (DE) and Smedegaard (DK) signed the agreement, whereas a few smaller producers did not agree on the content of the report and were not accredited on it. They did, however, later sign the agreement and included labels on their pumps.

Table 2
New energy efficient technologies (Bidstrup et al., 2001).

Variable speed drives – were first introduced at the beginning of the 1990s as a way of electronically controlling the speed of a pump.
Permanent magnet motors – were a radically more efficient motor type, but their high purchasing cost slowed the implementation process.
Efficient pump housing design – a more efficient hydraulic design and better manufacturing tolerances were possible with a little increase in price.

At the time when these agreements were being made within the circulator industry the rather new concept of lifecycle cost started gaining attention in the overall pump industry (World Pumps, n.d.; LCC, 2000). From a paradigm of focusing only on the capital cost of pumping systems a shift was now made to the total cost of ownership and lifecycle cost (LCC) as the cost parameter when determining new purchases. These changes in the overall pump industry affirmed the early efforts in increasing the energy efficiency of pumps and circulators. Fig. 4 provides comparisons of estimated LCC for two comparable pumps in the market around year 2005 and then again around year 2013. Both comparisons show payback periods of two years or less, pointing to the great economic savings possible over a pumps lifecycle. Furthermore the 2013 example shows both an increase in energy efficiency and a reduction of capital cost.

5.5. *Commitment and the race to market, 2004–2008*

The industry agreement led to the implementation of the circulator energy label by 1 March 2005. The energy labelling scheme reassembled the classic A–G rating known from white goods, consumer electronics, etc. See Table 3 for an overview of the labelling scheme. At the time of implementation the D-rated circulator was the most sold with approx. 55% of the market.

In 2005 four manufacturers signed the commitment and started displaying labels on their pumps. Grundfos, Wilo, Smedegaard and Circulating Pumps[6] were at the time accounting for more than 80% of the market for circulator pumps in Europe, making their position quite substantial in the market and subsequently the adoption of the energy label very rapid – especially for a voluntary agreement (see Fig. 4).

The first A-rated pump was available on the market at the yearly industry tradeshow by Grundfos right after the labelling scheme was implemented. Grundfos had done a highly accelerated product development process to be able to have the first A-rated pump ready at the 2005 European trade fair and take advantage of its “first to market” opportunity (Thiesen and Remmen, 2008). It would continue to have this front-runner position for several years.

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[6] Circulating Pumps UK was bought by WILO in 2006 (“Wilo buys UK's Circulating Pumps”, 2006).

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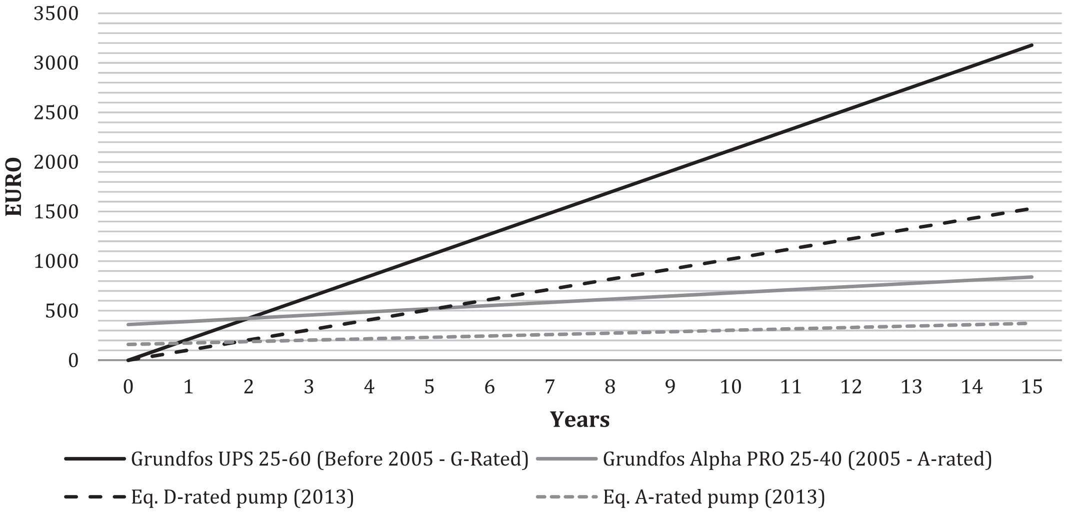

Fig. 4. LIfe Cycle Cost projections based on initial cost and lifetime energy costs (Manufacturer data – own calculations).

Some would argue that this success is also attributed to the specific region of Denmark, known for its attention to innovation in energy efficiency and environmental performance (Cooke, 2013).

At this time the price of the A-rated circulator was significantly higher than a conventional circulator, representing the addition of new advanced technologies as well as R&D expenditures. See Fig. 6 for an overview of the R&D budgets of the two largest circulator producers.

The labelling scheme acted as a stimulus for increasing and directing R&D efforts as it worked as a development trajectory acknowledged by the industry on which direction to develop new solutions (see Fig. 5). Rather quickly all circulator manufacturers had A-rated circulators in their product portfolios and for the next couple of years a significant industry transformation was underway.

In some countries national policies took up the labelling scheme. The Danish government followed up with national campaigns to promote the new energy efficient circulators as part of national energy saving programmes (Barthel et al., 2007; Lüders et al., 2009). These campaigns helped inform homeowners as well as installers on the benefits of energy efficient pumps. It was a deliberate strategy from the Danish Electricity Saving Trust to target both homeowners and installers as they saw imperfect information in both the cases, which were hindering the diffusion of the new pumps on the market.

Similarly, the Energy Saving Trust in the UK approved A- and B-rated circulators as energy saving measures. This furthermore enabled Grundfos to encourage the UK energy suppliers to use the energy efficient pumps as part of the Energy Efficiency Commitment scheme in the period 2005 to 2008 (Bidstrup and Seymour, 2006). Germany later introduced an economic cashback scheme that in combination with the energy label has proved very successful (Installer Online, 2014).

Table 3
Pump energy efficiency labelling scheme.

Class	Energy efficiency Index (EEI)	Est. yearly consumption (kWh)
A	EEI < 0.40	70
B	0.40 ≤ EEI < 0.60	–
C	0.60 ≤ EEI < 0.80	–
D	0.80 ≤ EEI < 1.00	380
E	1.00 ≤ EEI < 1.20	–
F	1.20 ≤ EEI < 1.40	–
G	EEI ≤ 1.40	–

These marketing efforts proved vital in influencing existing purchasing behaviour to enable environmental consideration primarily through a lifecycle cost perspective for homeowners and building managers.

Also, within the overall pump industry there was increased attention towards energy efficiency. When looking at keyword occurrences of "energy efficiency" in the leading industry magazine *World Pumps* there was a large increase in 2005 continuing to 2008, where the industry interest for energy efficiency reached its peak (see Fig. 7). Before this period there was a modest interest in energy efficiency. This increase can be attributed to the industry commitment as well as to a general increasing attention to climate and sustainability in the overall socio-technical landscape.

The best-selling pump in 2005 at the time when the label was introduced was D-rated but only two years after the label was introduced the best-selling pumps were B-rated, which showed the beginning of the overall market transformation. The B-rated pumps were at this point merely optimised versions of the former D-rated pumps, and they did not really bring any of the major technological advances projected for the circulator industry. These did, however, act as a quick and inexpensive replacement for the D-rated pumps before the complete integration of the energy efficient technologies and the major transformation towards A-rated circulators, which took place up until 2012.

Fig. 8 precisely illustrates the transformation of the market from low tech, low efficiency circulators to high tech, high efficiency circulators in the years 2005–2012. The speed of the transformation is quite remarkable considering the voluntary nature of the agreement. It should, however, be noted that only a few years after the label was introduced the immediate effect was noticed by European policy-makers who began investigating the possibilities of making it into European regulation. This interest from European policy-makers made the industry anticipate future regulation, which has increased the rate of change in the market transformation (see Fig. 9).

5.6. From industry commitment to European regulation and beyond, 2009–2013

In July 2009 a total of thirteen European manufacturers (up from four in 2005) had signed the commitment to use the labelling

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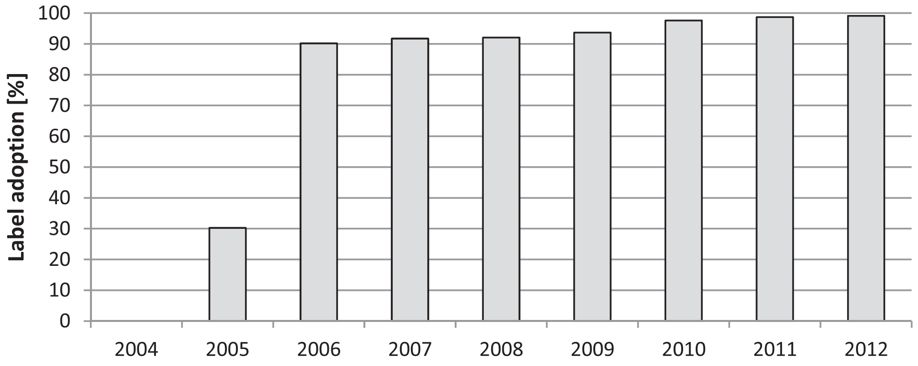

Fig. 5. Percentage of labelled pumps of the entire production (EUROPUMP, 2013).

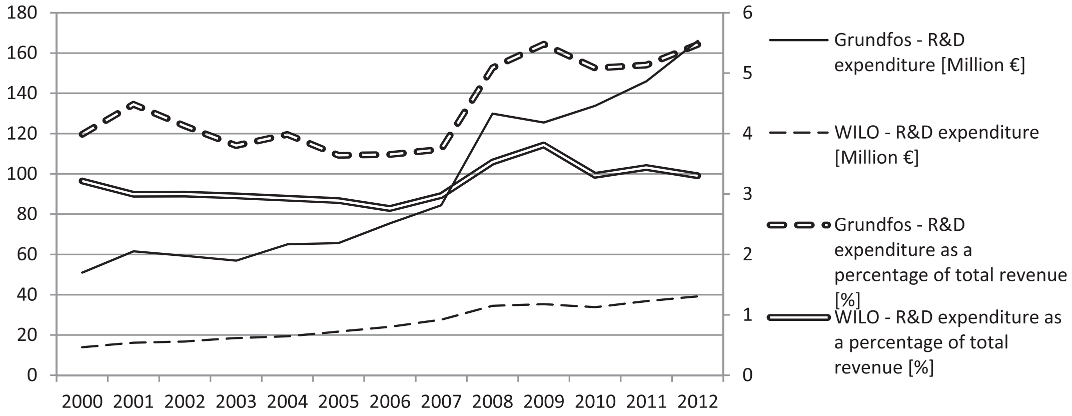

Fig. 6. R&D expenditure in million € and percentage of total revenue. Grundfos 2000–2012 [Grundfos annual reports] – WILO 2000–2012 [WILO annual reports].

scheme, making it apparent that the European circulator industry had aligned on the integration of energy efficiency efforts. European policy-makers caught on quickly after seeing the positive effects of the voluntary agreement and saw this as an opportunity to integrate it with the extensive Ecodesign directive.

By February 2008 the report “Circulators in Buildings” was made for the European Commission (AEA Energy and Environment, 2008). This was an extensive report on the circulator industry, circulator technology and potential policy scenarios. Several policy options were proposed to continue the transformation to more efficient circulators – as shown below in Table 4.

The policy process from consultation to regulation ran from the beginning of 2008 until August 2009 where European regulation for circulators No 641/2009 of 22 July 2009 was agreed upon. The directive had its outset in the 2008 report on circulators and defined a regulatory roadmap constructed as a two tier implementation of minimum efficiency demands for standalone circulators – see the overview in Fig. 8. Compared to the 2005 voluntary agreement these requirements for energy efficiency were very ambitious, with 2013 levels of EEI ≤ 0.27 and 2015 of EEI ≤ 0.23 compared to the 2005 A-rating of EEI ≤ 0.40.

An addition to the new stricter requirements for standalone circulators were boiler-integrated circulators now also included in the regulation, although with a longer adaption period as they were not as familiar with energy efficient circulators. The European boiler industry had long been working against the policy development.

By January 2013 as the Ecodesign directive superseded the voluntary industry commitment from 2005, manufacturers were already marketing new super-efficient circulators with an energy

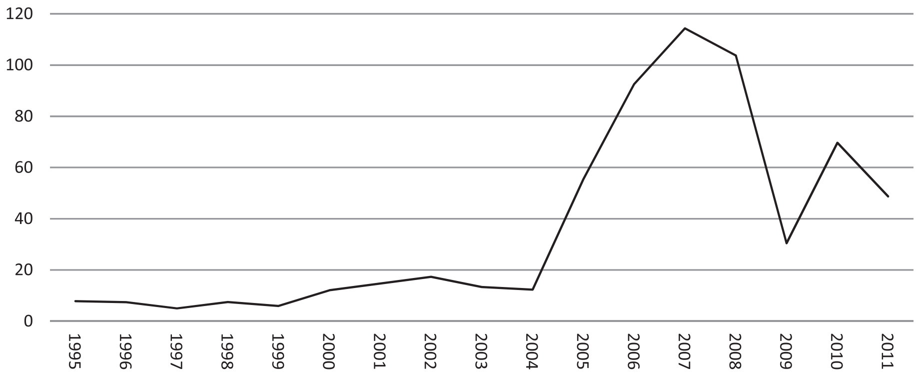

Fig. 7. “Energy efficiency” keyword occurrences per 10000 words in *World Pumps* industry magazine [Elsevier database – World Pumps 1995–2011].

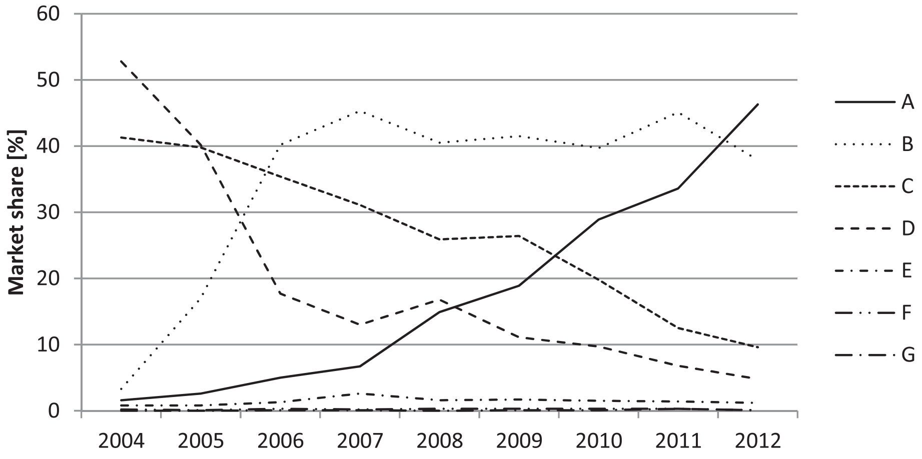

Fig. 8. Development in the market share of all energy labelled circulators, 2004–2012 (EUROPUMP, 2013).

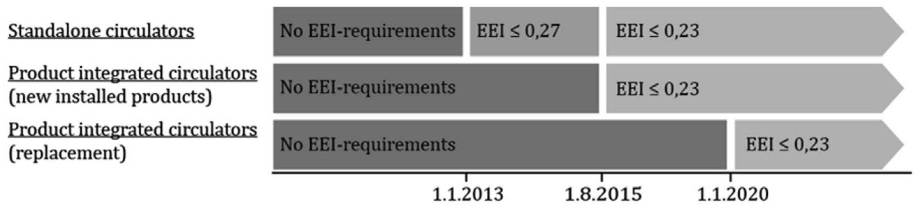

Fig. 9. Overview of the EEI requirements roadmap from the Ecodesign directive (EUROPUMP, 2011).

efficiency index as low as 0,15, outpacing even the 2015 requirements by a significant margin. This marked the end of the regime transformation so far and demonstrates how energy efficiency as a competitive parameter has been incorporated into the circulator industry, bringing with it innovation, market growth and a great reduction of the environmental impacts of new circulator pumps.

6. Case analysis and discussion

Retrospectively, an innovation journey (Van de Ven et al., 1999) is typically illustrated as a long and bumpy road where there are great uncertainties and where the end is never really clear or even known. This is especially the case for sustainable transformations, where there are an even greater number of barriers regardless of the availability of well-functioning products and technologies. Furthermore, energy efficiency can be seen as a particular contextual space since the environmentally-friendly element is only a secondary feature to the main functionality of the product or system. This will, however, enable the use of sustainability and environmental performance as a secondary competitive parameter as was hypothesised by Michael Porter (Porter and Linde, 1995) and to some extent illustrated in the circulator case.

The study describes the case of incumbent industry actors struggling within their own regime, unsuccessfully attempting to commercialise new energy efficient technologies. Internal efforts were initiated inspired by policy developments in the white goods sector when a few manufacturers began investigating the possibilities of integrating energy efficiency concerns into their industry. A breakthrough came in 2005 in the form of a voluntary energy labelling agreement that quickly gave circulator producers a way of differentiating their products in terms of energy efficiency. The label was almost immediately recognised by national policymakers and implemented in national energy saving policy. The combination of different policy efforts meant that the market started reacting and rather quickly energy efficient circulators started making their presence in the market despite the fact that the enabling technologies had been available since the early 1990s. Table 5 shows an overview of the policy influence on different innovation activities, based on the Kiss et al. (2013) framework. This clearly points to the diversity of policies needed to overcome the barriers towards energy efficiency improvements in existing products (Nadel and Geller, 1996; Bertoldi et al., 1999; Geller et al., 2006). This ongoing market transformation was quickly noticed by European policy-makers who wanted to accelerate the process and as a result made a regulatory roadmap for the energy efficiency of circulators in Europe. The circulator industry initially had mixed views of these new demands but at the time of actual implementation they were all in front of the regulation, showing that energy efficiency under the right circumstances can act as a powerful driver of innovation and have impact on the dynamics of established regimes and transform their inner workings.

This successful transformation of the socio-technical regime was realised by coordinating and enrolling institutional actors and linking visions with overall landscape developments (Geels and Schot, 2007). Furthermore, they front-runners mobilised support

Table 4
Policy options presented in the 2008 report “Circulators in Buildings”.

Minimum efficiency level of A+.
Splitting rating A into A, A+ and A++ (until minimum A+ efficiency).
Direct move from rating B circulators to rating A*. This was argued as better for both industry and consumers, as there would be fewer incremental steps.
Consider how to include boiler integrated circulators – as they have been left out of the voluntary agreement.
Change the existing voluntary commitment to being mandatory and move it to the EU Commission.
EUROPUMP must revise the EEI calculation methodology to level the difference between small and large pumps.

Table 5
Policy influence on the circulator innovation process (Adapted from Kiss et al., 2013).

Policy instruments:	Public R&D/↓	Building codes/↓	Product labels/↓	Information campaigns/↓	Voluntary standards/↓	Education & training/↓	Financial incentives/↓
Technology development:							
a) Direction of search and development	++		++		++		
b) R&D resources	++	+	+		+		+
c) Management of new knowledge	+	+	++	++		+	+
d) Testing	+						
Actors and networks development:							
a) Sophisticated user group		+	+	+	+	+	+
b) Form of producer–user interaction	+	+	++	++	++	++	++
c) Proximity & mutual interest of actors and networks	+	+	++	++	++	+	++

at all levels of the system (Callon, 1986) and in particular with policy-makers and end-users (Matos and Silvestre, 2013) that had earlier hindered the transformation. This regime transformation primarily takes the shape of *endogenous renewal* according to the framework by Smith et al. (2005). The change was envisioned and actively coordinated by “powerful” regime members who quickly established strong coalitions (Thiesen and Remmen, 2008). Initially new technological capabilities were external to the socio-technical regime, but they were quickly integrated, adapted and further developed according to the direction of the regime. You could argue that the resources were external to the regime, but actually they were integrated and developed at a very early stage, alongside similar developments. So the development of capabilities was mostly within the regime members.

The regime transformation was incremental and path-following, as most developments in energy efficiency are, but retrospectively the change to the system was quite radical in terms of reducing barriers inherent in energy efficiency and increasing innovation and environmental performance in the products.

The somewhat controversial part of the case is the large role of industry in the shaping of its market and related policies, although the outcome is appraised positively (Smith et al., 2005). The activities made by the involved industry actors resemble activities combined in the transition management cycle (Loorbach, 2007). In this literature, industry and business are seen as an important part of transitioning towards sustainability (Loorbach and Wijsman, 2013) equally to what was seen in the circulator case. This is different from most management and business literature that depicts firms as steering away from change and sustainability. The case does however show how some industries can benefit economically from the integration of sustainability concerns while creating shared value for users and the environment.

7. Conclusion

The necessity for systemic change is great in these times of resource scarcity, climate change and environmental issues. Increasing energy efficiency and achieving energy savings are a necessary part of mitigating these challenges. Even though there are valid economic and societal reasons for increasing the energy efficiency of products and systems it doesn't occur by itself – as with many other types of sustainability challenge (Rennings, 2000). Here the literature typically argues for policy to intervene and help environmentally-friendly products and services to succeed on the market (Kemp, 1997). Policy is usually vital in innovation processes, but exactly how it is created and how it interplays with industry, technology development and market dynamics is not well known in the current literature.

The circulator pump case presented in this study describes the positive effects of having energy efficiency integrated into an existing socio-technical regime to guide its technological trajectory and market development. The case is viewed as an evolutionary innovation process where one activity doesn't necessary lead to the next, but where all elements are co-evolving over time. This in-depth way of understanding innovation processes proves especially important in sustainable innovation where there is high complexity along certain institutional and organisational barriers which are hindering the widespread diffusion of environmentally-friendly products and services (Soete and Arundel, 1993). The study shows how policy doesn't necessarily come first and industry second. These relations and interactions are much more complex than what is generally depicted in the literature.

The design and timing of policy intervention is crucial in removing these barriers and assisting the innovation process of environmental-friendly products (Nill and Kemp, 2009). Perhaps even more important was the drive and agency for policy coming from industry actors that had envisioned for policy efforts to support their R&D and future business development. The voluntary energy label and subsequent minimum efficiency regulation meant a change in market dynamics and a transformation of the industry in only a few years. This new paradigm in the circulator industry has led to yearly energy savings on circulators upwards of 85% and an estimated 23 TWh a year in 2020 while supporting growth in the industry (ECEEE, 2014).

According to the International Energy Agency there are vast energy savings possible through energy efficiency improvements in both industry and households (IEA, 2011). This paper illustrates the good example of how energy savings, growth, technology and policy can co-evolve and enable innovation and sustainability.

7.1. *Policy implications*

From the findings in the study there are three main lessons to take into future policies.

- *The role of public policy in regime transformations*

Regime transitions and transformations towards sustainability are very difficult and public policies are crucial in order to overcome barriers towards change. The case illustrates the perfect example of how policies can help guide new directions of existing regimes by reducing market barriers and enabling innovation and business development.

- *Synergies between policy efforts*

Policies rarely stand alone, which is why coordination between policies can be crucial to obtain synergies (Birner and Martinot, 2005; Kemp and Pontoglio, 2011). The case shows how synergies between several policies such as energy labels, information

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campaigns, public RD&D funding and building codes are crucial to enable the greater transformation of established regimes.

- *Stakeholder involvement, interaction and engagement*

The case points to the importance stakeholder enrolment, interaction and mobilisation in the transformation of existing socio-technical regimes. Without a few leading companies creating the voluntary energy label, the manufacturers as a whole were not able to convince the consumers. This requires the merging of diverse sets of interests, which can be very difficult (Matos and Silvestre, 2013). Using common visions and shared future opportunities can be a way of enticing and enrolling (Callon, 1986; Akrich et al., 2002) stakeholders according to transition management (Loorbach, 2007).

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7.2 PAPER #2 – PUBLIC POLICY AS DRIVER OF ENERGY EFFICIENCY INNOVATION - ACTOR-LEVEL EVIDENCE FROM PUBLIC R&D PROJECTS IN DENMARK

PUBLIC POLICY AS DRIVER OF ENERGY EFFICIENCY INNOVATION - ACTOR-LEVEL EVIDENCE FROM PUBLIC R&D PROJECTS IN DENMARK

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Abstract

Increased energy efficiency is of crucial importance in addressing climate and sustainability issues but the drivers of energy efficiency innovation are not well-researched. Where the literature concerning energy efficiency predominantly focuses on the barriers towards increasing energy efficiency, this article investigates to which extent public policies are driving innovation activities. Where previous studies either have had a single sector focus or a very broad economic focus, this study uses an actor-focused approach with coverage across different sub-areas. The analysis is based on a questionnaire with project leaders in public research and development activities within energy efficiency in Denmark. The paper finds that a mix of different public policies is driving a significant share of innovation activities aimed at increasing energy efficiency. These vary across different sub-areas of energy efficiency, but the policies also appear to have very broad influences across different sub-areas. Furthermore, the study finds that public policies are not isolated from other drivers like technology- and market development, but that it is in a successful interplay that innovation in energy efficiency is best supported.

1. INTRODUCTION

Energy efficiency improvements are of central importance for addressing the serious climate and sustainability problems the world is facing today. Together with a transition to sustainable energy supply systems based on renewable sources, continued efforts for energy efficiency improvements are needed in order to reduce the problems without at the same time hindering the possibility of societal development and progress. Energy efficiency improvements in many cases include elements of technological development, innovation and build-up of new competences and know-how. In the growing attention to energy innovation for climate protection and sustainability, energy efficiency solutions and improvements of end-use technologies are however low prioritized and often overlooked and marginalized compared to energy supply technologies (Wilson et al., 2012). This is the case even though energy efficiency can contribute large potential emission reductions and in many cases promise high social returns on investments also compared with energy supply technologies (IEA, 2014).

Hence, there is need of more knowledge and insight in the dynamics of energy efficiency innovation, i.e. the activities related to the invention, commercialisation and diffusion of new energy efficient solutions. This study contributes through an actor-orientated analysis of the influence of public policies on energy efficiency innovation as they occur in connection with a larger number of publicly supported research and development projects (R&D) in the energy efficiency area in Denmark. The study addresses whether public policies in energy efficiency are acting as a driver of innovation activities based on the experience of the embedded actors. The background for this is that it is the experience from a number of studies that find that policy efforts are a prerequisite if the barriers towards energy efficiency shall be reduced and significant energy efficiency improvements shall be made (Shama, 1983; Geller and Nadel, 1994; Geller et al., 2006; Noailly and Batrakova, 2010; Kiss et al., 2013). These studies do however not contribute with much understanding of how these policies influence innovation, they only focus on the barriers towards diffusion. The study furthermore offers insights across different sub-areas of energy efficiency and different policies, hereby making an important contribution and supplement to the case-specific barrier analyses that are most often seen in the literature.

Energy efficiency efforts take place in many sectors and in many activity fields. It is as such, a highly distributed phenomenon. It is not a one-sector issue or a matter of one technology area only. Hence, there is good reason for attention to policy as a driver for energy efficiency across many sectors. What ties it together as a common phenomenon is the shared discourses of the needs for energy savings and efficiency improvements and, moreover, the policy efforts on energy efficiency established in many countries and internationally. The study builds on the assumption that policy efforts are of central importance for creating energy efficiency improvements that become significant on a societal level and make substantial changes to the energy consumption within a sector.

This however makes it difficult to study energy efficiency development dynamics in general and if one wants the specific development dynamics in detail. It cannot be assumed that the innovation and change dynamics are identical from one area to another or between different sectors (Pavitt, 1984). To study energy efficiency innovation in general is a difficult task as it is not delimited to one sector or one societal field only. It takes place in many sectors and fields.

Within a general research objective of contributing to a better understanding of the relationship between energy efficiency policy efforts and innovation, the research question guiding this study is: *whether public policies are driving energy efficiency innovation activities*. In this study we attempt to identify policies which are driving energy efficiency innovation, which is a reverse approach to most of the existing literature on energy efficiency, which attempts to explain the lack of diffusion due to economic and social barriers (Shama, 1983; Hirst and Brown, 1990; Lovins, 1992) and do not apply an overall innovation perspective. This is not to undermine the research efforts to remove barriers towards energy efficiency, these must continue, but it is a unique look into specific focus areas where public policies for increased energy efficiency is making an impact on the innovation activities as well. With this article we will argue that an actor-focused cross-sectoral and mixed-policy understanding of energy efficiency is needed, in order to highlight the impact of policies going across individual areas of energy efficiency innovation activities.

The article is structured as follows: In the next section, a short introduction to innovation and the notion of drivers where after the main findings of existing studies of policy drivers in energy efficiency innovation are described. Thereafter follow firstly a section on the analytical framing applied in the paper. Next, a description of the research methodology and the empirical data which is subsequently followed by the analysis results and finally the conclusions are presented and discussed.

2. EXISTING KNOWLEDGE OF DRIVERS OF INNOVATION AND THE ROLE OF ENERGY EFFICIENCY POLICY IN DRIVING INNOVATION

The following firstly provides an introductory overview of drivers of innovation and how these have been conceptualised differently in the innovation studies and sociotechnical systems literature. Secondly, the main studies of environmental and energy efficiency policy and its impact on innovation and technological change are presented illustrating the gap in which this study contributes.

Drivers in innovation studies and science and technology studies

The notions of driving forces[1], drivers, determinants and sources of innovation as elements influencing the direction, rate and overall characteristics of innovation processes have been addressed in number of studies of innovation and sociotechnical change. The studies differ considerably concerning perspective and there is no general consensus of how driving forces of innovation shall be approached or which types of driving forces that are addressed. In many cases the driving forces addressed are defined pragmatically as those aspects the study focuses on, rather than using a specific systematic or comprehensive theory in the selection.

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[1] Driving forces and drivers are used interchangably throughout the text. Determinants is a common in the quantitative literature whereas sources of innovation is more common in the firm-level innovation management literature.

A large number of studies on driving forces of innovation focus on individual firms as locus of innovation. Of these, one group of studies understand driving forces of innovation as an issue of firm internal characteristics e.g. concerning organisation of innovation processes, R&D, creativity, human resources, knowledge management, and IPR practices (Nelson, 1991; Teece et al., 1997). Other studies include characteristics of the firm as such, e.g, size of the firm, patents, collaboration networks, or high-tech or low-tech firms as important factors for the innovation (Bhattacharya and Bloch, 2004). In addition to this, a relatively big group of studies address firm-external aspects as driving factors of the firms' innovation. Many different aspects are taken up by these studies. One major sub-group deals with knowledge sources and knowledge collaboration by the firms. Often there is emphasis on formalized knowledge and firm-university collaboration, however as shown knowledge in the shape of learning by doing, learning by using, learning in interaction are also important types of knowledge sources influencing firms innovation (Jensen et al., 2007). Users and customers as well as suppliers have been identified as important knowledge and information sources for firms' innovation and user knowledge and user-producer interaction are in many cases central driving forces of innovation (Hippel, 1988; Laursen and Salter, 2006; Laursen, 2011).

A group of studies address aspects of the firms' contexts like market and industry structures, geographical clustering's etc. on a regional or national level as possible factors driving innovation (Porter, 1990; Love and Roper, 1999; Edquist and Hommen, 2008; Vaz and Cesario, 2008; Kourtit et al., 2011). Matters of public policy are primarily addressed in the shape of public research, education and R&D funding. Apart from this public policy is rarely included as possible innovation driver. A reason for this can be that most of the mentioned studies are about innovation in general and not focused on a specific sector or societal field where policy efforts might be of specific importance.

One of the most extensive scientific debates of driving forces of innovation has been the discussion within innovation studies of technology push versus demand pull as primary dichotomy for driving forces, the former arguing for that science and technology developments as exogenous forces of society are the main driver of innovation, while the latter pointed to needs and market demands as the primary driver and argued that technology development is an endogenous force and part of the societal economy (Freeman, 1979; Mowery and Rosenberg, 1979; Dosi, 1982). The two perspectives of driving forces of innovation and technological change appeared in studies in the 1950s and 1960s and were debated for years as opposite and conflicting. The debate however reached a consensus that a combination of technology push and demand-pull often appears and that they interrelate (Nemet, 2009; Peters et al., 2012). This led to a shift away from linear models of innovation to more interactive models with higher complexity and emphasis on co-evolution and feedback processes between different activities (Kline and Rosenberg, 1986; Di Stefano et al., 2012; Horbach et al., 2012).

The perspective of innovation and socio-technical change as a matter of co-evolutionary, multi-actor processes has developed in the recent decades (Kemp et al., 1998; Geels, 2004a). These studies have identified the complexity and heterogeneous character of processes of innovation and technological change and showed how innovation and technology development do not follow a specific, predetermined pattern or a linear model of development, but appear as result of activities and interactions usually by many different actors and in interplay between different levels of activities. New niche experiments and niche developments occur in a complex

interplay and rivalry with existing systems and regimes. Change processes that become of societal significance usually appear through activities over longer periods of time.
In this perspective, drivers of innovation are a matter of actor efforts, relations, and enactments at different systemic levels and within different institutional contexts. Public policy does not have just one role only in this, but can also appear in different shapes both as regime preserving element and as driving force and enabler of innovation (Chappin et al., 2007). It can support niches and protected spaces for bottom up experiments and it can be a part of the rules and institutions that structures an activity area. Influence of efforts by public authorities has for example been identified to appear in connection to technology developers (firms, engineers and designers), users, and research organisations (universities, technical institutes and R&D laboratories) (Geels, 2005).

Public policy as driver of energy efficiency innovation

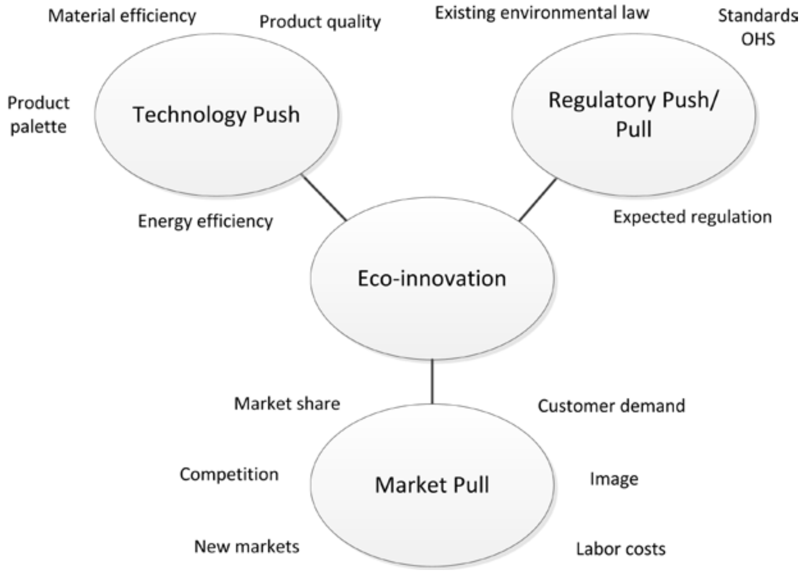
There are few existing studies specifically concerning public policy as a driver for energy efficiency innovation activities. However, a number of studies addressing energy efficiency and technological change have been carried out over the latest decades (Jaffe et al., 1993, 1999; Popp et al., 2010). A general finding across many of these studies is the so-called energy efficiency gap: the paradox that despite immediate economic and environmental benefits from new energy efficiency solutions, the adoption of the new solutions do not appear to the extent that could be expected from techno-economic estimates of the benefits (Shama, 1983; Hirst and Brown, 1990; Reddy, 1991; Jaffe et al., 1993; Jaffe and Stavins, 1994). Hence, it is identified that cost reductions and similar economic aspects can be drivers of energy efficiency innovation, but often they are weaker drivers than techno-economic rationalisations would suggest. Usually they are not sufficient in themselves to drive innovation.

Not least building on this insight, a body of studies have addressed barriers to energy efficiency (Hirst and Brown, 1990; Jochem and Gruber, 1990; Reddy, 1991; Sutherland, 1991; Howarth and Andersson, 1993; Weber, 1997; Brown, 2004; Sorrell, 2004; Fleiter et al., 2011; Ryan et al., 2011). Following the overview by Sorrell et al. (2000), barriers of organisational, behavioural and economic character are identified, including issues of bounded rationality, imperfect information, and involvement of multiple rationale dimensions, not just one single. As pointed out by many scholars (e.g. Shama, 1983), the energy efficiency rational does not stand alone but is dependent on rationales of the need fulfilment and function a solution delivers. Energy efficiency is seldom the only feature of a new product or service innovation, but a feature on top of the primary function or service the solution delivers. This implies that the innovation dynamics vary considerably from area to area (Pavitt, 1984).

In many cases the studies of barriers also address policy efforts (Lovins, 1992; Golove and Eto, 1996; DeCanio, 1998; Fleiter et al., 2011) and identifies that policy efforts are often needed and can be important drivers for energy efficiency innovation. This is not always the case though, as it is dependent on the policy design and the combinations of policies. The attention to policy and regulation as a driver of innovation is parallel to the now infamous Porter hypothesis about environmental policy in general as a driver for innovation and competitiveness (Porter and Linde, 1995a, 1995b). Empirical studies in the energy efficiency area tend to show varying effects of policies on energy efficiency technological change depending on the product areas and their characteristics (Newell et al., 1999). Large, cross-going reviews of the literature find partly conflicting results (Jaffe et al., 2002; Popp et al., 2010) but overall conclude that the empirical evidence and theoretical findings show that market-based instruments for environmental protection are likely to have significantly greater, positive "innovation inducing" impacts over time than command-and-control approaches on the invention, innovation, and diffusion of desirable, environmentally-friendly technologies. They also find support for the impact of product labels in conjunction with rising energy-prices on substitution of inefficient products with more efficient ones. A major caveat in their studies is however that their command-and-control policies are not progressive and tend to follow behind the majority of the market.

Some researchers in Europe likewise have an interest in this relation between environmental regulation and eco-innovation and propose a more dynamic perspective of a "regulatory push/pull effect" - FIGURE 1 (Hemmelskamp, 1997, 1999; Kemp, 1997; Leone et al., 1998; Cleff and Rennings, 1999; Hemmelskamp et al., 2000; Chappin et al., 2007).

FIGURE 1 – Determinants of innovation (Cleff and Rennings, 1999)



This perspective rejects a linear understanding of policy and innovation in favour of a systemic understanding where the innovation occurs in a co-evolutionary system influenced by several factors (Kemp and Pontoglio, 2011). Generally in their studies they find that individual policy instruments have a positive impact on environmental product innovation and in particular influence from "soft" regulatory instruments (environmental liability, eco-audits, voluntary commitments) and from eco-labels (Cleff and Rennings, 1999; Hemmelskamp et al., 2000). Furthermore they stress that environmentally innovative firms seem to be less dependent on "hard" state regulation than other, more passive firms. Hence "soft" and voluntary environmental policy measures may be sufficient for pioneers. However, "hard" measures (command-and-control instruments, duties) seem to be still necessary for a diffusion of environmental innovation to non-innovative firms.

Further along these lines Bergek & Berggren (Bergek and Berggren, 2014) reviews studies of the impact of policy on innovation with three main conclusions - "*(1) Policy plays a key role for the development and diffusion of environmental innovation in the studied sectors. (2) Different types of instruments promote different types of innovations: general economic instruments has primarily encouraged incremental innovation, general regulatory instruments has enforced improvements based on modular innovation, and technology-specific instruments appears to have been needed to support the development and deployment of radically new technologies. (3) All types of policy instruments face challenges in design and implementation: understanding the selection impact of the chosen instruments, implementing increasing stringency levels, committing to an appropriate scale, and safeguarding policy stability." p. 112*.

In accordance with these findings, a number of strategically planned policy efforts with emphasis on market transformation have proved to make a difference in Europe (Neij, 2001). The examples are typically for appliances, consumer products and components where there have been significant changes in the energy efficiency performance of products due to the implementation of energy ratings, labels and minimum energy performance standards (MEPS) (Bertoldi et al., 1999, 2012). Geller and Nadel (1994; 1996) find successes of market transformation programs for refrigerators, fluorescent ballasts, compact fluorescent lamps, adjustable speed drives, personal computers, windows and automobiles in the US. They argue that the successes occur because "governments, utilities, and the private sector have taken complementary actions (consciously or unconsciously) involving (a) R&D to develop new energy-efficiency measures, (b) market-pull or bulk purchase programs to facilitate commercialization, (c) financial incentives to stimulate early adopters, and (d) efficiency codes and standards to eliminate inefficient technologies and practices" (Geller and Nadel, 1994, p. 336), and hence points to the combination of different types of policy efforts.

Looking further into specific studies of policy efforts and energy efficiency innovation, Braungardt et al. (2014) found that the eco-design and energy labelling directives in EU have innovation impact and identified a positive correlation between the ambition level/stringency of policy requirements and the innovation impact. Similarly a case study of projects in a Japanese R&D programme showed that the public R&D support can lead to new commercial energy efficiency innovations, however only does it exceptionally as the success is dependent other factors as well, a.o.t interplay with deployment policies, continuity of R&D support, and an active marketing strategy by the involved (Kimura, 2010). An additional study found that building codes and voluntary agreements had a positive impact on the development of thermal insulation in Sweden, Germany and the UK along with encouraging interaction and knowledge sharing between industry actors (Kiss et al., 2013).

From the existing literature we can therefore expect that energy efficiency has a hard time on its own and that the diffusion of new energy efficient innovations is to some extent determined by the public policy efforts. These dynamics are approached from a sociotechnical systems perspective in this study, to better understand the diffuse nature of policies and its impact on the innovation activities. Different policy approaches are known to have different impacts on the diverse products where increased energy efficiency is desired, but in general no single policy effort, whether financial, informative or normative. A successful transformation requires a combination of all three types of policies and a stable long-term market development. Most of these institutional elements have been in place for several products in Denmark since the 1970's and we would expect this to have an impact on the level of energy efficiency innovation identified in this study. This paper complements the existing broad economic and the in-depth sector case studies within energy efficiency innovation and environmental innovation with a micro-level, mixed-policy and cross-sectoral perspective on the co-evolution of public policies and energy efficiency innovation, from the perspective of the actors involved in the activities.

Most studies in energy efficiency and policy are demanding more comprehensive and ambitious policies in order to overcome the barriers towards energy efficiency. This study takes the opposite perspective to present some of the good cases of complementary effects of public policy and innovation activities in energy efficiency.

3. ANALYTICAL FRAMING

Broadly studies of policy and innovation in energy efficiency take either a wide economic focus or a deep empirical focus into a single sector or application area. This study uses an alternative analytical framing where the attention will be on the actors embedded in the innovation activities and how they experience the impact of different policies.

As earlier mentioned a socio-technical system perspective (Geels, 2004b; Markard et al., 2012) with attention to the role of actors (Latour, 1988, 2005; Bijker, 1997; Markard and Truffer, 2008a) will act at the main theoretical perspective of the study. The socio-technical change- and system-oriented perspective where innovation is addressed as a series of interlinked change processes on multiple levels (Geels, 2004b; Markard and Truffer, 2008b; Hekkert and Negro, 2009; Markard et al., 2012) is crucial as this perspective accounts for multiple actors and has attention to the interplay and synergies between activities, meaning that innovation does not follow a linear process but is more dynamic and complex. It is in this dynamic perspective where drivers are typically numerous, heterogeneous and interrelated that public policies can act as a driver of innovation activities (Chappin et al., 2007). Therefore a socio-technical understanding is beneficial to highlight the complexities of these drivers, how they are acknowledged and eventually impact innovation activities across different areas related to energy efficiency.

The study addresses innovation activities on the level of the actors involved. This actor-orientated focus has earlier been emphasised as a perspective to understand socio-technical change in innovation systems by looking at the role and actions of actors (Markard and Truffer, 2008a). Markard and Truffer (2008a) explain the importance of the actor-level by arguing that *"Actors are of key importance for innovation systems as they influence the pace and direction of technology development with their innovation activities. Each innovation activity contributes to one or several functions of the innovation system. The aggregated effect of all innovation activities of all actors within the innovation system will finally determine its overall performance." p. 630*. Jacobsson and Johnson (2000) use the notion of "prime movers" meaning *"actors who are technically, financially and/or politically so powerful that they can initiate or strongly contribute to the development and diffusion of a new technology.", p. 630* (Jacobsson and Johnson, 2000). It is therefore of high relevance to use the actors involved in the activities as the source of data as they are expert actors or "prime movers" embedded in the socio-technical system. As earlier mentioned, this perspective perceives driving forces of innovation as a matter of actor efforts, relations and enactments in specific contexts. Drivers will typically vary over time and can appear in many different shapes. Public policy does not have just one role only in this, but can also appear in different shapes both as regime preserving element and as driving force and enabler of innovation and change (Chappin et al., 2007). It can support niches and protected spaces for bottom up experiments and it can be a part of the rules and institutions that structures an activity area (Smith and Raven, 2012). Niche experiments and niche developments appear in a complex interplay with well-established regimes and systems. With an outset in these theoretical perspectives this study contributes with insights into drivers of innovation from the point-of-view of the actors involved in the niche developments.

In the socio-technical system perspective, public funded R&D projects on energy efficiency are one out of multitude of activities that together can lead to innovation and socio-technical change. R&D projects are not necessarily the most central type of activities (Geller and McGaraghan, 1998; Cohen et al., 2002). Often other development activities, market formations and institutional developments are more, or at least as, important (Lutzenhiser and Shove, 1999). Moreover, R&D projects are usually not the only origin or starting point of a development, but build on other developments and ideas (Hagedoorn et al., 2000; Brown and Hendry, 2009). What R&D projects often can imply is a protected space for preparing, demonstrating or testing a solution experimentation in one way or the other for a period of time (Smith and Raven, 2012). A space where some of the selection conditions are more favourable and less tough on new technological niches, either in economical, technical or socio-organisational sense. In addition, the public R&D projects can play a communicative role and contribute to shared visions and in some cases also to coordination between actors as intermediary between actors in a field. This is the case for most publicly supported R&D projects and especially for projects in a declared application-oriented R&D programme as those included in our analysis.

The public R&D activities in energy efficiency occur in multitude of niches under various conditions. These efforts are not bound within a single niche and competing to influence a single regime. The heterogeneous nature of energy efficiency efforts makes it quite impossible to determine which niches and regimes are interrelated, but this study provides some insight based on the focus areas and impacts of policy efforts according to the actors involved.

4. RESEARCH METHODOLOGY AND EMPIRICAL CONTEXT

The study's research methodology and data is centred on publicly supported R&D projects and indications of policy drivers of innovation as they appear to the actors managing the projects. Alternative approaches to this could be using common output measures such as patents or product introductions. But as this study's emphasis is on the experienced impact of public policies on the activities of the embedded actors, conventional input and output measures are therefore unusable.

There are both advantages and disadvantages in using public R&D projects as the central empirical data. The primary advantage is the access to a relatively large number of activities within a broad range of energy efficiency areas. This would otherwise have been challenging to frame and a high level of consistency in the data would therefore not have been possible. As the main emphasis of the study is on the cross-sectoral nature of public policies in energy efficiency this was a crucial requirement of the data. The main disadvantage is the limited coverage of the data, which only provides a momentary and static single-actor perspective on activities and processes which must be understood in a longitudinal and dynamic way. It only covers a share of publically funded innovation and R&D activities in energy efficiency, which by no means covers the entirety of innovation activities in energy efficiency. Despite the disadvantages, the data offers some unique insights which are completely lacking in the current literature on energy efficiency policy and innovation.

The study takes its outset from the ELFORSK programme, which is defined as an interdisciplinary research, development and demonstration[2] program about efficient energy use and is seen as energy efficiency innovation in the making. They are typically not about finished and fully implemented solutions, but appear at times where there is a degree of uncertainty of how things will turn-out. The project actors leading R&D projects are not necessarily industrial firms. On the contrary, the empirical material of the study shows a variety of project leading actors, amongst others industrial firms, research institutions, technological service organisations, consultancy companies, architect companies, designers, larger user organisations (e.g. hospitals, housing associations), energy companies, public authorities, trade associations and other NGOs (Energinet.dk et al., 2007, 2011; Energiforskning.dk, 2014).

Governmental authorities define the overall priorities of the programme in dialogue with among other the energy sector actors. The day-to-day management of the programme is located in Danish Energy Association, which is the central professional organisation of Danish energy companies. The size of the programme is 25 million Danish kroner per year (app. 3,3 million euro) and has been constant on this level since 2002. The programme is much smaller than the general public energy R&D programmes in Denmark. This confirms the picture seen in other countries and on internationally level of energy efficiency as relatively low prioritized or even marginalized in the public R&D support in the energy area.

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[2] The abbreviations of R&D and RD&D are used interchangeably. The activities in the programme best resemble RD&D as the application and commercialization is of great importance in the activities.

The dataset is composed of data from two main sources: Firstly, the existing project database of the ELFORSK programme. Secondly, a questionnaire about energy efficiency and innovation was made. The questionnaire was sent to the project leaders of the projects supported by the programme. The questionnaire addressed amongst other things the organisation and innovation activities of the projects and the policy drivers of innovation experienced. From the ELFORSK database amongst other things data about the projects' subject area, contents and participants were obtained. The data from the two sources were integrated in a new database, still with the individual R&D projects as the central parameter and analysis unit. Additional material about the program and the projects has been used, for example statistics and other empirical information from the programme management.

The data material is unique in the sense that it covers a full ten-year period of the energy efficiency R&D program from 2002 to 2011 and that all projects of the programme have been approached. In total 212 projects were approached with a questionnaire response rate of 44% or equal to 93 projects in total. This is relatively high given that the survey was voluntary to answer for the respondents. The study follows a classification in seven overall subject areas of energy efficiency defined in the programme. These subject areas have been historically consistent in the funding programme and according to the authors knowledge they are some of the most comprehensive and specific categorisations in the field of energy efficiency. The subject areas are shown in Table 1 together with the distribution of projects within them. Around three quarters of the projects in the programme are about specific areas of technology/application (the six first mentioned subject areas), while the last well over a quarter of the projects deal with behaviour, including projects on barriers and instruments for change. The seven subject areas together cover a large and broad part of energy efficiency in connection to energy end use in general. The transport-area is however excluded from the program.

Table 1: The seven theme areas in the Elforsk R&D programme and the distribution of projects covered in the present analysis and in the programme in general in the period 2002-2011.

Subject areas:	Projects analysed (number / percentage)	Distribution in the programme
Buildings	19 / 20%	18%
Ventilation	10 / 11%	10%
Lighting	14 / 15%	15%
Cooling	12 / 13%	12%
Power and control electronics	3 / 3%	5%
Industrial processes	12 / 13%	12%
Behaviour	23 / 25 %	28%
Total	93 / 100%	100%

It appears that the coverage of the seven overall areas of energy efficiency in the analysis is fine and well-distributed among the areas in general, however only three projects are represented in the area of power electronics. This is however also the smallest of the seven theme areas in the ELFORSK programme in general, accounting for only around 5 % of the projects. In general, the distribution of the included projects between the seven areas is close to the general distribution in the programme. This is also the case for the yearly distribution and the distribution between different types of project leaders, with the most frequent project leader coming from a technical consultancy. The data material the analysis builds on can be considered representative for the full programme. Power electronics is not considered in the analysis, due to the relatively low coverage of the area.

The investigation of drivers was structured in the following way: For each R&D project, drivers of two kinds are identified: *1)* policies as drivers for the innovation of the specific technology/product dealt with in the project (in short 'innovation drivers'). Innovation is in this connection understood as the further commercialization and market dissemination of the technology/product. And: *2)* project initiating policy driver, illuminating the specific main reason for establishment of the project. Both kinds of policy drivers are addressed as narrowly connected to the project and the project's subject. They are not defined as addressing broader sector developments, development of a technology area as such, or similarly. While the latter type of driver is what played a role right at the time of project start, the former can appear under, around, and after the project. In this sense, it is a degree broader and more generally defined than the latter.

As a first level of classification of drivers, three categories are used: *1)* market and user needs; *2)* technology development and *3)* policy efforts. Techno-scientific developments are considered included in the technology development instead of working with a separate category of science as driver (science push). In order to enable a more detailed insight in the role of policy efforts as drivers, legislation and policy instruments are addressed in five categories: *1)* building code; *2)* product requirements & labelling schemes, *3)* information campaigns, *4)* other national legislation & policy efforts, and finally, *5)* European legislation. The authors defined the categorization with advice from experts in the energy efficiency area and from the management of the R&D programme. It uses existing categorizations, not least the International Energy Agency's Policies and Measures database (IEA 2014b), as inspiration, but is highly simplified compared to these. More generalized policy instrument typologies were discarded as the focus was on communicating to the actor-level. The fact that the R&D programme itself is a policy effort and hence a driver for the projects is obvious, but it was not considered feasible or relevant for an actor-orientated approach.

While the four first-mentioned categories of policy drivers are considered as classes that are not mutually overlapping, European legislation can be overlapping with the others. It is a matter of different levels of policy efforts as directives by the European Union are frames that are filled in by more specific legislation in the member countries.

The approach in our study is a supplement to the single sector specific and product specific approaches and to the general statistic approaches to energy consumption and economic development that also can offer valuable insight. Compared to the latter, the strength of our approach is a more innovation-close focus with attention to the specific actor efforts in building up of new competences and experiences, technological as well as other. Compared to the former, our approach does not directly map the development and improvements in a specific sector or product area, but if offers insight in what R&D-active actors in general experience as driving innovation and change within energy efficiency developments.

Denmark as the context of energy efficiency innovation activities

When building on publicly funded energy efficiency R&D project in Denmark we get empirical material from a country that has a considerable experience with energy efficiency efforts (Togeby et al., 2009, 2011). Energy savings and energy efficiency improvement have been on the societal agenda with bigger or smaller emphasis since the oil crisis in the 1970s (Lutzenhiser and Shove, 1999). A number of policy efforts have been established and worked for shorter or longer periods over more than three decades. This includes e.g. cleaner technology and cleaner production efforts in the 1980s and 1990s. Considerable energy efficiency improvements and gains have appeared. In some periods in the 1990s to the extent that economic development was de-coupled from energy increases by the energy efficiency gains (ENS, 2008). In many cases, Danish actors, not least the energy authorities have played an active role in European and international policy development concerning energy efficiency. The goal for the period from 2010 to 2020 is a reduction in total energy consumption on 7% (transport excluded) (Danish Government, 2012).

The experience with institutionalisation and establishment of policy efforts ranging from general fiscal instruments as energy taxes market forming instruments to sector or product-specific efforts. In recent years, many of these are following the EU policy and legislation e.g. on energy labelling and eco-design, integrated product policy. The R&D programme is in this context not the biggest or most central policy effort. Rather it must be considered a supplement to the other efforts. A supplement that enables a degree of experimentation with new solutions sometimes cross-going activities that naturally follows from the other policy efforts.

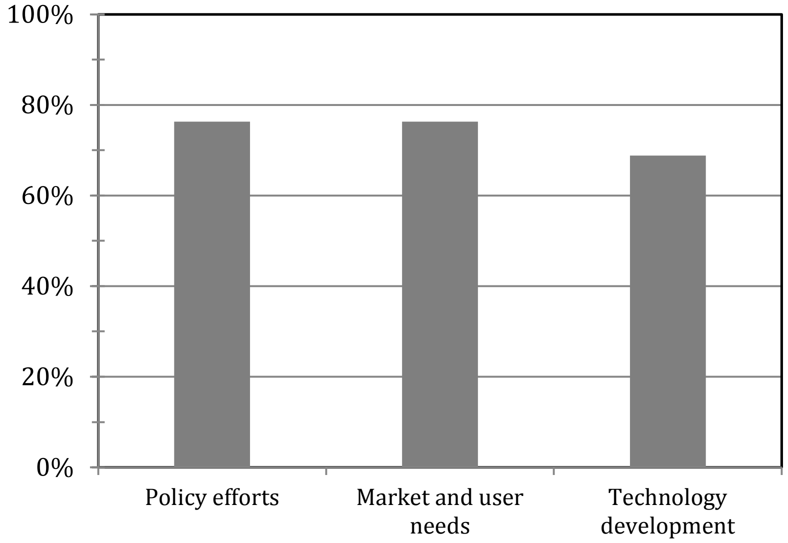
5. RESULTS

In the following the results of the analysis are presented through descriptive statistics; firstly the overall findings on respectively innovation drivers and project initiating drivers in general. Thereafter the results will go in-depth with the impact of mixed-policy drivers on different sub-areas of energy efficiency innovation activities.

Policy as a driver of innovation activities

On the overall level, the analysis finds that the two overall types of drivers, market and user needs and policy efforts each appear in connection with more than three quarters of the projects (76%). Technology development as a driver is observed in 69% of the projects and is hence less frequent than policy efforts – Figure 2. The indication that the demand related drivers are stronger than technology drivers goes well with the literature that argue that energy efficiency innovation is more predominantly about the diffusion of well-known technologies than the development of new technologies (Shama, 1983; Costa-Campi et al., 2014). Similarly the results find that the same three categories each appear as a barrier in 10% or less of all the projects.

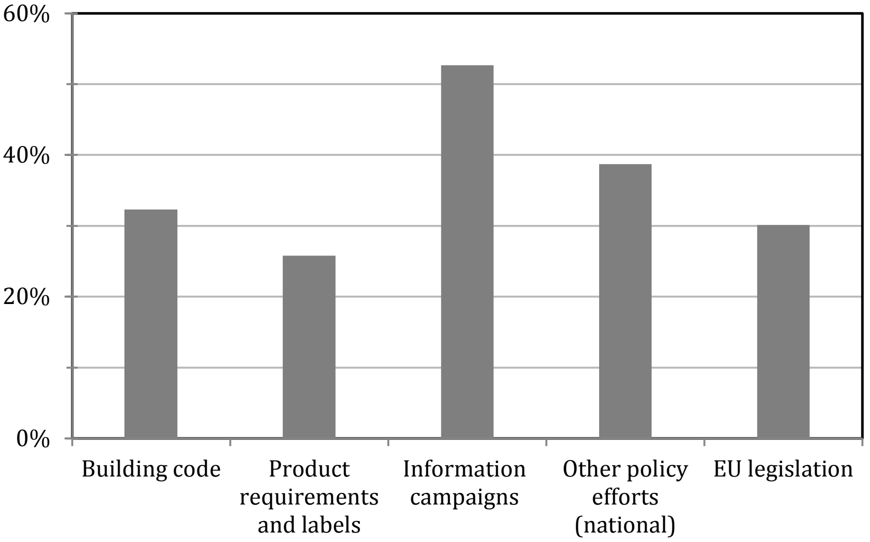
Figure 2: Share of projects influenced by generic drivers of energy efficiency innovation (share of projects, N=93).



Individual policy efforts as drivers

Turning to the individual types of policy efforts addressed in the analysis, the frequency of each individual type as innovation driving force is obviously smaller than for policy efforts in general. Still, as can be seen in Figure 3, all five types of policy efforts appear as driving force in connection to a considerable share of the energy efficiency projects. The most frequent type is information campaigns that appear as driving force of innovation in connection to around half of the projects (53%). Apart from product requirements and labels, the other types of policy efforts are influential in around one third of the projects (between 30% and 40%). Product requirements and labelling schemes that appear as the least frequent type of policy effort, still shows a frequency on 26% and hence plays a role in around one fourth of the projects. The differences between information campaigns and each of the three categories building code, product requirements and labels and EU legislation are significant (from a traditional point of view of 5% significant level). The same cannot be concluded concerning the other differences that appear in the figure.

Figure 3: Frequency of policy efforts as driving force for energy efficiency innovation (share of projects, N=93).

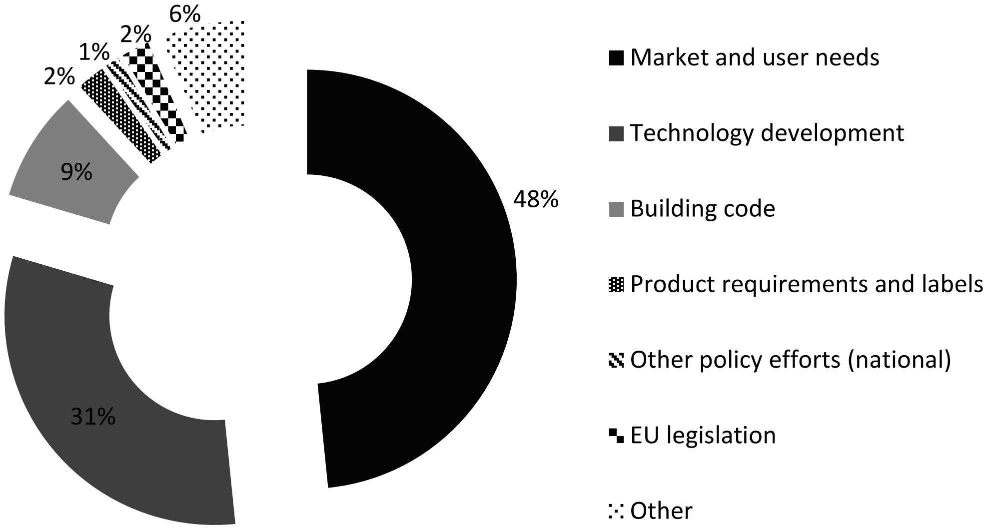


The result in Figure 2 and 3 clearly indicate that in many cases there is not just one driver identified in connection with the single energy efficiency R&D project, but a number of drivers. This confirms that innovation processes in general are complex and a matter of different, heterogeneous efforts and interactions. The rule is rather that the innovation is driven by, say, both market needs and new technological possibilities, or both policy efforts and market needs, than by one of the three factors exclusively. Also if one considers the five categories of policy drivers, there are in many cases more than one driving force identified for the single project. Here the average is 1,8 (SD: 1,5). This result, in addition to the general point about complex, heterogeneous innovation processes, points to the relevance of considering combinations of and synergies between policy efforts (policy mixes), instead of relying on one policy instrument only.

Project-initiating drivers

The analysis of the main project-initiating drivers shows similar results to the overall level and the as the analysis of innovation drivers. Market and user needs appear as the most important driver, with technology development and combined policy efforts as the second and third most important drivers, see Figure 4. Compared to the analysis of the general innovation drivers where policy efforts and market and user needs appear equally frequent, market and user needs appear significantly more often as a project-initiating driver than policy efforts do, indicating its greater immediate impact. Market and user needs are the primary project-initiating driving force for around half (48%) of the R&D projects. Policy efforts account for 14% of the projects. Technology development is also an important project-initiating driving force and constitutes the main factor for initiation of around one third of the projects.

Figure 4: Primary project initiating drivers, with policy efforts split in four categories (share of projects, N=93).



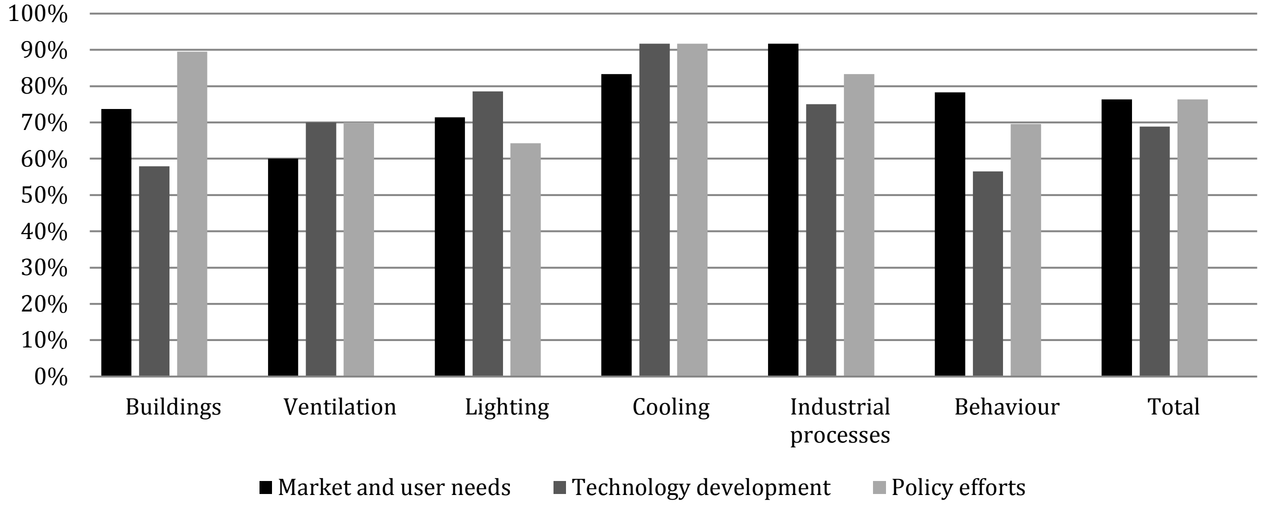
There is some degree of consistency between the results about project initiating drivers and about general innovation drivers. Policies do however not seem to be the crucial driver of initiating projects according to the project managers.

Overall characteristics of drivers in different areas

For all six subject areas, buildings, ventilation, lighting, cooling, industrial processes and behaviour, the observed share of projects that experience market and user needs as innovation driving force is 60% or higher, with industrial processes and cooling showing the highest shares, on respectively 92% and 83%, and ventilation the lowest. Similarly the share of analysed projects that experience policy efforts, as innovation driver is in all six areas around 2/3 or more. Lighting has the lowest share (64%) and cooling and buildings have the highest (92% and 89%). Concerning technology development as driving force the span observed is from 57% to 92%, with cooling as the highest. Not surprisingly, the area with the lowest share observed here is behaviour which is generally more related to social science research. Buildings also show a share in the lower end (58%).

Due to the limited amount of data in the individual areas and the statistical uncertainty this implies, one shall be careful not making *too* bold conclusions concerning differences and similarities between the six individual subject areas for the energy efficiency projects. Specifically, it cannot be concluded that each of the three overall drivers actually are influential in the majority of projects (> 50%) in all of the six areas. However, it can be concluded that all of the three are a driving force in connection with considerable share of the projects in all six areas. The uncertainty in the individual subject areas is from an ordinary significance-level consideration (5%) between 16 and 30 percentage points. The 'worst case' is market and user needs in the area of ventilation, due to the limited amount of data points in this area. Still, the share in this case is 'at worst' 30%. In all other cases it is at least well over one third of the projects.

Figure 5: Frequency of market, technology development and policy as driving force within different areas (N = 93).



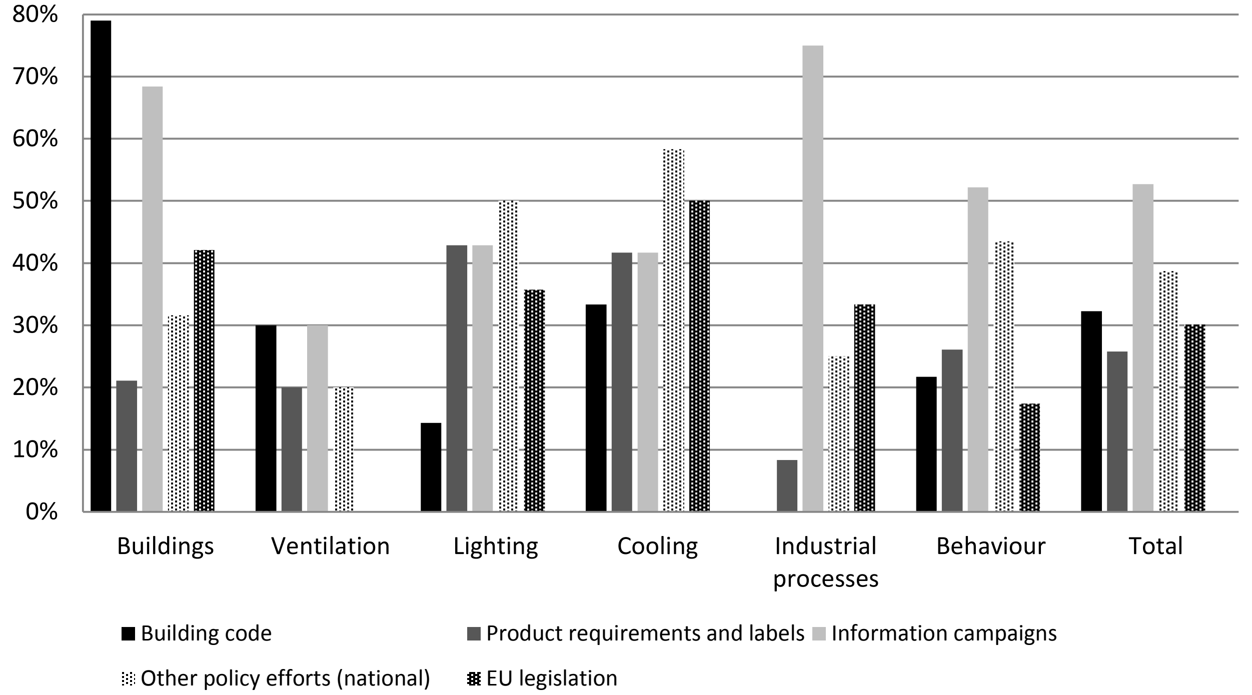
Though the innovation drivers show to be important in a considerable share of the projects, hypotheses about that some of the drivers should be decidedly obligatory points of passage for innovation, i.e., that it is impossible for innovation to appear without this driving force, do not find support in the data material. None of the drivers appear in connection with 100% of the projects.

It is interesting to notice that there is considerable variation in general in the set of drivers in connection to the projects within the individual subject area. It is not the same pattern we see from one project to another. This can again be seen as a confirmation of that innovation processes are complex processes that do not develop following a simple model or mechanistic rules.

Specific policy drivers in individual areas

The analysis of the role of the different types of policy efforts in the individual subject areas led to a number of interesting findings. First of all, that there are differences between the patterns of policy drivers in different areas, cf. Figure 6. The areas buildings, ventilation and industrial processes are the most outstanding, while the three areas lighting, cooling and behaviour are closer to the total average and only show smaller differences mutually between each other.

Figure 6: Frequency of different types of policy efforts as a driver of energy efficiency innovation in different subject areas (share of projects, N=93).



The building code is an important driver of innovation activities in the buildings area. It appears in connection with most of the projects and is significantly more frequent in this area than it is in the five other areas analysed. The difference to the frequency of product requirements/labels and other national policy efforts in the buildings area is also significant (5% level). In addition, information campaigns are a frequent driver in the buildings area. This is also the case in the area industrial processes. The difference to the frequency of the other four types of policy efforts is here bigger than in the other areas and significant with respect to product requirements/labels, other national policy efforts and, especially, the building code that is not identified as a driver within industrial processes. Within ventilation the frequencies of the individual types of policy efforts are not significantly different to what is seen in the three areas lighting, cooling and behaviour, apart from on one point: EU legislation does not appear within ventilation. In the other areas EU legislation is a driver for innovation in connection with a considerable share of the projects.

The differences within cooling are not statistically significant. The same is the case within each of the areas lighting and behaviour on a 5% significance level, however if one allows a 10% or 15% significance level (i.e. it is only 90% or 85% certain that the observations are true) a difference between the appearance of the building code and other national policy efforts in the lighting area and between information campaigns and EU legislation in the behaviour area can be pointed out.

There is considerable variation between the subject areas concerning the number of policy drivers influencing the single project. Within buildings and cooling the average number of policy efforts identified in connection to the single project is around 2,2-2,4 and hence higher than the general average on around 1,8 policy drivers per project. Compared to this the average number of policy drivers within especially ventilation, but also industrial processes is smaller (around 1,0 and 1,4). Finally, it is an interesting finding that each of the five types of policy efforts appear as innovation driver in all or almost all (at least five) of the six subject areas. They appear as drivers of energy efficiency innovation broadly speaking and not only in one area of energy efficiency.

6. DISCUSSION AND CONCLUSION

To sum up, the study finds that public policies, according to the actors involved, to a large degree are acting as a driver of energy efficiency innovation activities. Of the 93 project cases the data material contains, public policies have been influential in by far the majority of cases. The policies, however, cannot be seen as isolated from other drivers such as market- and technology development as several drivers and barriers will be impacting the innovation activities simultaneously. So while the R&D activities and experiments might take place in niches and policy-defined protected spaces they are according to the actors also influenced by the selection environment present at the regime level. A simplistic view of policy driven innovation therefore must be discarded in favour of a more dynamic perspective, such as "regulatory push/pull effect" (Cleff and Rennings, 1999; Hemmelskamp et al., 2000), where numerous policies are seen in relation to the other drivers of innovation and sociotechnical change (Chappin et al., 2007).

Of the individual types of policy efforts addressed, information campaigns are the most frequently driver for energy efficiency innovation. The others however also often appear though it is in less than half of the cases included. Within the building area, the building code is a highly important driver of energy efficiency innovation. Concerning energy efficiency innovation in the area industrial processes, it is surprising that product requirements and labelling schemes play a relatively small role. The results suggest that other policy efforts than information campaigns could be developed and become more effective drivers. This would probably also imply an increased weight on mandatory requirements instead of only voluntary efforts that information campaigns are. Although it is not certain that mandatory requirements always acts at the most effective driver (Ruby, 2015). The innovation activities in energy efficiency are however rarely only influenced by just one type of policy, according to the actors involved. The reality is that innovation activities most often is influenced by several different types of policies and that the impact might be because of the combined effect of the policy efforts. From a sociotechnical perspective it is therefore important not to reduce the relation between policy and innovation, but to understand the reality of multiple policies impacting differently according to the specific technology and how far in the innovation process it is (Chappin et al., 2007; Kemp and Pontoglio, 2011; Bergek and Berggren, 2014). The fact that European Union legislation appears as innovation driver in quite a number of cases, though still less frequent than the national policy efforts, is interesting. It is uncertain to what extent this finding reflects the double layer of legislative development on union and national levels or if the EU legislation is impacting independently of the country-specific policy measures.

The study provides a unique insight into the relevance of energy efficiency public policy efforts for innovation activities but it also points to the complexity of grasping its uneven impact across several subareas and sectors of energy efficiency. Further empirical and theoretical research must follow this direction in order to best support the continuation of energy efficiency policy efforts for cost-effectively reducing climate- and environmental issues while supporting industrial competitiveness.

Policy implications

The study originates from Denmark, a country that has a strong tradition of efforts to increase energy efficiency. This contributes to the impact of the drivers, where most literature emphasise the negative impacts of barriers towards energy efficiency. These barriers also appear in Denmark, but as the study shows market and policy drivers counteract them. The emergence of these drivers is not straightforward and is a result of developments occurring over several decades. The case of public policy as a driver for energy efficiency innovation in Denmark therefore illustrates a unique case that can be used for developing long-term policy strategies outside Denmark.

The study's emphasis on innovation is not an argument for replacing policy efforts with focus on creating significant and measurable energy efficiency improvements with an emphasis on innovation impacts. On the contrary, the study shows that exactly such clearly change-orientated measures can be important drivers for innovation. High ambitions on making significant efficiency improvements can often be an important prerequisite for creating useful and ambitious innovation, both in a technical and economic sense, as it reduces the barriers towards increased energy efficiency. These comprehensive policy efforts which target different sectors at different levels are therefore crucial for innovation in energy efficiency to occur.

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Author contributions

Both authors contributed to the intellectual content. TMR led study including study design and data collection. MB contributed to the analysis of data, to the framing of the study and to discussion of the results. Both authors contributed to the drafting of the text and to the reviewing and editing of the text.

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7.3 PAPER #3 – OPEN INNOVATION AND COLLABORATIVE PUBLIC RD&D PROJECTS IN ENERGY EFFICIENCY – A LOOK INTO PROJECT PARTICIPANTS AND PARTICIPANT DIVERSITY

OPEN INNOVATION AND COLLABORATIVE PUBLIC RD&D PROJECTS IN ENERGY EFFICIENCY – A LOOK INTO PROJECT PARTICIPANTS AND PARTICIPANT DIVERSITY

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Abstract

There are numerous elements influencing the innovation output of public research, development and demonstration (RD&D) projects. This paper uses an open innovation conceptual framing to investigate the influence of the participants, participant diversity and certain focus areas within collaborative RD&D in energy efficiency. This is done using logistic regression on RD&D project data and questionnaire data from Denmark. There are two major findings from the analysis. The first is how certain constellations, i.e. specific pairs of actors, are beneficial to have on a project – e.g. a user and an energy company. The second finding is that overall there is a benefit to having diverse project teams – actually the more diversity, the better!

Keywords: public R&D, energy efficiency, participant analysis, participant diversity

JEL: O31, O32, O38, O44

1. Introduction

Innovation activities occur in different constellations. This paper analyses the type of innovation activities that occur in public RD&D projects where multiple participants from the industry and academia work together on predefined project terms. These types of collaborations and knowledge interactions between different actors are considered vital parts of certain innovation theories, such as systems of innovation (Freeman, 1987; Lundvall, 1992; Nelson, 1993) and in particular open innovation (Chesbrough, 2003; Enkel et al., 2009).

The objectives of RD&D funding policies are numerous. Public funding helps mitigate risk in innovation projects and lowers the overall cost of innovation activities for companies. This kind of policy support is mostly applied in areas with great societal problems to overcome, such as climate change, and where it is deemed change will not occur without policy support. Recently, secondary effects, such as job creation, have also been emphasised.

This paper specifically analyses public RD&D projects in the context of energy efficiency in Denmark. Increased energy efficiency, in conjunction with efforts in renewable energy, is widely considered a vital part of the solution to current and future climate and environmental challenges (IEA, 2012).

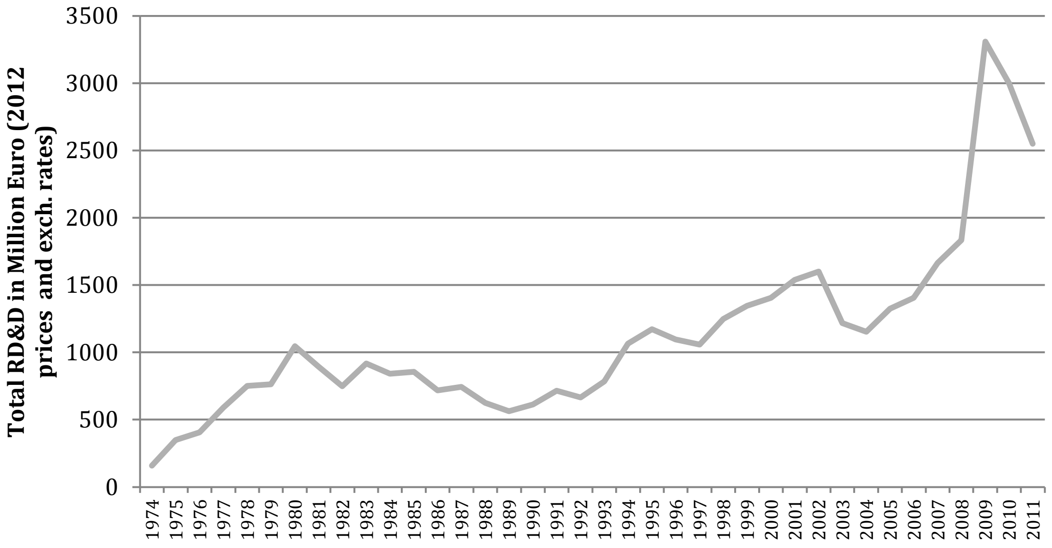

FIGURE 1 - Public RD&D funding for energy efficiency in million Euros (2012 prices and exch. rates) in 28 OECD countries 2003 – 2011 [IEA].

There has been increased interest in increasing the energy efficiency and enabling energy savings through public RD&D funding since the 1970s oil crisis, as seen in Figure 1. Still, there are only a few scientific studies that have investigated the impact of public RD&D programmes on energy savings (Griffin et al., 2012) and very few that have looked at the commercialisation effects of these efforts (Geller and McGaraghan, 1998; Kimura, 2010). Most of these studies have been carried out by governmental institutions as an evaluation of specific R&D programmes.

This study will take a different approach and focus on the innovation output of these collaborative RD&D projects in energy efficiency, and investigate how it might be influenced by the type and diversity of actors participating in them. Furthermore, the study will investigate how the funding schemes' different focus areas (*Buildings*, *Cooling*, *Ventilation*, *Lighting*, *Power Electronics*, *Industrial Processes* and *Behaviour*) contain different innovation dynamics.

The article is structured as follows. A literature review will present some of the current knowledge on collaborative innovation activities in a societal and systemic context. The review will also look at the existing findings on participant diversity and characteristics, and their connection to innovation, which will lead to the study's hypothesis. A section follows on the statistical methodology and the empirical data. The results and discussion section will present the findings from the statistical analysis and discuss the quality and robustness of the findings. The paper ends with a conclusion and policy implications.

2. Review of the literature

The literature review consists of three parts. The first part starts with a short overview of collaboration in innovation activities and moves to the more specific dynamics of R&D collaboration and how diversity and characteristics come into play. The second part will characterise public RD&D collaborations and introduce the empirical context of energy efficiency.

Attracting, internalising and commercialising new knowledge has always been a challenge for companies. In their seminal paper, Cohen and Levinthal conceptualised and operationalised the concept of absorptive capacity (Cohen and Levinthal, 1990) as the firm's capacity for absorbing external knowledge and commercialising it. This is also an argument against the idea of a firm's R&D capability relying solely on external knowledge. There will always be a need for internal R&D resources in order to facilitate the integration of external knowledge into the firm and enable commercialisation and future business.

More recently the concept of open innovation has gained considerable traction in research, industry and policy (Chesbrough, 2003; Enkel et al., 2009; Huizingh, 2011). This put somewhat of an end to the conception that firms are isolated entities inside which innovation occurs. The current scientific discussion is more on *how open* companies should be, and during which periods in the innovation process. Three core processes are characterised; *outside-in*, *inside-out* and *coupled* (Gassmann and Enkel, 2004; Enkel et al., 2009). The outside-in describes a one-way process of enriching a firm's knowledge base by interacting with suppliers, customers and other external sources. The inside-out process refers to firms selling ideas and IP to other firms and thereby generating revenue. The coupled process refers to alliances, cooperation and joint ventures where complementary partners are co-creating for the benefit of multiple companies. Different constellations of the coupled process has been widely researched with e.g. universities or research organizations (Perkmann and Walsh, 2007), partners from other industries (Enkel et al., 2009) and consumers (Hienerth, 2006).

The use of the three processes differs with different industrial sectors (Enkel et al., 2009). I high-tech industries almost 50% of all R&D projects were joint projects with external collaboration whereas joint R&D projects in low-tech industries such as leather, wood and printing occurred less than 20% of the R&D activities.

An evolutionary perspective on collaborative R&D broadens the understanding of a firm's desire to get the right resources as: *"The evolutionary theory asserts that diverse sources of knowledge allow a firm to create new combinations of knowledge (Nelson and Winter, 1982). Collaborating with different types of partners represents the diversity of knowledge networks, and increases the likelihood of achieving product innovation due to the variety of knowledge to be shared. The findings of this research imply that absorptive capacity formed by internal R&D may affect the relationship between knowledge diversity and product innovation performance"* p. 776 (Tsai, 2009). This evolutionary understanding of innovation activities contains many widely recognised elements such as new knowledge, collaboration and diversity.

The following sections will go deeper into *coupled* open innovation processes in the form of collaborative R&D, alliance portfolios and the impact of diversity among collaborators.

Collaborative R&D – Participant characteristics and participant diversity

When moving from a systemic perspective of collaborative innovation activities into the dynamics of R&D and innovation activities, the innovation management and R&D management literature is beneficial. Collaborative R&D, or research partnerships, are defined as cooperative arrangements engaging companies, universities, and government agencies and laboratories in various combinations to pool resources in pursuit of a shared R&D objective (p.568 in Hagedoorn et al. 2000; Hagedoorn 2002; Hagedoorn & Wang 2012)

Studies of firms' motivation for engaging in research partnerships have shown that they are mainly interested in maintaining their market share while being at the forefront of technological development, and having access to the right resources (Link and Zmud, 1984; Link, 1990).

Perkmann and Walsh (2007) thoroughly reviewed the literature on university-industry relationships through an open innovation perspective. They focused on research partnerships between university and industry because this is where there is a high relational involvement between the partners, which draws on the core processes in open innovation (Enkel et al., 2009). Through their review they highlight four main points. Firstly, university-industry links are not simple technology transfer processes but they use a wide variety of interaction mechanisms, with systemic differences across industries. Secondly, there is consensus that patents and IP are only moderately important for innovation, with long-term relationship-based mechanisms being more important. Thirdly, university-generated knowledge is not only important for novel inventions and radical innovations but it is also highly relevant in the later stages of the innovation processes, i.e. commercialisation and diffusion. Finally, a firms motivation for participating in research partnerships with university vary greatly and are not limited to their aim of generating and accessing commercializable innovations.

Sakakibara thoroughly investigated diversity in government-funded R&D collaboration from the perspective of participants having different business areas (Sakakibara, 1997, 2001), and found that "w*hen R&D consortia consists of firms with diverse technological knowledge, these firms offer learning opportunities and increase spill-*

over productivity, which imply more intensified R&D efforts of participants. In addition, when R&D consortia participants have diverse business backgrounds, the expected product market competition is less intense, which implies higher R&D expenditures by participants." (Sakakibara 2001,192).

Studies have shown that collaborative R&D is good for innovation and a firms economic growth (Miotti and Sachwald, 2003; Belderbos et al., 2004). When participating in an R&D consortium or research partnership, a firm's R&D expenditure has been found to increase between 2 - 9% (Branstetter and Sakakibara, 1998) but the effect of such participation is consistently positive. Although this paper will look more at diversity in terms of participant characteristics and not at firms with different business areas, the argumentation as to the positive effects should still hold because of the involvement of diverse technological domains.

Only a very few studies specifically investigate the influence of participant diversity on innovation despite the fact that it is key to why we conceive innovative activity as fuelled by diversity (Keller, 2001; Sampson, 2007; Raesfeld et al., 2012). A recent study looked at the influence of diverse collaboration in product innovation in the Spanish manufacturing industry (Nieto and Santamaría, 2007). The study found that the single greatest impact on product innovation in this case was the number of different types of partners involved in innovation activities, i.e. the diversity of the participants.

In line with previous research (Belderbos et al., 2004; Nieto and Santamaría, 2007), another study investigating the nanotech industry in the Netherlands (Raesfeld et al., 2012) showed that collaboration with different value-chain partners had a positive effect on firm innovation. Furthermore, a key finding, the study showed that this is also the case for publicly funded projects, not only firm-firm collaboration. Highly related to these studies is the strand of literature on alliance portfolios (George et al., 2001; Wassmer, 2010; Vasudeva and Anand, 2011). This literature seconds that collaboration with vertical value-chain partners has a positive effects while horizontal collaboration with for instance competitors can have a negative effect. It is however not only the types of partners that are involved as it is found also to be influenced by the experience level of the individual partner and the overall alliance experience level (Hoang and Rothaermel, 2005).

There is agreement on the positive effects of including vertical value-chain actors, like suppliers and users, in collaborative R&D as opposed to including horizontal value-chain actors. The vertical integration of value-chain actors supports the idea of different types of actors contributing with different knowledge, skills, perspectives, etc. Collaboration with universities and other research institutions generally occurs in more technologically advanced innovation projects, where the focus is on technological frontiers (Tödtling et al., 2009). In contrast, with more low-tech innovations, collaboration occurs more with business actors such as suppliers and users/ customers (Hippel, 1976, 1988).[1]

However, the distinction between high-tech and low-tech innovations does not take into account the difference between basic research versus applied research in terms of knowledge dynamics. Jensen et al. distinguished

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[1] To the author's knowledge, there are no studies that include or distinguish between technical consultants or energy companies, even though these types of actors clearly are different from firms, universities and users.

between two forms of knowledge in research and development (Jensen et al., 2007). The Science, Technology and Innovation (STI) mode is based on the production and use of codified scientific and technical knowledge, whereas the Doing, Using and Interacting (DUI) mode relies on informal processes of learning and experience-based know-how (Hendry et al., 2010). This distinction is particularly relevant in this paper as it investigates research, development & demonstration projects, which involve a complex mix of STI and DUI knowledge modes to a greater extent than "typical" R&D.

In collaborative research and development activities, between academia and industry in particular, there is a distinct problem termed 'valley of death' (Markham, 2002; Barr and Baker, 2009). This term describes the point where solutions and technologies are lost between invention and commercialisation because commercial and academic interests are unaligned and the industry is unable, or unwilling, to commercialise the technology. The failure of many new technologies discovered in collaborative R&D have been attributed to this gap – a problem that seems particularly prevalent for public RD&D projects in energy efficiency (Kimura, 2010).

2.1 Public research, development and demonstration projects and the context of energy efficiency

Governmental research and innovation policy has used R&D funding as a way of stimulating research and innovation since the 1950s. Public funding of R&D and innovation activities lowers the risks and the cost of innovation for firms – big and small (Arrow, 1962; Griliches, 1984).

Recent emphasis has been put on the demonstration aspect of these activities, which led to the notion of research, development and demonstration, or RD&D, being widely used (IEA, 2006, 2014). The demonstration stage is especially important in the energy sector where scaled experiments of new plants and technologies are necessary to *demonstrate* the technology and further progress the innovation process (Sagar and van der Zwaan, 2006).

Public R&D, or higher-level innovation policy, generally has the aim of high societal returns based on the idea that "science is a public good" (Salter and Martin, 2001). These policies typically move beyond the direct results and also consider employment, knowledge diffusion, new firms, etc. (Kleer, 2010). Kimura studied the innovation outcomes of energy efficiency RD&D programmes in Japan and posed an interesting dilemma: *"...on one hand, an outcome closer to the program's objectives (more innovative energy-efficient technologies on the market in the case of R&D in energy efficiency) is desirable; on the other hand, public R&D should also be directed toward risky but important technologies that private R&D cannot undertake by itself"* (Kimura, 2010). This dilemma is certainly present in RD&D programmes, which are relatively close to the market and where the programme's objective is of societal relevance.

Open innovation and public collaborative RD&D

Although the current literature is comprehensive and very applicable for innovation management and strategy in firms there are missing insights into complex inter-organisational R&D and innovation processes together with multiple partners. Particularly within the Open Innovation literature participant dynamics and diversity is under researched. A recent agenda for open innovation (West et al., 2006; Perkmann and Walsh, 2007) highlighted the need for more research in specific areas – see Table 1.

Table 1 - Research agenda: university-industry relationships in an open innovation scenario (West et al., 2006; Perkmann and Walsh, 2007).

Search and match processes	Role of networks mechanisms: proximity, invisible colleges, education networks, user-producer relationships
	Relationship between precipitating social networks and types of innovative activity/outcome
	Role of brokers and intermediaries
Organization and management of relationships	Variation of individual-level incentives and motivations across different types of university-industry collaboration
	Variation of organizational models and innovation-relevant outputs
	Firm strategies for exploiting university knowledge in an open innovation scenario
	Impact of institutions on shape, extent and effects of university-industry relationships

This paper contributes directly to the research agenda presented above as it will provide a unique look into the complex innovation activities associated with public RD&D to investigate the influence of specific collaboration pairs and the overall diversity of actors involved.

This paper will therefore investigate some key influences of innovation output in public energy-efficiency RD&D projects through the following three main hypotheses:

- **H1 (Model 1)** *Specific combinations of actors (when in pairs) on collaborative RD&D projects will have a positive influence on the likelihood of a new product as the project output.*
  The hypothesis is that the type of actors influence the outcome of the projects, with, for instance, horizontal value-chain partners such as users contributes to the project with knowledge about the market and product application.

- **H2 (Model 2)** *The higher the diversity of actors (i.e. number of actor types) involved in a project, the more likely the project is to have a new product as the project output.*
  Diverse actor types bring different knowledge domains, capabilities, skills, and resources into a project, i.e. it has a greater likelihood of a product output (Sakakibara, 1997; Nieto and Santamaría, 2007).

- **H3 (Model 3)** *There are differences in the likelihood of a product, as the project outcome depends on the technological focus area of the project.*
  The seven different focus areas have different maturity levels and technological dynamics (Pavitt, 1984; Malerba, 2002; Perkmann and Walsh, 2007), which will have great influence on whether there is a new product as the project outcome. The seven focus areas in this data set are: *Buildings, Cooling, Ventilation, Lighting, Power Electronics, Industrial Processes and Behaviour*.

The context of energy efficiency RD&D

Policy efforts to increase energy efficiency and save energy primarily started back in the 1970s with the global oil crisis – see Figure 1. (Griffin et al., 2012). Energy efficiency has gained renewed interest recently as global warming, climate change and energy security issues started making their way into many public policy domains (Geller et al., 2006). Energy efficiency and energy conservation have become two of many policy options, together with the promotion of low carbon energy production technologies such as wind, PV, nuclear and CCS.

Energy efficiency and energy savings are, however, very different from sustainable energy sources in scale, users and complementarity, i.e. in their innovation dynamics (Sagar and van der Zwaan, 2006). The energy efficiency of products and services will always be a secondary aspect to their primary function. For example, the energy efficiency of a water pump will always be secondary to its ability to pump water.

This inherent characteristic, along with several other market barrier such as imperfect information, split incentives and bounded rationality (Sorrell, 2004; Palm, 2010), makes it difficult for energy-efficient products and services to succeed. So even though the rational choice for business and consumers is the energy-efficient product, it is rarely their choice, which is also why there are numerous policy efforts within this area (Morvaj and Bukarica, 2010). There is also a negative effect resulting from "just" increasing the energy efficiency of products, known as the rebound effect (Ruzzenenti and Basosi, 2008). The rebound effect occurs, for instance, when the increase in efficiency of a product leads to the purchase of more products, i.e. a higher overall energy consumption (Sorrell, 2004; Herring and Roy, 2007).

Public RD&D funding is primarily used in combination with other energy-efficiency policies to develop and test new efficient technologies and products, while also considering their diffusion into the market (Geller and McGaraghan, 1998; Brown and Hendry, 2009; Bointner, 2014). In successful energy technology demonstration programmes, there has to be an ideal mix of technical, economic and commercial goals (Brown and Hendry, 2009; Harborne and Hendry, 2009). For RD&D in energy efficiency, efforts in new business development, process optimisation and benchmarking, etc. should also be included, and this certainly is the case in this paper's empirical data from Denmark.

This paper investigates the direct innovation outcomes of public RD&D projects in energy efficiency and provides new insights into the innovation dynamics of RD&D projects. This is achieved by investigating how the project output is influenced by the diversity and characteristics of the participants on the projects. Furthermore, the study seeks to investigate the influence of seven focus areas: *Buildings*, *Cooling*, *Ventilation*, *Lighting*, *Power Electronics*, *Industrial Processes* and *Behaviour*.

3. Methodology and data

The study builds on a database for RD&D projects from the Danish funding agency ELFORSK, which is part of the Danish Energy Association. This main database is combined with the results from an online questionnaire given to all project managers in the project database.

Project database

The study uses a unique database of about 220 publicly funded RD&D projects in the broad field of energy efficiency – but only energy efficiency in terms of electricity use and not heat use. ELFORSK's yearly funding budget is about EUR 3,3 million for, on average, 20 projects, which means it is quite a small funding programme in comparison with other energy research programmes in Denmark and elsewhere. In general, RD&D in energy efficiency can be regarded as a combination of applied research, product development and demonstration activities, with an emphasis on mostly development and demonstration activities. The commonality of the projects in ELFORSK is their overall aim of developing new technologies, products, systems, and tools for reducing electricity use. This makes it a very diverse field to study, but also an interesting one due to the limited knowledge of the innovation dynamics of such projects. See an overview of the focus areas in figure 2.

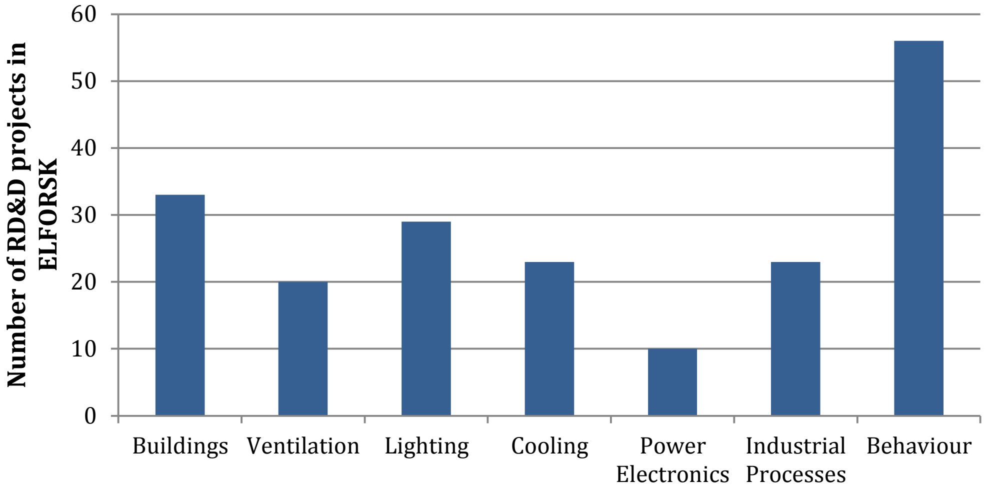

FIGURE 2 - Number of RD&D projects in each ELFORSK focus area [2002 - 2012].

Survey data

In collaboration with the funding agency ELFORSK, an online questionnaire was administered to gather information about the outcomes of the projects. The questionnaire was constructed with inspiration from the Oslo Manual (OECD and Eurostat, 2005) and the Community Innovation Survey (Eurostat, 2010) with respect to questioning technique and structure. It was setup with identical pages according to the number of projects each project manager had led, so every project manager would fill out an introductory page and a page for each project they were project managers on. This will inevitably lead to a bias as the project manager is asked about the "success" of his or her own project. There are however five main reasons why the data is deemed valid. 1) The funding program is small and has close interactions across projects and with funding managers. Furthermore about 68%[2] of all projects are led by experienced project managers, who's reputation is crucial to attract further funding from the program. 2) The survey was done together with the funding program to establish trust and encourage commitment with the project managers. 3) The formal evaluation of the projects done by the funding program does not focus on similar output measures and the projects are not frowned upon for not delivering marketable products. 4) Project managers were aware that the survey was only a supplement to their normal assessment and entering a product innovation could therefore easily be discovered by the funding program. 5) The survey deliberately used closed-ended and very clear questions regarding the outcomes of the projects and how it might be regarded an innovation.

The statistical analysis only uses two of the questions from the survey as most variables are defined through the project database from ELFORSK. The project manager's experience level with energy efficiency is used as a control variable, and, as the dependent variable, the project manager is asked what kind of product outputs there were from the project. The possible answers were: *No products; 1 product, 2 products, 3 or more products, Only demonstration, Other value creating business*. The project managers' answers are used as a dichotomous independent variable of whether or not there was a product innovation as an output of the project.

3.1 Operationalizing actor diversity

Diversity is generally operationalized through an index that contains the distribution of different types. This paper uses a rather simple diversity index based directly on the number of actor types included in the projects. This defines a normalised index from 1 to 6, according to the number of different actor types included in the project, which is calculated directly from the project database – see Fomula 1. In ecological literature, this index is called Richness (Tuomisto, 2010) and will be used as a measure of actor type diversity in this paper.

$$p_{diversity} = act_{consultant}[0,1] + act_{user}[0,1] + act_{producer}[0,1] + act_{university}[0,1] + act_{energycompany}[0,1] + act_{TI\&SBI}[0,1]$$

Formula 1 – Formula for actor diversity

In the literature, there are commonly three diversity indices used: the Simpson Diversity Index (1949), which is also called the Herfindahl Index in management literature (1950); the Shannon-Weaver Diversity Index (1948); and the Gibbs-Martin index (1962). Early experiments using the Simpson/Herfindahl and the Shannon-Weaver

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[2] 68% of projects have project managers with managing experience from two or more projects.

indices but actually they were not intended as measures of diversity. The reason for this was the fact that these diversity indices take into account the abundance or number of each species, which is not the intention in this analysis. In this analysis the assumption is that each type of actor contributes with a certain knowledge and set of skills. The aim is then to find out whether the involvement of each certain type has an impact and not the number of each type of actor, as would be the case with the common diversity indices.

3.2 The statistical model

Because the independent and control variables include both categorical, binary and interval a binominal logistic regression model is chosen to predict the binary dependent variable.[3] The logistic regression fits the probability function of the following form.

$$\hat{p} = \frac{\exp\left(\alpha + \ \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_p x_p\right)}{(1 + \exp(\alpha + \ \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_p x_p))}$$

As specified in the earlier sections, the analysis uses two models to investigate the stated hypothesis. It is necessary to use two models as all variables related to actor pairs and diversity indices are built on the same data and multicolinearity therefore occurs. This multicolinearity is verified by the variance inflation factor (VIF > 18), as, according to Kutner, the phenomenon is present when the variance inflation factor is above 10 (2004). It is furthermore confirmed by a tolerance measure in SPSS (tolerance < .10). As such, it is necessary to use two models – Model 1 and Model 2. A full model with both actor pair variables and diversity is included as Model 3 for clarification.

Alternatively a probit model could also used, but the logistic regression model was chosen because of the ability of further developing it towards the use of a categorical dependent variable with more than two categories. This direction was although never pursued because of limitations in the data.

The statistical analysis is done in the IBM SPSS 22 statistics software package. Model 1 and Model 2 are reduced backwards using the Backward Stepwise (BSTEP) method based on optimisation of the Likelihood Ratio. Subsequently a reduced model is chosen through maximising the variance covered as estimated by the Nagelkerke R Square and Cox & Snell R Square. An overview of all variables is included in the appendix.

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[3] At the start of the study, a social network analysis methodology was to be included in the analysis. From the project database, a relational network database was created based on project participation and basic centrality measures for the project groups were included as variables for the analysis. The early statistic models did not return any effects of these variables however and so this part was excluded from the paper.

4. Results and discussion

This section will present the logistic regression results and discuss their fit, robustness and limitations. Additional descriptive statistics are in the appendix.

4.1 Model fit and predictability

Table 1 shows estimations of model fit and explanatory power of the logistic regression. The highlight is the Nagelkerke R Square, which estimates that Model 1 is able to account for about 44% of the variance, and Model 2 and 3 about 27% and 67%, respectively.

The Hosmer and Lemeshow test is not statistically significant (Sig. > 0.05), which tells us that the predictive ability of the model is good even though the sample size is quite small for this particular test. The classification tables confirm this predictive ability.

Table 2 - Model fit and predictability

	Model 1 - ***Actor pairs***		**Model 2 –** ***Actor type diversity***		**Model 3 -** ***Full model***	
	N = 111		N = 111		N = 111	
Omnibus Tests of Model Coefficients	Chi-square	Sig.	Chi-square	Sig.	Chi-square	Sig.
	38,633	0,011	21,656	0,086	63,999	0,001
Log Likelihood	82,211a		99,187a		56,845a	
Cox & Snell pseudo R²	0,294		0,177		0,438	
Nagelkerke pseudo R²	0,443		0,267		0,661	
McFadden pseudo R²	0,319		0,179		0,529	
	Chi-square	Sig.	Chi-square	Sig.	Chi-square	Sig.
Hosmer and Lemeshow Test	7,939	0,439	2,683	0,953	1,075	0,998
Classification Tables	85,6 (76,6)		77,5 (76,6)		88,3 (76,6)	

4.2 Regression results

	Model 1 – ***Actor pairs***				**Model 2 –** ***Actor type diversity***			**Model 3 -** ***Full model***		
	β	Wald	Sig.	Exp(B)	β	Sig.	Exp(B)	β	Sig.	Exp(B)
act_conANDact_pro								3,192	,157	24,342
act_conANDact_uni	1,894	4,446	0,035*	6,646				6,200	,041*	492,952
act_conANDact_usr	-1,391	2,196	0,138	0,249				-4,276	,135	,014
act_conANDact_ti								-3,040	,272	,048
act_conANDact_sbi								5,769	,018*	320,288
act_conANDact_eng	2,053	3,964	0,046*	7,795				12,281	,002*	215543,135
act_proANDact_uni								,460	,821	1,585
act_proANDact_usr								-2,893	,301	,055
act_proANDact_ti								7,014	,037*	1111,681
act_proANDact_sbi								-2,482	,376	,084
act_proANDact_eng								-8,292	,033*	,000
act_uniANDact_usr								6,597	,039*	733,124
act_uniANDact_ti								-2,048	,482	,129
act_uniANDact_sbi								3,186	,259	24,201
act_uniANDact_eng	-3,446	5,643	0,018*	0,032				-5,611	,077	,004
act_usrANDact_ti	2,602	6,435	0,011*	13,491				8,643	,002*	5670,916
act_usrANDact_sbi								-8,016	,197	,000
act_usrANDact_eng	1,851	2,868	0,09	6,368				3,262	,143	26,100
act_tiANDact_sbi	2,213	1,683	0,195	9,14				5,825	,094	338,536
act_tiANDact_eng								1,350	,630	3,856
act_sbiANDact_eng								-30,782	,997	,000
p_diversity_alltypes					0,49	0,047*	1,632	-2,482	,201	,084
p_hours	0		0,123	1				,001	,04*	1,001
p_funding	0		0,189	1				,000	,068	1,000
Project_type									,232	
Project_type(1)								-,027	,989	,973
Project_type(2)								-,720	,673	,487
Project_type(3)								3,147	,156	23,272
p_lag					0,146	0,175	1,157	-,040	,858	,960
focus_a7			0,627			0,611			,221	
focus_a7(1)	1,959		0,068	7,091	1,258	0,111	3,518	5,688	,007*	295,343
focus_a7(2)	0,64		0,585	1,897	0,114	0,904	1,121	4,007	,051	54,977
focus_a7(3)	2,136		0,088	8,47	0,52	0,527	1,682	9,286	,008*	10790,515
focus_a7(4)	1,201		0,317	3,324	0,422	0,645	1,525	3,647	,121	38,362
focus_a7(5)	-500,85		1	0	-499,97	1	0	-18,981	,999	,000
focus_a7(6)	0,179		0,899	1,197	-0,884	0,475	0,413	2,484	,246	11,995
pm_type			0,34			0,219				
pm_type(1)	2,683		0,085	14,631	1,52	0,197	4,574			
pm_type(2)	3,235		0,101	25,399	2,666	0,103	14,378			
pm_type(3)	1,998		0,252	7,375	1,157	0,383	3,18			
pm_type(4)	3,899		0,04*	49,334	2,961	0,05	19,317			
pm_type(5)	1,783		0,315	5,951	1,022	0,493	2,78			
pm_type(6)	0,92		0,648	2,509	-0,368	0,814	0,692			
Constant	-5,827		0,002	0,003	-5,066	0,003	0,006	-6,495	,142	,002

Note: *** Significant at** ***p*** **< 0,05**

Model 1 – Combinations of participants in pairs

Hypothesis 1 proposes that some combinations of actor types have a positive impact on the likelihood of a product innovation as the result of the RD&D project. This hypothesis is confirmed in Regression Model 1 (5.2 Regression results), which indicates four combinations of actors that either increase or decrease the likelihood of a successful project outcome when not controlling for the single actor type variable – see Table 2 below. According to the Wald test, the combination of User and Technological Institute seems to be the most significant. When controlling for the initial dummy, the results change slightly. Most interesting is the combination of a User and an Energy company, which has a significant positive impact on the outcome of the projects.

Without actor type dummy control

Effect	Actor combination	
+	Consultant	University
+	Consultant	Energy company
-	University	Energy company
+	User	Technological Institute

With actor type dummy control

Effect	Actor combination		Sig.
+	Consultant	Energy company	,051
-	University	Energy company	,05
+	User	Technological Institute	,016
+	User	Energy company	,019

Table 3 - Actor pairs, which influence the project outcome – with and without dummy control variable.

These results comply with the existing research showing that involvement of vertical value-chain partners in R&D increases innovation. This study extends this point and identifies certain pairs of actor types in the value-chain, such as User and Technological Institute, which are specifically beneficial to include in collaborative R&D partnerships.

Model 2 – Diversity of actor types

Hypothesis 2 proposes that the diversity of actor types, i.e. the number of different actor types, has an influence on the likelihood of a product innovation as an output from the project. This hypothesis is confirmed in Regression Model 2 (4.2 Regression results), where there is a small and positive relationship between an increasing diversity index and the likelihood of a product innovation. The positive effect of high diversity is possibly explained by its influence on lowering 'valley of death' issues and including more vertical integration of the whole value-chain. High diversity ($p\_diversity \geq 4$) means that there are actors included from all phases of an innovation process, from invention to application; therefore they experience ownership and knowledge integration early on and this lowers the risk of 'valley of death' issues.

Model 1 – Technological dynamics and focus areas

Hypothesis 3 proposes a quantifiable difference between the product output characteristics of the seven focus areas in the funding programme. There is no statistically significant difference between the focus areas in Regression Models 1 or 2. A larger sample size could potentially help with this issue. Indications do however show that the *Buildings* focus area might be particularly innovative compared to the others. These could be interesting results as the literature on innovation in the building sector (Gann and Salter, 2000; Gann et al., 2010) consistently points to the non-innovative nature of the sector. A possible explanation of this effect could be that the buildings sector in general isn't very innovative, while the subgroup focusing on increased energy efficiency in buildings is in growth. Further qualitative analysis of this aspect could be relevant for further research.

4.3 Model robustness and limitations

The robustness of the models has been validated through multiple model variations and iterations. With the three-model setup applied, the results are consistent. There is the issue of multicolinearity between the actor pairs and the diversity indices, but as they are kept in separate models, the results are deemed robust in this configuration.

Initially a multinomial logistic regression model was chosen for the analysis as a categorical dependent variable would be able to handle more varied outputs from RD&D projects, e.g. products, processes, tools, positive lists, etc. This varied output measure was available from the online questionnaire, but because of the small sample size and the high number of categories, it did not perform will with a multinomial logistic regression model.

5. Conclusion

Public research, development and demonstration funding is a vital support mechanism for innovation activities directed at solving societal challenges. This funding's impact on mitigating risk and lowering the cost of innovation activities is well known, but likewise it has a significant positive influence on the systemic knowledge production and commercialisation of new products. The fact that coupled open innovation processes in particular collaborative R&D activities where participants from the vertical value-chain are included increase innovation is also well known in the open innovation literature. Empirical analysis of complex collaborative R&D activities are however missing in the open innovation literature, a direction this paper pursues as it investigates deeper into collaboration dynamics between different actor types in public RD&D to investigate its impact on open innovation dynamics.

Through unique data on completed RD&D projects in Denmark, the study reveals that there are specific combinations or pairs of actors that are beneficial for innovation in projects. These innovative pairs (see Table 2) seem to ensure the presence of the right capabilities, knowledge and resources on projects to complete the innovation process and commercialise a product innovation. In particular the involvement of Users and Energy companies on RD&D projects has a significant impact on the likelihood of an innovation resulting from the projects.

Furthermore, the analysis shows that for the creation and diffusion of new knowledge, it is crucial for diverse actor types to collaborate – actually, the more diversity of actor types the better. The confirmation of this hypothesis is in line with previous studies on collaborative diversity (Sakakibara, 2001; Nieto and Santamaría, 2007; Raesfeld et al., 2012), which argue that collaboration between diverse actor types ensures the availability of diverse knowledge domains and supports learning. In the case of RD&D projects in energy efficiency, it seems beneficial to have a diversity index equal to or above four, i.e. four or more actor types on a collaborative RD&D project is optimal.

The 'valley of death' effect is reduced in collaborative RD&D between academia and industry when four or more actors from the entire innovation process are included, and the new innovation is therefore less likely to fail through project misalignment and miscommunication.

Relevant for the empirical area of energy efficiency, the study also investigated whether there were noticeable differences in the innovative output of the seven individual focus areas. This could not be confirmed in the logistic regression analysis, but the descriptive statistics indicate that there are differences in their outputs. For instance, when comparing the focus areas of *Building* and *Industrial Processes* in terms of their product innovation output it is clear that the buildings area appears much more innovative. This could be due to the fact that projects in *Industrial Processes* typically are dealing with specific industry processes, which is hard to develop mass-market solutions for, as opposed to the standardised *Buildings*-area. These results are however conflicting with the general understanding of innovation in the buildings sector (Gann and Salter, 2000; Harty, 2005).

Overall the study finds public RD&D projects in energy efficiency to be very innovative in terms of commercialising new products from the projects. This was the case in 23% of the projects, which highlights the maturity of the innovation activities and how innovation policy in the area of energy efficiency is highly beneficial to the industry, society and the environment. Publicly funded RD&D activities in energy efficiency are still not just a matter of developing new technologies and products, as it is equally important to develop ways of removing the known institutional, organisational and economic barriers to realising energy savings through more efficient use of energy. This perspective, is due to methodological and data limitations, is not covered sufficiently in this paper and will form the basis of further research.

5.1 Policy implications

The findings of this paper should serve as input for all strategic research programmes where there are intentions of supporting innovation and in particular open innovation. This paper is in line with previous research on open innovation and collaborative R&D to emphasise the inclusion of vertical value-chain actors in collaborative R&D. Furthermore, it contributes new knowledge on the beneficial combinations of actor types and gives input for understanding how a diversity of participants is crucial because of the influence on innovation.

Few of these considerations are included in large funding schemes such as the European FP7 and Horizon2020 as they typically only include very basic requirements for type and number of participants. In FP7 there is only a required minimum of three partners from different member states, but according to the European Commission, there was, on average, 14 participants per project in FP6 (European Commission, 2006). This does, however, not include any insight into the diversity of the involved partners.

These funding schemes rarely apply an overall innovation perspective in their setup and do not consider how to integrate their public RD&D activities into an overall innovation system context. Specific initiatives at the funding programme level could, for instance, be an increased effort in matching profiles and activities of the applicants.[4] This will, however, require substantial resources from the funding organisation while also adding more bureaucracy and management at the project-level. A different way could be to implement diversity index calculations for projects and urge that these be higher than, for instance, 4. This would force the applicants to consider the actor-width of their project and hopefully create beneficial relationships with other types of actors.

The insights from this paper are only relevant for RD&D policy and not for basic research policy, however, where higher risks are present and where commercialisation isn't a direct possibility or aim.

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[4] Besides their existing partnering programs.

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7. Appendix – Overview of variables

Name	**Description**	**Type**	**Range**	**Mean/Median**	**S.D.**	***N***
Dependent variable:						
p_outcome	Whether or not there was a product as project output.	Binary	0/1	0,2342	0,425	111
Control variables:						
p_funding	Amount of funding for the project	Continous	160000 - 53990000	1710154,85	884616,38	194
p_hours	Duration of the project - in hours	Continous	252 - 13788	2356,97	1735,88	194
p_lag	The duration since the project beginning - in years	Continous	0 - 9,25	4,545	2,71	194
pm_exp	Project manager experience with energy efficiency	Ordinal	0 - 3	1		194
Project_type	The project type - *Technology, Tool, Label, Behavioural.*	Categorical	1/2/3/4	2		194
Independent variables:						
focus_a7	Focus area variable - *Buildings, Ventilation, Lighting, Cooling, Power Electronics, Industrial Processes, Behaviour.*	Categorical	1/2/3/4/5/6/7	4		194
pm_type	Actor type of the Project Manager.	Categorical	1/2/3/4/5/6/7	3		194
act_conANDact_pro	Is there a *Consultant* and a *Producer* on the project?	Binary	0/1	0,3247	0,46949	194
act_conANDact_uni	Is there a *Consultant* and a *University* on the project?	Binary	0/1	0,2784	0,44935	194
act_conANDact_usr	Is there a *Consultant* and a *User* on the project?	Binary	0/1	0,2629	0,44134	194
act_conANDact_ti	Is there a *Consultant* and a *Technological Ins.* on the project?	Binary	0/1	0,201	0,40181	194
act_conANDact_sbi	Is there a *Consultant* and a *SBi* on the project?	Binary	0/1	0,1649	0,37209	194
act_conANDact_eng	Is there a *Consultant* and a *Energy comp.* on the project?	Binary	0/1	0,2784	0,44935	194
act_proANDact_uni	Is there a *Producer* and a *University* on the project?	Binary	0/1	0,3093	0,46339	194
act_proANDact_usr	Is there a *Producer* and a *User* on the project?	Binary	0/1	0,2216	0,41643	194
act_proANDact_ti	Is there a *Producer* and a *Technological Ins.* on the project?	Binary	0/1	0,2784	0,44935	194
act_proANDact_sbi	Is there a *Producer* and a *SBi* on the project?	Binary	0/1	0,1031	0,30487	194
act_proANDact_eng	Is there a *Producer* and a *Energy comp.* on the project?	Binary	0/1	0,1495	0,35749	194
act_uniANDact_usr	Is there a *University* and a *User* on the project?	Binary	0/1	0,1598	0,36736	194
act_uniANDact_ti	Is there a *University* and a *Technological Ins.* on the project?	Binary	0/1	0,1598	0,36736	194
act_uniANDact_sbi	Is there a *University* and a *SBi* on the project?	Binary	0/1	0,1031	0,30487	194
act_uniANDact_eng	Is there a *University* and a *Energy comp.* on the project?	Binary	0/1	0,1392	0,34702	194
act_usrANDact_ti	Is there a *User* and a *Technological Ins.* on the project?	Binary	0/1	0,1649	0,37209	194
act_usrANDact_sbi	Is there a *User* and a *SBi* on the project?	Binary	0/1	0,0464	0,21088	194
act_usrANDact_eng	Is there a *User* and a *Energy comp.* on the project?	Binary	0/1	0,1649	0,37209	194
act_tiANDact_sbi	Is there a *Technological Ins.* and a *SBi* on the project?	Binary	0/1	0,0258	0,15887	194
act_tiANDact_eng	Is there a *Technological Ins.* and a *Energy comp.* on the project?	Binary	0/1	0,1289	0,33592	194
act_sbiANDact_eng	Is there a *SBi* and a *Energy comp.* on the project?	Binary	0/1	0,0722	0,25943	194
p_diversity	Diversity index based on the number of different actortypes on a project	Continous	0 - 6	3,05	1,1	194

8 DISCUSSION

The discussion section of the thesis will synthesise the main contributions and findings from the three individual papers into three overall subjects relevant for the overall research aim of the thesis. The discussion will end with prospects for further research.

8.1 UNDERSTANDING AND FRAMING INNOVATION ACTIVITIES IN ENERGY EFFICIENCY

Innovation activities to increase energy efficiency are straightforward in terms of technical complexity but are heterogeneous and uncertain in other ways (Lutzenhiser and Shove, 1999), making it a challenge to analyse and generalise their dynamics. Research and development activities to increase the efficiency of an energy service can occur in any kind of energy using product or service, making it difficult to identify common elements across focus areas. This also makes it difficult to frame energy efficiency innovation as something with specific innovation characteristics.

Despite these inherent challenges, this thesis and in particular papers #3 and #4 show how different areas of energy efficiency innovation activities are interconnected in terms of the involved actors and organisations. This is the case because of shared knowledge institutions, consultants and energy companies across the different focus areas. What characterises innovation in energy efficiency is therefore not merely the scientific and technical knowledge needed to increase the efficiency of an energy service, but also, more importantly, knowledge about how to integrate and diffuse it into application on existing markets and in households and industries. This is where the shared organisations contribute to the innovation process, as it is well known that it is in the diffusion and application phase that the new innovations meet most resistance. The coordinated actions of cross-sectoral organisations and institutions are therefore of great importance for energy efficiency innovation activities.

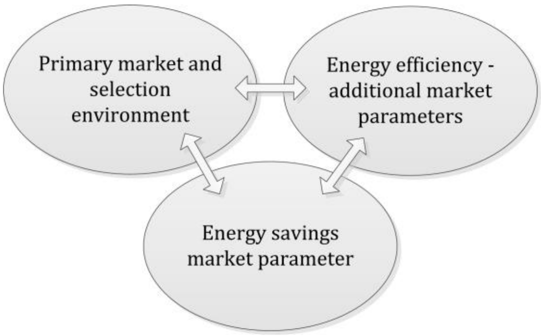

FIGURE 23 – THE THREE MARKET AND SELECTION ENVIRONMENTS WHICH INFLUENCE THE INNOVATION PROCESSES IN ENERGY EFFICIENCY

The innovation processes of energy efficient products are influenced by the dynamics of three “markets” or selection environments – see FIGURE 23. The primary one is the existing products market, which was there before increased energy efficiency demands. Closely related to the primary market is the secondary market where energy efficiency and other environmental considerations have an impact. The third and more recent market is the market for energy savings (IEA, 2013b; Lutzenhiser, 2014). These three markets have different dynamics and influence the innovation process differently, but they are rarely included in any scientific innovation studies. This complexity of interlinked focus areas and multiple markets makes energy efficiency innovation a challenge to characterise. This also means that it is difficult to frame an analysis that looks at the innovation dynamics of energy efficient products. The underlines the need for research in energy efficiency innovation, and in particular the need for evolutionary perspectives on innovation as innovation systems and transitions research, because of their ability to analyse dynamics in complex and ambiguous innovation and transition processes.

8.2 MODERN POLICY PROCESSES

The existing research on the interactions between regulation and innovation tends to simplify the policy-making process and its impact on the innovation process. This has already been pointed out by several scholars (Hemmelskamp, 1997; Kemp and Pontoglio, 2011) but rarely is this policy process seen as part of the innovation process. In reality most of these processes tend not to occur behind closed doors among policy-makers only, but instead are more interactive. In energy efficiency policy these processes typically involve industry and other interests, as was seen in the circulator pump case in paper #1 and the additional ventilation case on page 141. Actually very few innovation studies go into the policy process and how it interacts with industry and innovation activities.

When setting energy efficiency goals, very specific technical, industrial and socio-economic knowledge is needed. This knowledge is typically supplied from technical consultants and industry experts, but the firms are also very intertwined in these processes (Keeley and Scoones, 1999). Such processes contain a negotiation of the direction of the energy efficiency policy but also determine the speed of change in terms of specific policies. All these elements are crucial when determining the impact on innovation. The pump case in paper #1 illustrates the extreme case where industry forms a coalition to set its own policies in order to change the dynamics of the regime to support its innovation efforts. This disregards the common understanding of policy and regulation only being implemented top-down by policy-makers. These kinds of example are rare; however, they do show how progressive industries in collaboration with policy-makers are able to support a transformation towards sustainability (Loorbach and Wijsman, 2013). The market transformation literature offers examples of this but rarely with as much drive coming from the industry (Geller and Nadel, 1994; Nadel and Geller, 1996).

8.3 POLICY, MARKET TRANSFORMATION AND COMPETITIVENESS IN ENERGY EFFICIENCY INNOVATION

It is clear that increased energy efficiency does not occur by itself because of diffusion and market barriers, despite economic and environmental benefits. This presents the most significant challenge for innovation in energy efficiency as it limits the diffusion and commercialisation of new energy efficient products. It is therefore well established in the literature that public policy efforts are crucial in removing economic, behavioural and organisational barriers towards increased energy efficiency and innovation activities. This necessity is often missed or neglected in innovation studies on the topic of energy efficiency despite Jaffe et al. arguing for more in-depth research with the aim of *"examin[ing] whether and how specific policies will affect the processes of invention, innovation, diffusion, and intensity of use of products"* (Jaffe et al., 1999, p. 15). Public policies are crucial for firms to innovate in energy efficiency, but they are supplementary to the specific market dynamics of each product. Energy efficiency can act as an important competitive factor, but it is rarely the case without public policies to prioritise the increased efficiency. Furthermore, energy efficiency needs to be seen in conjunction with competitive parameters such as product functionalities, price, quality, etc.

The literature on market transformation argues for the role of strong policies to rapidly increase energy efficiency. This is done through a combination of labels, minimum efficiency demands, information campaigns, and public R&D funding. Policies are crucial in this context as they communicate directly with consumers and users regarding the added value of increased energy efficiency. Besides changing the dynamics of these markets they also immediately establish energy efficiency as a competitive parameter. In paper #1 the case study also shows that policies can create certainty concerning the industry's future and which technologies to integrate. This can lower the cost of innovation activities, establish actor networks (Kiss et al., 2013) and create competitiveness within shared parameters (Gann et al., 2010). Paper #3 furthermore highlights the collaborative nature of energy efficiency innovation activities related to public R&D project and what influences their innovative output.

The reality of innovation processes is that they are almost always influenced – both positively and negatively – by a series of different public policies. According to paper #2 it is confirmed that policy is often among the drivers of innovation activities in energy efficiency. The literature on energy efficiency and market transformation would argue that policies need to create support along the innovation process to reduce barriers and uncertainty. A good example of this is the Danish approach to energy efficiency and research policy where there is a high degree of coordination between policies in order to create the best setting for energy efficiency innovation to occur. At this level of strategic intent it might be beneficial not only to talk about the transformation of individual markets but also to discuss an entire institutional setup (Wallace, 1995) or innovation system (Freeman, 1987; Lundvall, 1992; Nelson, 1993), both of which support innovation activities and the uptake of new energy efficient solutions.

8.4 PERSPECTIVES FOR FUTURE RESEARCH

It is common in research that when one research question is answered, several new ones appear. Throughout the work on this thesis the following perspectives have become subjects for further research.

- **Impact of public policies on stages of innovation activities**
  In order to overcome barriers towards energy efficiency innovation, public policies are needed (Kiss et al., 2013). But exactly which and how to implement and maintain these policies most effectively is rather unknown. It is also crucial to know better how command-and-control policies work in combination with market-based policies in order to design better policies.

- **Dynamics of different focus areas – to what extent is energy efficiency a driver?**
  There are major differences between different energy efficient products and services in terms of innovation dynamics, which makes it interesting to know further about the influence of energy efficiency demands on different focus areas. This could have its outset in a comparison between households and industry.

- **The build-up of knowledge, skills and competences in energy efficiency**
  Further research could go into analysing the specific knowledge domains, skills and competences related to energy efficiency innovation. The research in the thesis indicates a high degree of learning by doing and technology demonstration in order to validate the performance of energy efficiency innovations. It would also be important to go deeper into the extent to which knowledge needed for energy efficiency innovation is primarily technical or is a mix of technical and application-based knowledge domains.

- **The direct and indirect effect on creation of new businesses**
  Increased energy efficiency and energy savings have several societal and economic benefits, but to what extent are new businesses created based on energy efficiency innovation? It is known that public R&D funding has led to new innovative solutions that turned into new businesses, but to what extent is this common and how can policies support new businesses while also supporting the change of existing industries and sectors.

- **Temporal aspects of energy efficiency innovation**
  Energy efficiency innovation is a goal-orientated action, which has an end when continued R&D activities are no longer technically or economically feasible. It is unknown what happens at this point and whether it might lead to innovation activities to reduce other environmental and sustainability issues. This could be researched, for instance, through an analysis of the white goods market, which early on has seen energy efficiency integrated into its products (Bertoldi et al., 1999).

9 CONCLUSION

The need for rapidly increased energy efficiency in all parts of society's energy end-uses is ever greater with global environmental issues of climate change and resource scarcity. But despite these immediate environmental issues and the economic benefits of increased energy efficiency, it does not occur by itself. This challenge is attributed to known economic, behavioural and organisational barriers towards increased energy efficiency. The removal of these barriers and the acceleration of the development and diffusion of new energy efficient products in households, offices and industry have been the aim of public policy efforts since the oil crisis in the 1970s. Despite these increased policy efforts the potential savings for energy efficiency are still vast.

This leads into the research topic of this thesis, which investigates the relationship between public policy efforts in energy efficiency and innovation activities. For various reasons there are actually quite few studies looking into the innovation dynamics of energy efficient products and the role of policy efforts. The insights we have from the literature on environmental regulation and innovation are scattered and somewhat inconsistent. It is however commonly accepted that various policies mostly have positive impacts in terms of technological change and competitiveness but also that more insight into the specific dynamics is needed – Jaffe et al. argue that we should *"examine whether and how specific policies will affect the processes of invention, innovation, diffusion, and intensity of use of products*" (1999, p. 15). This thesis contributes with increased understanding, to how different policies influence the innovation processes through a systemic and dynamic innovation perspective. These theoretical perspectives emphasise the dynamics of change in complex socio-technical and actor-orientated systems. A combination of quantitative and qualitative research methods is used to get a comprehensive insight into the empirical context of energy efficiency innovation activities. This gives the thesis a broad understanding of the cross-sectoral characteristics of the innovation system elements in energy efficiency.

The scientific contributions of the thesis are unique as it contributes at two different analytical levels. Firstly, it provides insight into the characteristics and drivers of energy efficiency innovation across different sectors by investigating public collaborative R&D activities. Secondly, the thesis goes into depth by looking at the long-term change dynamics of a socio-technical regime where energy efficiency is 'successfully' integrated and the system undergoes of transformation.

The analysis of publicly funded RD&D activities was used to gain insight into some of the "public" parts of the energy efficiency innovation system. This enables a closer look at the heterogeneous networks of actors that exist in different areas of energy efficiency and to which extend they overlap – see paper #4 in the appendix. By using the RD&D project data, a clear overview of the network can be made and the most important actors are identified. Furthermore, the econometric analysis in paper #3 shows how collaborative nature of public R&D efforts in energy efficiency is influenced by the diversity of actor types and that specific combinations of actors have a positive impact on the likelihood of product innovation coming from public R&D projects.

Most of the literature regarding energy efficiency discusses the barriers towards the diffusion of energy efficient products. This project takes a different approach and looks to the actor-level in order to understand whether public policy is acting as a driver of energy efficiency innovation – paper #2. The actors perceptions were clearly that, within their respective sectors, public policies were a frequent driver of innovation activities, with market and user needs as well at technology development closely following. Specifically, information campaigns were most frequently indicated, as being a driving factor and building codes were believed to have a large impact in the building area.

Overall these results highlight the complexity of innovation activities in energy efficiency as they are impacted by several public policies at once as well as more conventional drivers of market and technology. These are most often inseparable and a dynamic perspective on the innovation dynamics must be applied. None the less the study finds that comprehensive policies to promote the development and commercialisation of new energy efficient technology is crucial, but that the dynamics of each policy instrument and sector requires a more comprehensive understanding from both researchers and policy makers.

From a historical narrative in the circulator pump industry a unique insight into the co-evolutionary development of energy efficient technology, policy efforts and market development was presented – paper #1 (Ruby, 2015). This was fundamentally different from the common understanding of a linear innovation processes and the negative impact of policy and regulation on innovation and competitiveness. Increased energy efficiency might resemble a series of simple technical improvements but in reality its innovation processes are complex and rarely succeed without the introduction of policies as well as changes in the market and overall institutional setup. Policies are therefore clearly needed to enable and guide energy efficiency innovation activities while also supporting the creation of institutions and sustainability transformations of entire socio-technical regimes. There is no one-size fits all perfect type of policy instrument to support energy efficiency innovation and regime transformation. It all depends on the specific products, industry, users and where barriers towards energy efficiency are placed. Undoubtedly ambitious, strategic and integrated policies are needed to remove the barriers towards energy efficiency and subsequently the uncertainties in innovation activities to continuously increase energy efficiency and economic development.

When analysing Denmark as an empirical context it is clear that historical events and the build-up of institutions matter. Denmark is known to have a strong overall energy innovation system, but this thesis will argue that it also has a strong energy efficiency innovation system. The strength of the Danish system is its ability to promote innovation activities for increased energy efficiency in a wide range of sectors from households to industry. Most of these efforts to increase energy efficiency are also supported by market-based policies – e.g. building regulations, energy labels and energy saving demands, etc. – which further incentivises the diffusion of new products. This approach of addressing all potential barriers towards energy efficiency, whether early in the invention phase or later at the commercialisation stage, is key in supporting innovation in energy efficiency and the creation of lead markets (Beise and Rennings, 2005). The success of the Danish energy efficiency innovation system is therefore mostly attributed to three elements: strategic and strong policy efforts; well-established policy and knowledge institutions (Wallace, 1995); as well as strong interaction and collaboration patterns between all types of organisation in the system. This thesis concludes that only with this setup is it possible to continuously support innovation and sustainable development.

10 INDUSTRY AND POLICY RECOMMENDATIONS

The thesis investigates the phenomena of energy efficiency policy efforts and innovation from different viewpoints and bases the following policy recommendations on these findings. The recommendations are divided in a firm/sector-level and a policy-level. The firm- and sector-level perspective emphasise the benefits of collaborative innovation and competitiveness for firms and industries which successfully incorporate energy efficiency. At the policy-level the emphasis are on interactive, integrative and stringent policy efforts for support of increased energy efficiency and innovation.

10.1 FIRM- AND SECTOR-LEVEL

COLLABORATIVE INNOVATION ENVIRONMENT

The integration of energy efficiency in well-established industries, markets and product portfolios can be a challenge for firms. The technical challenge typically involves the integration of technologies from other sectors, for instance electronics and micro-controllers, which typically is achievable despite the interdisciplinary aspects (Lutzenhiser and Shove, 1999). The difficult challenge is typically in the commercialisation of new energy efficient products, which are prone to encounter barriers towards increased energy efficiency.

A way to reduce these challenges is to collaborate on R&D with users and suppliers in the vertical parts of the value chain. It is shown through an econometric analysis of publicly funded R&D projects that collaboration with diverse actor types is beneficial for innovation. In particular, collaboration with research institutions specialised in applied research together with the users and energy companies is crucial in enabling energy efficiency innovation, for the benefit of both the environment and the firm.

SUSTAINABILITY AND OPPORTUNISTIC FIRM STRATEGY

Environmental and sustainability issues present future business opportunities for firms, although they are rarely perceived this way. First-mover behaviour in terms of environmental performance can benefit a firm's competitiveness in existing markets but also lead to new markets and business opportunities. This thesis presents a unique case where firms create a voluntary industry agreement that paves the way for new market parameters and enables firms to recover their investment in R&D to increase energy efficiency. These voluntary agreements can have an impact on overcoming market barriers and bringing new business opportunities, but they do require alignment within the industry and coherence with societal goals.

10.2 POLICY-LEVEL

INTERACTIVE POLICY PROCESSES

Interaction between public and private organisations is crucial throughout the innovation system but often it is lacking in actual policy processes. Research shows that the potentially negative impacts of upcoming regulation are reduced through interactive policy processes because they reduce uncertainty within industry and create ownership of policies. Wallace (1995) proposes the *Industry-Regulator Matrix for Environmental Policy* as a tool for explaining why, for instance, Denmark has success with its policy efforts. In the matrix, Denmark, as of 1995, is positioned as a "Responsible innovator" because of its high political independence and high quality of dialogue between public and private organisations. The effect of this position is certainly seen in the planning, development and implementation of energy efficiency policy in Denmark, which has a high degree of interrelation between policy makers, knowledge institutions and the private sector.

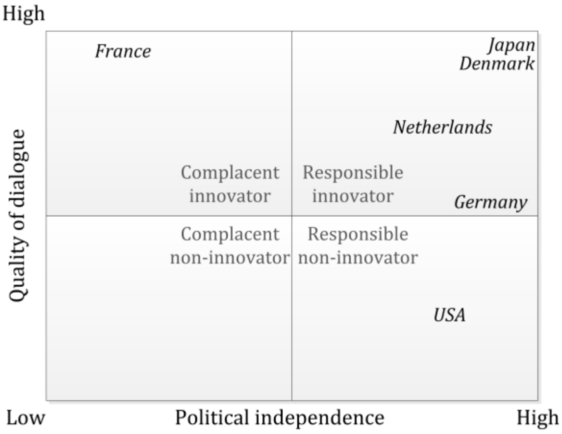

FIGURE 24 – THE INDUSTRY – REGULATOR MATRIX FOR ENVIRONMENTAL POLICY (WALLACE, 1995)

INTEGRATED POLICY EFFORTS

Policy efforts in energy efficiency must consist of different policies that complement each other and in combination are able to support development, commercialisation and diffusion of new energy efficient solutions. Isolated command-and-control or market-based policies will not suffice (Shama, 1983). The transformation of existing industries and markets requires incentives for both firms and users in order to change the dynamics of the socio-technical system. Some success of such efforts is seen in the market transformation literature that shows that the integrated use of information campaigns, energy labels and minimum efficiency demands has tremendous impact on the dynamics of the industry, reducing environmental impact and supporting technological change and innovation. To create even stronger incentives it is crucial to also include public funding for RD&D as it is important for the creation and diffusion of knowledge between actors.

STRINGENCY AND POLICY LEARNING

The third and crucial recommendation for policy is the importance of long-term policy stringency and continual policy re-evaluation. Long-term policies are important to reduce uncertainty for firms and support their long-term R&D efforts. This stability is crucial for firms when attempting new technologies, business segments or markets as with energy efficiency and other sustainability issues (IEA, 2010). The success of long-term policies requires insight, re-evaluation and continual policy learning (Kiss and Neij, 2011). Gregersen and Johnson propose seven elements of policy learning for supporting sustainable development, which fit well with the findings in this thesis.

TABLE 9 – SEVEN ELEMENTS OF POLICY LEARNING FOR SUSTAINABLE DEVELOPMENT (GREGERSEN AND JOHNSON, 2010).

(a)	Forming visions about the learning economy as an environment for innovation and sustainable development and forming the value premises of innovation policy.
(b)	Developing a system of innovation approach to policy making including development of new concepts, data, and theories of innovation and systems of innovation.
(c)	Establishing new practices and routines in the conduct of policies stimulating learning and innovation including gradually trying, testing, and evaluating new practices and routines.
(d)	Stimulating regional and local experiments in policy areas in need of reform and developing new methods to evaluate the outcomes of such experiments that take into account learning effects.
(e)	Institution building that supports the production and reproduction of human and social capital and diffusing international, regional and local 'good practices' in this field.
(f)	Analysing and comparing systemic features and critically important indicators in a form for benchmarking across regions, organizations and nations.
(g)	Stimulating democratic participation in the design and implementation of innovation strategies including forms of ongoing dialogues between employees, unions, researchers and governments.

Policy learning is especially important when pursuing long-term policies that emphasise radical change in technology, industry and markets. As with any innovation process, the outcome of future efforts cannot be predetermined, which makes it important to re-evaluate and reiterate policies to support unforeseen breakthroughs. An example of this is how energy labels must be reiterated along with industry innovation efforts as the majority moves towards the A-rating, thus removing the incentive for further developments.

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12 THESIS APPENDICES

12.1 BARRIERS TOWARDS ENERGY EFFICIENCY

Overview of barriers to energy efficiency (Sorrell et al., 2000)

Perspective	Sub-division	Barrier	Description	Comments
Economic	Rational behaviour	Heterogeneity	Technology may not be cost effective in a particular instance	An empirical question
		Hidden costs	Technology investment entails extra costs or loss of benefits that are not reflected in engineering models	Examples include overheads for staff, overheads for energy information systems, disruptions, hassle, and inconvenience
		Risk	Stringent investment criteria may represent a rational response to risk	Energy efficiency investments may be a higher risk than others, or there may be business/market risk
		Access to capital	Some agents cannot obtain capital to invest	A key issue is the level of gearing of a company and the expected consequences of further borrowing
	Market or organisational failure	Imperfect information	Agents lack sufficient information to make economically efficient decisions	Information has public good characteristics and may be undersupplied by markets.
		Adverse selection	Agent cannot transmit or discover energy properties of a good	A form of asymmetric information in which transaction costs prevent the energy efficiency benefits of a good from being signalled
		Split incentives	Agent cannot appropriate benefit of investment – landlord-tenant type relationships	Examples included departments not being accountable for energy consumption, and equipment purchasers not being accountable for running costs
		Principal-agent relationships	Principal may impose strict investment criteria to compensate for imperfect information	Asymmetric information creates incentives for the agent to maximise his utility to the detriment of the principal. Principal-agent relationships are pervasive within organisations
Behavioural	Bounded rationality	Bounded rationality	Cognitive limitations lead to agent's satisficing rather than optimising and relying on routines & rules of thump. Organisational routines may systematically neglect energy efficiency	Well-established opposition to mainstream tradition in economics. Strongly supported by empirical studies of energy decision-making. Routines are an organisational solution to bounded rationality
	The human dimension	Form of information	Form of information may be inadequate to stimulate action	Results from social psychology. Form of information as important as cost
		Credibility and trust	Agent may not trust source of information	Credibility enhanced by interpersonal contacts
		Inertia	Agents resist change because they are committed to what they are doing and justify inertia by	Derives from theory of cognitive dissonance

		downgrading contrary information	
	Values	Lack of environmental awareness leads to neglect of efficiency improvements	Not necessarily a barrier but an important explanatory variable
Organisational	Power	Agents lacks sufficient power within an organisation to initiate action	Energy manager may lack status and authority
	Culture	Environmental awareness and energy efficiency play no part in corporate culture	Not necessarily a barrier but an important explanatory variable

12.2 LIST OF INTERVIEWEES

Contact	**Content**
Peter Bach, Danish Energy Agency	On the historical energy efficiency policy development in Denmark and recent efforts for energy companies.
Kamilla Tingvad, Danish Energy Association	Energy efficiency policy in Denmark.
Henning Grønbech, Exhausto	Internal and external RD&D efforts in ventilation products and energy efficiency.
Henning Holm Sørensen, Exhausto	Internal and external RD&D efforts in ventilation products and energy efficiency.
Ole Hansen, Exhausto	Internal and external RD&D efforts in ventilation products and energy efficiency.
Søren, Exhausto	Internal and external RD&D efforts in ventilation products and energy efficiency.
Jørgen Føns, Exhausto	Internal and external RD&D efforts in ventilation products and energy efficiency.
Christian Grønborg Nicolaisen, Technological Institute	RD&D efforts in ventilation products and energy efficiency.
Nils Thorup, Grundfos	Talk about energy efficiency and innovation in the circulator industry.
Niels Bidstrup, Grundfos	Talk about energy efficiency and innovation in the circulator industry.
Tommy Andersen, Smedegaard A/S	Talk about energy efficiency and innovation in the circulator industry.
Kevin Lane, Kevin Lane (Oxford) Ltd	In-depth talk regarding the first report on energy efficiency in circulator pumps.
Jørgen Borup, ELFORSK	Talk regarding ELFORSK and the outputs from RD&D projects.
Ditte Mikkelsen, ELFORSK	Talk regarding ELFORSK and the outputs from RD&D projects.
Pernille Skjershede Nielsen, Gate21	Head of the evaluation committee at ELFORSK – to provide initial feedback on online questionnaire.
Professor Arsen Melikov, DTU Buildings	Ventilation industry and innovation efforts in recent years. How energy and energy policy has had an influence.
Jens Ellevang, Schneider Electric	Talk about the market for energy efficiency improvements.
Stine Madsen, Dong Energy	Talk about the market for energy efficiency improvements.
Finn Bruus, Københavns Energi	Talk about the market for energy efficiency improvements.

12.3 LIST OF PHD-RELATED ACTIVITIES

12.3.1 PH.D. COURSES

Course title	University	ECTS	Presentation
Research Objects and Methods in Design and Innovation (Compulsory)	DTU	7,5	X
Getting my research published	CBS	1,5	
Research at DTU Management Engineering (Compulsory)	DTU	2,5	
88553 Teaching and Learning	DTU	2,5	
Innovation and entrepreneurship theory	AAU - DOME	5	X
EIS PhD summer school and expert forum 2012	AAU/AU/DTU	4	X
Applied quantitative methods for non-quantitative doctoral students	CBS	2,5	
Social Network Analysis	AU	5	X
Measuring and Modelling Dynamics in Innovation Systems	Utrecht University, NL	3	X
Innovation and Learning in Energy Policy	NNTU, Norway	5	X
EIS PhD summer school and expert forum 2014	AAU/AU/DTU	-	X
	TOTAL ECTS	38,5	

The required number of ECTS points for 3-year Ph.D.'s at DTU is 30.

12.3.2 CONFERENCES AND WORKSHOPS

- DRUID Winter Academy Conference 2012, Cambridge

  Extended abstract, full paper (review by senior researcher) & presentation.

  Ruby, T.M., 2012, Policy driven innovation-the role of energy saving obligations for energy distributors in Denmark, in: DRUID Academy Conference 2012.

  Available at http://orbit.dtu.dk/fedora/objects/orbit:131383/datastreams/file_27dfa309-cd4e-4641-bb7b-dea8de67c230/content

- EU-SPRI Early Researchers Conference - Science dynamics 2013, Madrid

  Extended abstract, full paper (senior reviewer) & presentation paper #4 "Characteristics of networks in energy efficiency research, development and demonstration – a comparison of actors, technological domains and network structure in seven applied research areas"

- UKERC SPARK symposium 2013 – UK Energy research, Oxford

  Two-day symposium on UK Energy research efforts and collaboration - Group presentations only.

- DTU International Energy Conference 2012

  Ph.D. poster presentation of results from analysis of energy efficiency RD&D network analysis.

- Extended abstract (Paper #1) accepted for ERSCP-EMSU 2013 Conference in Istanbul

  Unable to participate because of personal reasons.

- Extended abstract (Paper #1) accepted for 19th annual International Sustainable Development Research Conference in South Africa

  Unable to participate because of personal reasons.

12.3.3 TEACHING ACTIVITIES

Autumn semester 2012 - 42075 Knowledge and Innovation in Networks

In the Master course Knowledge and Innovation in Networks at DTU I taught on three four-hour sessions regarding theories of knowledge and innovation (Science and Technology Studies, Actor-Network Theory and Communities of Practice). This included self-prepared lectures, group exercises and project feedback. I also contributed with corrections of written exams.

Approx. 50 students attended the course.

12.4 MECHANICAL VENTILATION CASE: INCREMENTAL POLICY AND INCREMENTAL INNOVATION

Ventilation in homes and offices has received increased attention because of the increasing demands for more insulated and tighter houses while also improving indoor air quality. Earlier on, ventilation was done “naturally” through a leaky building and open windows. With low-energy or passive houses natural ventilation is no longer beneficial. Here efficient mechanical or hybrid ventilation is needed.

In most north European countries there are several demands for mechanical ventilation with building codes with minimum efficiency demands, EuroVent energy classification, Ecodesign, electric motor regulation just to name a few. These policies typically target the heat-recovery efficiency and electricity consumption of ventilation aggregates and have over the last years had tremendous impact on the ventilation industry.

Energy efficiency demands in the Danish building regulation for the heat recovery and motors have been some of the most ambitious in Europe. At the technology level this has led to breakthroughs in air heat recovery technology with a move from counter flow and rotary systems to cross-flow systems with efficiencies upwards of 90%. Similarly advanced EC motors have lowered the electricity consumption of the ventilation aggregates significantly.

In Denmark these developments occurred together with knowledge institutions, consultants and users over several years, often supported by public R&D funding. The policy demands where therefore manageable for industry and the technological challenges were overcome in a collaborative manner. These ambitious demands for energy efficiency has led to Danish companies having strong market positions and increased exports. This has not only had an impact on Danish ventilation industry but the construction and engineering consulting industries as well.

These dynamics resemble the transition context of purposive transition as defined by Smith et al. (2005) because of the relatively high coordination and the integration of external capabilities and technologies.

This is a short summary of a much longer case narrative. Literature, desktop research and interviews with industry and experts were used as empirical data.

12.5 PAPER #4 - CHARACTERISTICS OF NETWORKS IN ENERGY EFFICIENCY RD&D A COMPARISON OF ACTORS, TECHNOLOGICAL DOMAINS AND NETWORK STRUCTURE IN SEVEN APPLIED RESEARCH AREAS

Additional paper added for contextual and empirical understanding. Presented EU-SPRI Science Dynamics 2013 in Madrid.

CHARACTERISTICS OF NETWORKS IN ENERGY EFFICIENCY RD&D
A COMPARISON OF ACTORS, TECHNOLOGICAL DOMAINS AND NETWORK STRUCTURE IN SEVEN APPLIED RESEARCH AREAS

Peer reviewed for: Early Career Researcher Conference (ECRC) - Science dynamics and research systems: The role of research in meeting societal challenges

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Abstract

The need for more energy efficient products and technologies has increased recently in connection with meeting today's energy and environmental issues. Research, development and demonstration (RD&D) is one way of supporting technological innovation and knowledge diffusion - but there is no such thing as "just" RD&D in energy efficiency as it encompasses a multitude of different sub-areas, institutions, actors, markets etc.

Through the use of network analysis on unique RD&D project data from Denmark the study provides new insights into knowledge and inter-organisational networks in energy efficiency research and development. The results show how certain knowledge institutions that connect the scientific knowledge with specific applications seem to be especially important for progress in the field. Overall the study enriches the understanding of RD&D in energy efficiency with a new view on the knowledge and innovation dynamics in seven sub-areas that were otherwise simplified and regarded at a homogenous group.

Keywords: energy efficiency, RD&D, research collaboration, network analysis

1 INTRODUCTION

Increasing energy efficiency and enabling energy savings is often seen as a crucial part of the solution to the current energy and environmental challenges. Many opportunistic and ambitious estimates of the potentials of energy efficiency have been put forward in the last couple of decades all with the main conclusion that there are vast energy savings available and that they are cost effective (IEA 2012; IEA 2011; Larsen & Petersen 2012; Wilson et al. 2012).

Since the 1970's oil crisis Denmark has been implementing and enforcing ambitious energy policy combining informative, normative and economic policies together with strategic funding into research & development along with demonstration projects (RD&D) (Lund 2000). These historical efforts to improve energy efficiency has given a Denmark frontrunner position in terms of having an energy efficient industry and efficient households but it also has established a significant industry determined to develop and produce energy efficient technologies and products.

This paper takes a closer look on how new technological knowledge is created and applied in new energy efficient products and systems through a look at research, development and demonstration projects in Denmark. It follows the understanding of innovation and new knowledge creation from evolutionary economics and innovation systems (Freeman 1987; Lundvall 1992; Nelson 1993), which puts emphasis on the systemic nature of innovation and how it occurs in interactions between several organisations and institutions and not only inside private companies. This perspective is especially suitable with the nature of the empirical data used in this study which is formed of public research collaboration and connects research institutions (universities and research institutions) and commercial organisations (producers, consultants, users and energy companies).

The paper uses a research methodology from social network analysis (Scott 2000; Wasserman & Faust 1994) on RD&D project data from Denmark with a total of 212 projects categorised into seven focus areas – *Lighting*, *Buildings*, *Behaviour*, *Industrial processes*, *Power electronics*, *Cooling* and *Ventilation*. The empirical data shows how different organisations have been collaborating on RD&D projects in the time period 2002 – 2011, which is used as relational networks in the network analysis. These networks of relations between organisations show important structures of collaborations between actors such as knowledge-institutions, producers, users, energy companies and consultants.

The paper investigates and conceptualises the characteristics of energy efficiency RD&D based on those actors involved in the project and how they are interrelated. The aim will be to explain important systemic and structural dynamics while analysing the roles of the actors as a comparison of the different networks within the seven focus areas.

Research questions

The study will partly act as a mapping of research efforts in energy efficiency in the Danish context illustrating the diffuse character of energy efficiency efforts in terms of different technologies, actors and relations, and partly it will be a contribution to the understanding of knowledge creation and diffuse networks in energy efficiency. The investigation will follow these research questions.

- What are the structural characteristics of the seven focus areas in energy efficiency RD&D in terms of actor composition and relations?
- What are the major differences in network structure across the focus areas?
- Which actor types, groups and relations seem most important for the creation and diffusion of new knowledge in the different focus areas?

2 REVIEW OF LITERATURE

Characteristics and dynamics of energy efficiency

The main topic in energy efficiency seems to be diffusion and adoption - more specifically the barriers towards it (Jaffe et al. 1993). Considerable research has been looking into the adoption of energy efficient products – whether identifying barriers at consumer- or business-level (Mills & Schleich 2012; Trianni & Cagno 2012) or focusing on the characteristics of the barriers (Sanstad & Howarth 1994). For a thorough overview and assessment of the barriers please see (Sorrell 2004; Palm & Thollander 2010).

These barriers illustrate some of the important innovation dynamics for energy efficient products. This is however a very rough generalisation of all energy efficient products as they are very different and their adoption is more complex because they are also dependent on product, market and sectorial dynamics (Tidd et al. 2005). An example can be of an energy efficient circulation pump that can be seen as a general energy efficient product but first and forehand it must comply with the pump market demands such as quality, reliability and performance.
These large differences across each area cover sectorial dynamics and institutional factors, which are crucial to the understanding of each areas distinct innovation dynamics. The buildings sector is for instance highly regulated whereas industrial processes are less indirectly influenced (Gann & Salter 2000; Reichstein et al. 2005). These differences across energy efficiency in terms of sectors, institutions, users etc. are influential in the structure of RD&D networks, but it has not been investigated in any previous research.

Research, development and demonstration in energy efficiency

Public efforts in energy efficiency research, development and demonstration (RD&D) is usually tied up in general energy research and energy policy (Geller et al. 2006; Gallagher et al. 2011), but draws heavily on buildings research, materials research, mechanical engineering and electronics[1]. Energy as a research field is therefore very incoherent and dispersed (Tijssen 1991), consisting of different large research areas such as energy production, renewable energy, energy transmission, energy consumption, energy efficiency etc.

There have been some studies into research, development and demonstration projects in the energy area, typically as a part of a research strategy analysis but these tend to either neglect energy efficiency or simply its role in the energy system (Kaloudis & Pedersen 2008; Sagar & Holdren 2002; Wilson et al. 2012).This lack of attention which recently was pointed out by Wilson et al. (2012) who argue that end-use technologies have been marginalized by institutions and policies despite of the fact that "*efficient end-use technologies occupy a greater share of energy system investments and capacity, engage higher levels of private-sector activity, offer higher potential cost reductions, return larger social benefits and promise greater future mitigation of climate change.*" (p. 784 Wilson et al. 2012). This marginalization also seems to be present in innovation studies and socio-technical studies of sustainability transitions (Ruby 2014b).
Actual investigations as to how RD&D in energy efficiency "works" and who is involved in it does not seem to be

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[1] Energy efficiency RD&D policy generally works in conjunction with other policy efforts of economic, normative or informative character.

present in the current literature. Furthermore, studies of energy innovation tend to focus on public RD&D only as there is a lack of knowledge and data of private RD&D and interactions with institutions (Sagar & van der Zwaan 2006; Gallagher et al. 2006; Sagar & Holdren 2002).

A study by Lutzenhiser and Shove does however illustrate a comparison of the historical efforts in energy efficiency in the US and the UK (Lutzenhiser & Shove 1999). This study underlines the interdisciplinarity necessary in energy efficiency research and development but it mainly signified through those researchers inside research institutions and universities and does not account for the diverse patterns of cooperation across organisations in general (outside public funding programs).

There have however been many studies of energy efficiency in subareas such as in sustainable buildings (Shove 1999; Gann et al. 2010), lighting (Mills 1995), industrial processes (Thollander & Palm 2013) etc. What seems to bind these subareas together are the general dynamics inherent in energy efficient solutions – the barriers to its adoption – and not so much shared technologies and systems.

Innovation systems and networks

The innovation system perspective has been applied to energy technology numerous times and given way for valuable studies of the energy sector and how it interplays with energy research (Foxon et al. 2005; Gallagher et al. 2012). There is however limited research that looks into energy efficiency and energy demand using an evolutionary innovation perspective[2].

The innovation system theory originates from evolutionary economic thinking and the works of Joseph Schumpeter (Schumpeter 1942). Innovation systems conceptualise innovation as occurring at the intersection between companies, universities and institutions with the creation of new knowledge as the main agent for innovation and economic growth (Nelson & Winter 1982; Lundvall 1992).

The innovation system perspective puts emphasis on the knowledge development as a process occurring between several actors (Lundvall 1992) and some studies in particular show how the knowledge and learning dynamics associated with RD&D support specific kinds of innovation (Jensen et al. 2007; Sagar & van der Zwaan 2006).

Specifically the fields of transition studies (Geels 2002) and technological innovation systems (Bergek et al. 2008) are recently giving more attention to actors and their relations. Some recent research in this field puts emphasis on the networks and network resources in technological innovation systems (Musiolik et al. 2012) as these resources are crucial in the process of formation and coordination every innovation system must undergo.

Networks play a crucial role in innovation systems studies although studies rarely focus specifically on networks (Coulon 2005). Numerous other studies have looked at organisational networks and innovation and found a relation between an organisations position in a network and its innovative output (Burt 1980; Tsai 2001). With for instance a more central position giving better access to resources (e.g. knowledge and capital) in the network and potentially more power over other actors in the network.

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[2] As opposed to a traditional linear understanding of innovation (Kline & Rosenberg 1986).

Using the network analysis methodology has also been applied as a way of evaluating research programs as for instance with EU FP programs (Breschi & Cusmano 2004; Roediger-Schluga & Barber 2006; Barber et al. 2006). These studies specifically look at the overall structures of European research programs to identify dynamics of the networks, which is a somewhat shared approach to what is applied in this paper although at a more micro-level.

3 RESEARCH METHODOLOGY AND DATA

The paper uses social network analysis in a partly explorative and partly descriptive manor on the RD&D project data from ELFORSK (DanskEnergi n.d.). Inspiration for the research methodology is drawn from network studies in other relevant research fields (e.g. Crawford 2012).

Research methodology

The paper uses methods from social network analysis (Scott 2000; Wasserman & Faust 1994) to analyse the relations between actors in energy RD&D. The analysis will consist of two levels – an overall network-level analysis and a more actor focused structural-level.

The analysis also relies on qualitative data in the interpretation of certain actors and their relations. This data is collected through a thorough desktop research along with general knowledge of the research projects and the technological domains involved.

The network analysis is carried out in the UCINET software – version 6 (Borgatti et al. 2002).

Network-level

At the network-level the analysis uses the basic network metrics of Density and Avg. Distance (Wasserman & Faust 1994; Scott 2000). The density of a network is the ratio between the number of relations and the maximum number of relations possible in the network if all actors were connected and it is very valuable in understanding overall network interrelatedness. The average distance in networks refers to the average of the distances between all combination of actors in a network and it is very useful in the understanding of the size and width of a network. The metric of avg. distance is very dependent on the size of a network, which should be taken into account when comparing these.

Structural-level

At the structural-level of the analysis the main method will be structural equivalence (Burt 1976). Two nodes or actors are said to be structurally equivalent if they have the same relationships to all other nodes. It is however rarely the case that several nodes have identical relations so when the method is operationalized a margin of error is introduced. In this paper the method is used to reduce the seven large networks and create groups of actors, which to some degree are structurally equivalent in the network. This reveals the basic structural characteristics of the seven networks and an analysis of the important relations between actors and groups of actors in the networks are possible.

Data collection and handling

The data originates from the ELFORSK research fund that was founded and administrated by the Danish Energy Association. From 2002 and forward approximately 3.35 Million € has been offered per year to co-fund research, development and demonstration (RD&D) with the aim of developing new energy efficient technologies. They state their aim as: ”ELFORSK supports projects with the purpose of securing a more efficient use of energy, with the outset in electricity. ELFORSK emphasises that the results are realized in actual energy savings, more efficient production processes, jobs and exports as well as an increased awareness in society about efficient use of energy”.

ELFORSK provides funding for applied research projects in seven separate focus areas within energy efficiency. See table 1. Between 2002 and 2011, 212 projects have received funding with approx. 400 unique actors involved. As the emphasis is on actual energy savings the research is somewhere between applied research and specific product development. ELFORSK encourage that projects have a mix of companies, research institutions, users and universities involved, which makes the relational data quite unique.

Table 1 - Overview of project data

Focus area:	Behaviour	Buildings	Cooling	Industrial processes	Lighting	Power electronics	Ventilation
# of projects	57	36	25	25	30	10	21
# of organisations	143	73	83	72	73	29	55

For each of the 212 projects the following data were collected.

Focus area:	Participants:	Organisation:	Type of participant:
Classified as one of seven focus areas. *Behaviour, Buildings, Cooling, Industrial processes, Lighting, Power electronics* or *Ventilation*	Name of the individuals on each project. Approx. 6,5 participants per project.	Name of the organisations involved. It is possible to have multiple participants from the same organisation. Approx. 3,5 organisations per project	Classified as a type of participant on the project. *University, Consultant, User*[3]*, Technological Institute, Energy Company* or *Producer*.

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[3] Meaning a company or institution where the outcome of the project will be implemented.

Data interpretation

The data is interpreted as relational data in the way that individuals are related if they have participated on a project together. Furthermore, is it assumed that organisations are related to other organisations if they have had employees that have participated on joint projects. These assumptions form the basis of the network data in this paper.

So the membership on projects is regarded as a relation in the network. The strength of the relations is determined by the number of people from each organisation whom are participating on each project. As the focus is on organisational relations the data is changed from two-mode (organisation to project) to one-mode (organisation to organisation).

Historical development is of great importance in an analysis, which uses a systemic and evolutionary perspective. This would intuitively mean that the networks development over time would be the aim of the analysis but in this research the focus is on the comparison of the existing networks and not their evolution over time. The data consists of projects conducted over a nine year time period and they are viewed as accumulated relations to establish knowledge networks within each focus area. This can be regarded as a static view on an evolutionary process.

FIGURE 1 shows the distribution of the organisations participating where out of the 398 organisations approx. 45% have done more than one project or had multiple persons on one project. Approx. 13% of the organisations have been involved in more then five projects or had five or more participants involved in one or more projects. This distribution of participating organisations shows an exponential development, which is appropriate for further network analysis as there is a clear difference in the number of relations between actors.

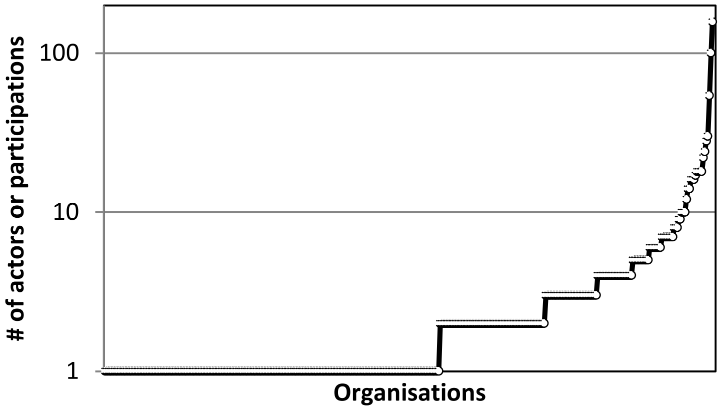

FIGURE 1 - The distribution of organisations and participation in projects

Overall characteristics of the relational data

The structure of the empirical data naturally follows the structure of the research projects supported by ELFORSK. An understanding of the projects and the data is therefore vital for understanding the network analysis and the results.

The research projects have different sizes and compositions of participants. FIGURE 2 shows the average project composition in each of the seven areas. The major differences are the size of the projects and the type of organisation that is participating. Here an indication of how the focus areas are interrelated with the network structure begins to emerge. This will be used further in the network analysis.

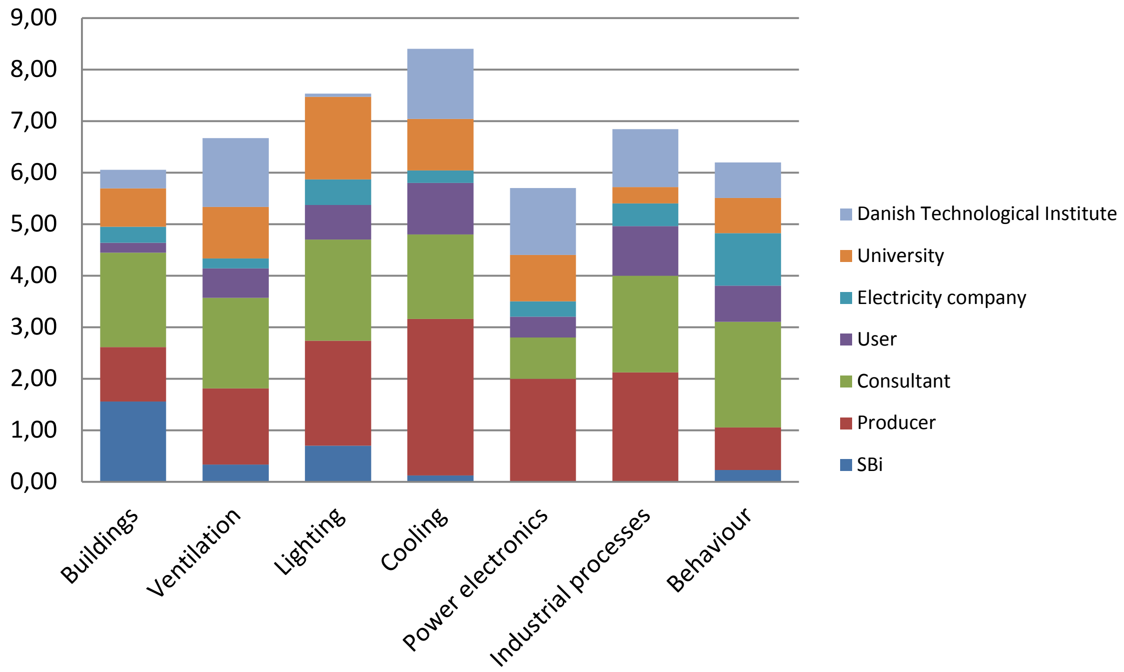

FIGURE 2 - Actor overview and distribution - per project (ELFORSK 2002 - 2011+)

Across the seven focus areas there are some shared organisations that participate in projects in multiple areas. Table 2 shows the percentage of shared organisations between the areas. There are more or less shared organisations depending on whether there are overlapping technological areas as for instance with *Industrial* and *Ventilation*. Furthermore is there also differences in the type of organisations there are involved in each area. Organisations such as *Universities* and *Consultants* are assumed to be involved in multiple areas, where as a small technology provider is not.

Table 2 – Percentage of shared organisations between focus areas.

	Industrial	Lighting	Buildings	Cooling	Ventilation	Behaviour	Power Elec.
Industrial	100,0	8,2	6,6	15,1	24,6	12,5	27,6
Lighting	8,3	100,0	17,1	8,1	14,0	13,9	31,0
Buildings	6,9	17,8	100,0	14,0	21,1	15,3	20,7
Cooling	18,1	9,6	15,8	100,0	17,5	12,5	13,8
Ventilation	19,4	11,0	15,8	11,6	100,0	9,7	34,5
Behaviour	25,0	27,4	28,9	20,9	24,6	100,0	37,9
Power Elec.	11,1	12,3	7,9	4,7	17,5	7,6	100,0
# of projects	72	73	76	86	57	144	29

Data structure and validity

There are certain limitations to the study based on the available data and how it is interpreted.

- There are large differences in the number of projects within each focus area, which will limit the comparison between them. This is for instance the case for *Behaviour* and *Power electronics*. This should however not change the final characteristics of the areas, as this is relatively independent of the size.
- In the original project data there is one project manager indicated on each project. The fact that one of the participants is the project manager is not included in the network analysis, as it would not change the relations, only the interpretation of actual roles in the network.
- There are clearly differences in the scope of the focus areas. Some target a specific technological area (e.g. *Lighting, Ventilation, Cooling*) whereas the areas of *Behaviour*, *Buildings* and *Industrial processes* are different with regards to their scope and delimitations. This is however also the strength of the data and it will be discussed further later in the paper.

4 RESULTS

The results of the network analysis will be derived from two levels of analysis. The first level will be the overall network level where a comparison will be made based on a two key parameters (Density and distance). The second level will be a structural level analysis to determine the structural characteristics of the different areas based on the participating organisations and their relations.
The quantitative measures gained from the network analysis methodology are interpreted in a qualitative approach to best understand the dynamics of the focus areas.

Network-level

At the network level the comparison of the seven networks will be based on two parameters, i.e. network density and average distance.

Network density

The density of a network is a simple relation between its total number of relations and the number of paired nodes. A high-density network can mean a more interrelated network where for example knowledge is able to flow easier compared to a low-density network ((Burt 1976; Burt 1980)). Higher density will also limit the importance of intermediaries and knowledge brokers to facilitate flows in the network.

FIGURE 3 shows the densities of the seven focus areas with *Behaviour* having the lowest and *Power electronics* having the highest. As mentioned earlier should a comparison using the *Power electronics* area be done with caution, as the data are somewhat incomparable. It is however clear that the focus areas defined by a technological area i.e. *Lighting*, *Cooling* and *Ventilation* have a more dense network than those defined by a broad application area i.e. *Behaviour*, *Industrial processes* and *Buildings*. This can be explained by the homogeneousness of the areas with *Behaviour* being the extreme where many different organisations are working on many different ways of influencing energy using behaviour. On the other side of the scale we have the more stable areas of *Cooling* and *Ventilation*, which opposite to *Behaviour* is embedded in structures outside the network for example through industry, sector, suppliers etc.

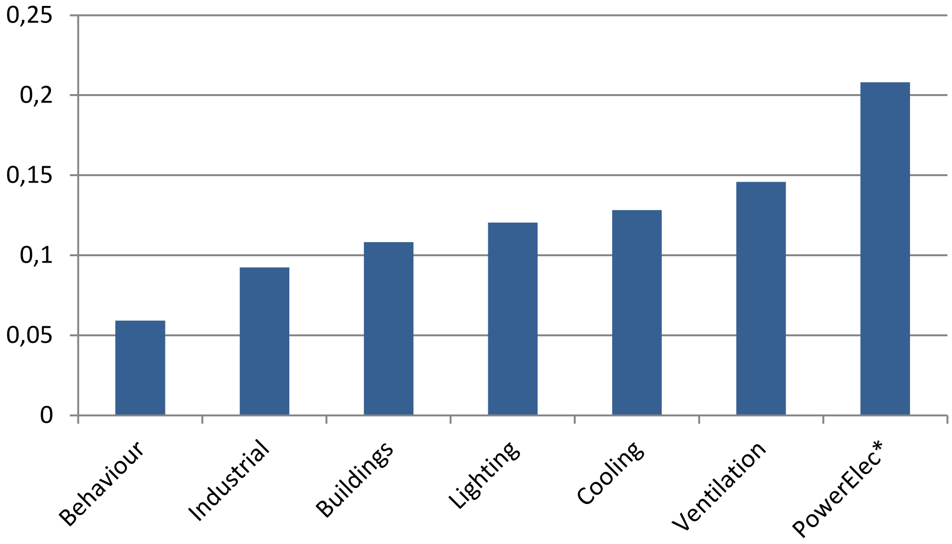

FIGURE 3 - Network density

Distance

In almost every network there are actors, which are not adjacent to each other. For these to connect they must go through other actors. Distance in networks refers to the number of relations there must be present for two actors to stay connected. The average distance (average geodesic distance) is the mean of the shortest path lengths among all connected pairs in the network. Having a network with short distances makes knowledge diffusion to the entire network quicker.

There are no large variations in the average distances in the networks – See FIGURE 4. It is however clear that the application based focus areas i.e. *Industrial* and *Behaviour* are more diverse and in general have larger distances between distant actors. This hypothetically makes it slower to fully diffuse knowledge in the application-based networks.

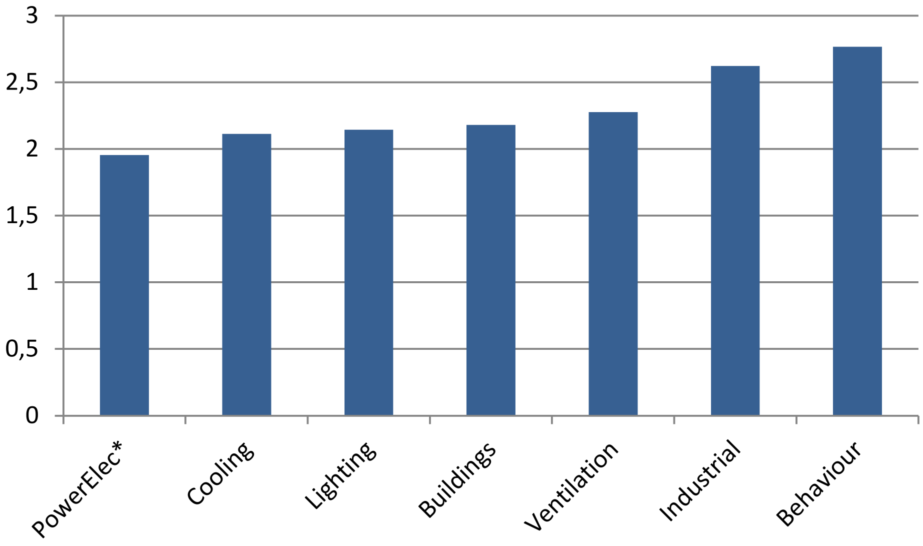

FIGURE 4 - Average distances in the networks

Summary at network level

Summarising the analysis at the network level shows slight variations across the seven focus areas. The technology-based areas of *Ventilation*, *Cooling* and *Lighting* tend to have more dense networks with shorter distances between actors, whereas the more application-based areas of *Buildings*, *Industrial processes* and *Behaviour* show less interconnected networks with more diverse actors and relations. These are in coherence with the descriptive statistics in Figure 2 and Table 2.

Structural-level

The second level of analysis is at the structural level where the aim will be to identify the structural characteristics of each focus area. The structural equivalency method from social network analysis by Ronald S. Burt (Burt 1976) is used to enable a simplification of the large research networks so an understanding of the structural characteristics of each is possible. Through this methodology and the resulting graphic representation of each of the seven areas it possible to analyse how and where the important interactions in the networks are occurring.

Lighting

The research area of *Lighting* is concerned with the development and application of low energy lighting solutions primarily using LED technology to achieve energy savings. The area shares several organisations with *Buildings* and *Behaviour* (Table 2) that is logical as *Lighting* shares many elements with energy use in buildings and end-user interaction.

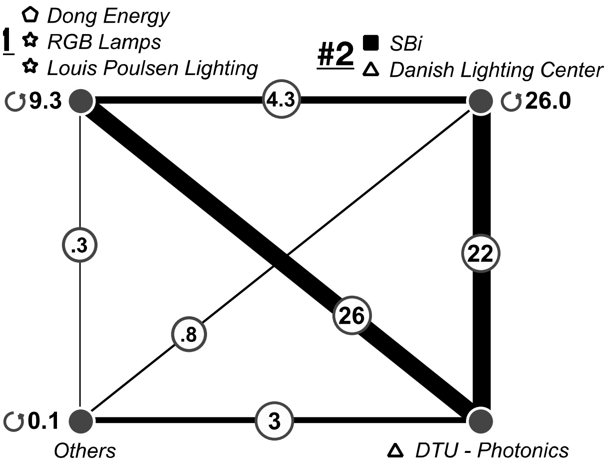

FIGURE 5 - Structure of the *Lighting* network

FIGURE 6 - Legend for network structure graphs

The network is driven by DTU Photonics as the focal actor with strong relations to two secondary groups. The first secondary group consists of business and application resources in the form of two lighting producers and an energy company. The second group - #2 – consists of research and technical consulting organisations contributing with technical and system resources. These two secondary groups have little interaction with the rest of the network, which are mainly involved through the focal actor.

Lighting outlines a structure where it seems that organisational and technological resources and knowledge are originating from the focal actor and where application knowledge is included through the two secondary groups by the focal actor.

Behaviour

The research area of *Behaviour* is a very diverse and somewhat diffuse area where energy savings are realised through efforts in technical, organisational and social aspects. This can be seen in Table 2, which illustrates how *Behaviour* is sharing many organisations with all other focus areas. This diversity in organisations and their relations result in a complex network structure.

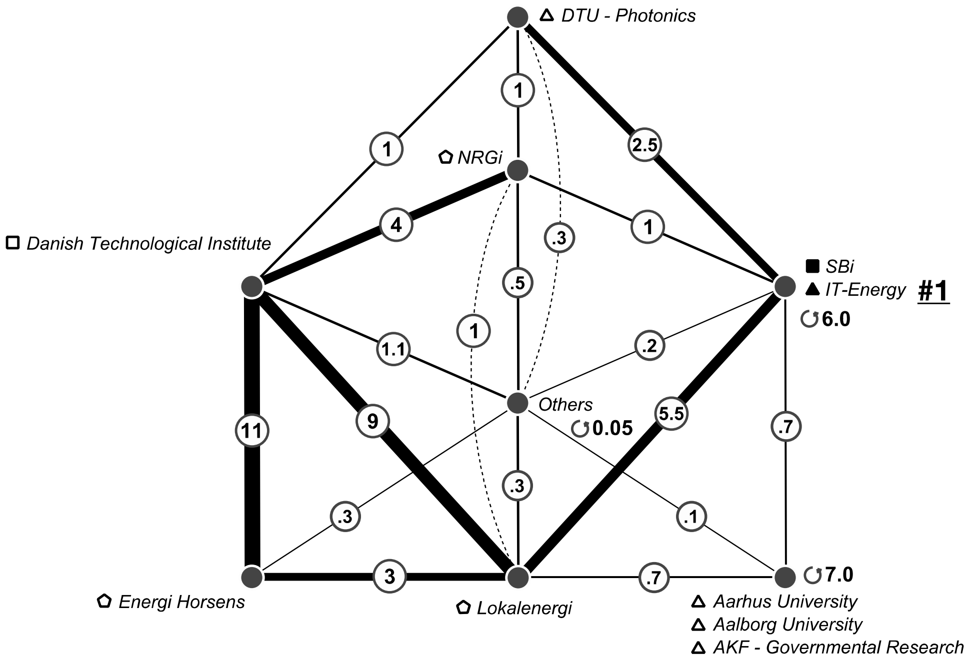

FIGURE 7 - Structure of the *Behaviour* network

The driver of the network is not one focal actor as seen in *Lighting* but more a constellation of multiple actors. The DTI is acting together with three different energy companies while two of the energy companies also are interlinked with a grouping (#1) of SBi and a consulting company. This is an interesting constellation where the two energy companies are combining the two competing knowledge institutions. This clearly illustrates the diverse nature of *Behaviour* where the heterogeneousness nature of the energy saving solutions leads to a complex relational structure.

Power Electronics

The research area of *Power electronics* is aiming to either improve the efficiency of electronic systems or introduce electronics to enable energy savings for instance through control and automation. The research area is under represented in the empirical data, which must be considered in the structural analysis.

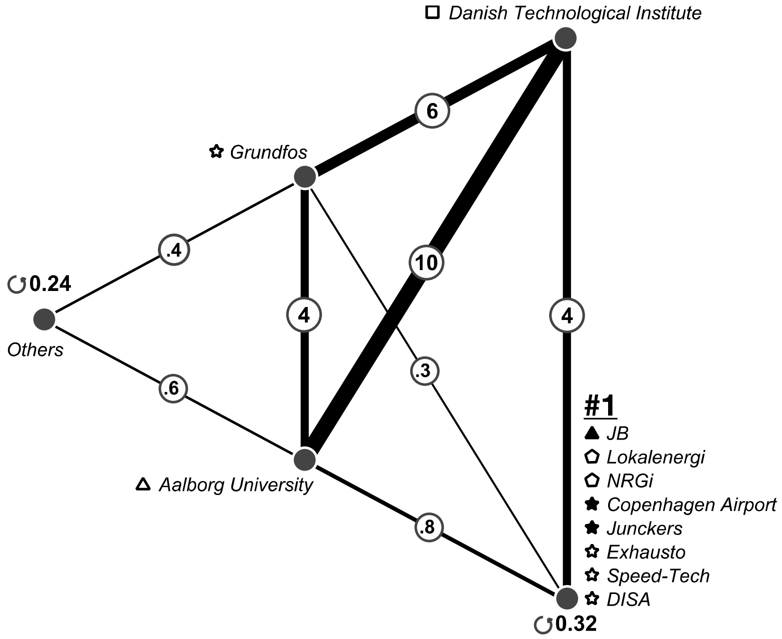

FIGURE 8 - Structure of the *Power electronics* network

The network has a constellation of actors driving the network. The DTI, a producer and a university are highly interrelated and besides the main constellation there is a large support group, which includes producers, users and energy companies. The secondary group is primarily involved through DTI.

<u>*Industrial processes*</u>

The research and development area of *Industrial processes* is aiming to reduce energy consumption through the optimisation of production facilities in all industrial sectors. These kinds of projects are usually context specific to each type of production facility and each specific site, making generalisation especially difficult in this area. The projects require special knowledge on a multitude of industrial processes and their interaction in a large production system.

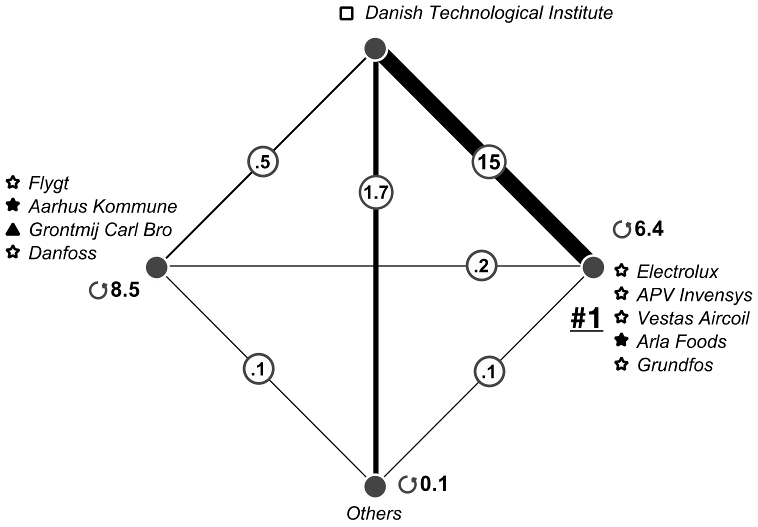

FIGURE 9 - Structure of the *Industrial processes* network

The focal actor in the network is DTI, which only has a strong relation to group #1 while having relatively weak ties to group #2 and to the rest of the network. Group #1 consists of five producers and one user and act as the preferred project partners together with the DTI. The DTI act as project organisers and are knowledgeable of the overall production systems, while they include technologies from individual producers when necessary.

Group #2 seems to have very little interaction with other groups, which can be explained, by their high internal interaction. The group consists of multiple types of actors, which could indicate that they are sufficient with each other and only include outsiders when necessary.

Cooling

The research area of *Cooling* is aiming at increasing energy efficiency in two contexts. Cooling and air conditioning refers to the indoor environment in houses and offices while cooling also can be related to refrigeration in food- and retail-sector. These two types of technologies are similar but its application is very different which will have influence on the network.

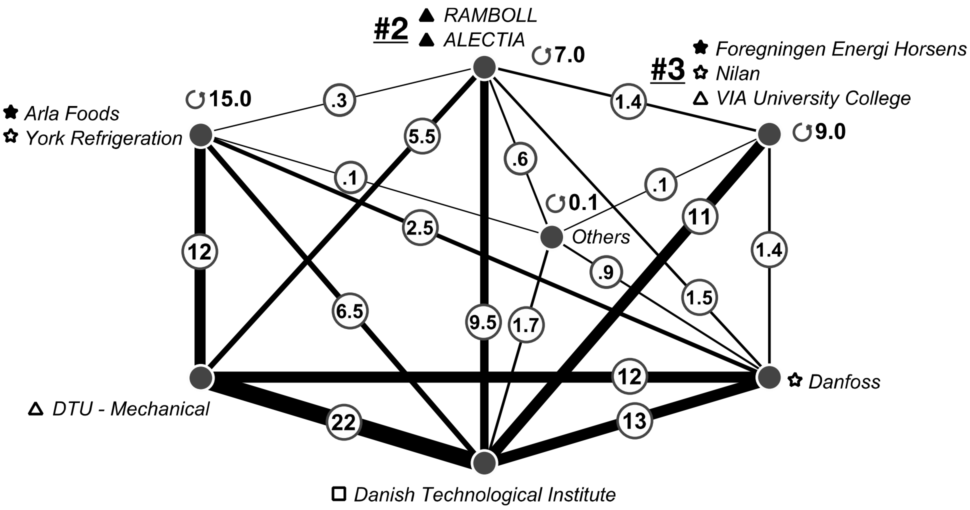

FIGURE 10 - Structure of the *Cooling* network

The network consists of a constellation of driving actors with three supporting groups. DTI, DTU and the producer Danfoss are making up the constellation while three main supporting groups are connected through different parts of the constellation. The constellation itself has scientific-, application- and organisational-knowledge with very strong supporters contributing with contextual knowledge on either cooling and refrigeration (#1) or cooling and ventilation (#3). Furthermore is group #2 containing two building consultants involved to provide knowledge on the building integration aspects of cooling.

The very high density of the network also indicates that the network is very interconnected and that the “power” is distributed among several actors even though there are two separate groupings attached to the constellation.

Ventilation

The research area of *Ventilation* is aiming to lower the use of energy in ventilation systems for homes, offices and industrial buildings, which primarily mean optimising fan, duct and heat recovery systems.

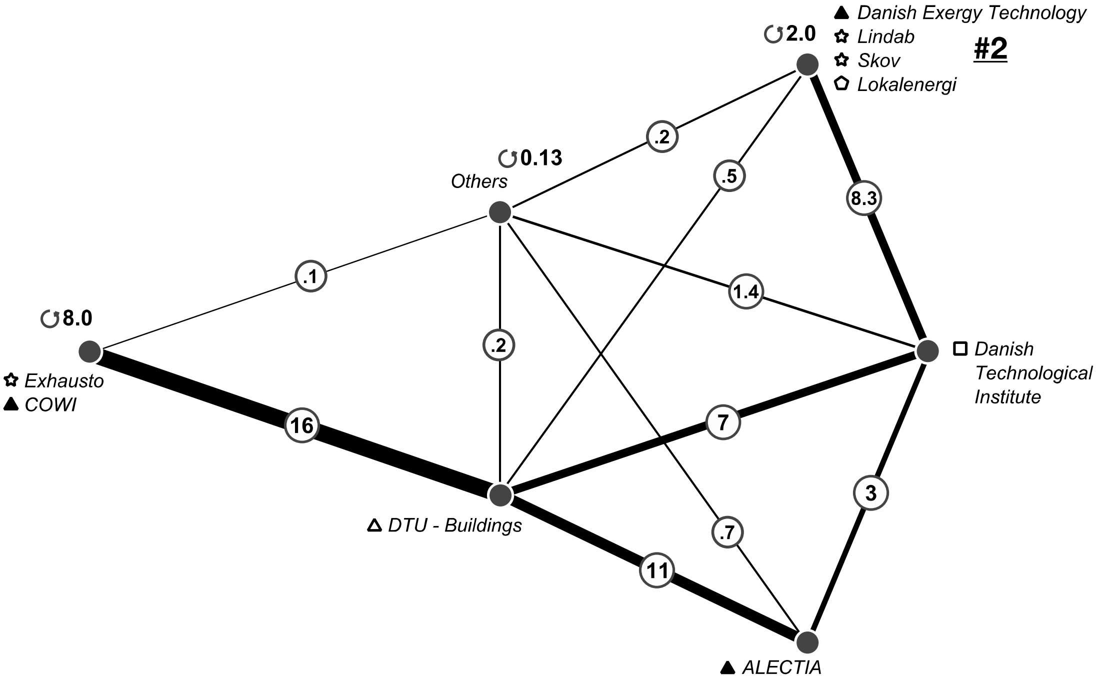

FIGURE 11 - Structure of the *Ventilation* network

The network shows a constellation of DTU, DTI and ALECTIA with strong support coming from two separate groupings to either DTU or DTI. The two supporting groupings appear similar in their actor composition with a combination of producers and technical consultants indicating a competitive aspect to the constellation.

The rest of the network seems involved through multiple actors, which supports the occurrence of a broad constellation.

Buildings

The research area of *Buildings* is aiming to improve primarily the non-energy using elements of the houses, offices and industrial buildings. This means improving the building envelope, windows, building techniques etc. for new and existing buildings.

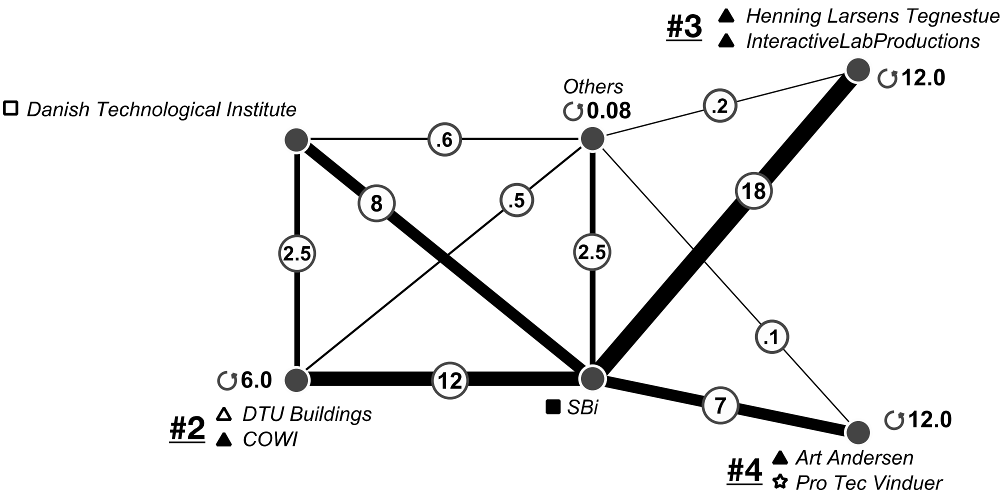

FIGURE 12 - Structure of the *Buildings* network

The network has SBi as the focal actor with strong support coming from several groups. The two sides of the groupings (#1 & #2 vs. #3 & #4) show two important elements in the area of energy efficiency in buildings. The research area is a merger of technical knowledge coming from research institutions and technical consultants (#1 & #2) together with architectural knowledge coming from architectural consultants (#3 & #4). The rest of the network seems to be involved primarily through the focal actor.

The construction companies themselves seem however to be missing from the network completely, which seems as an inefficiency of the network.

Summary at the structural level

The networks show distinct differences in structure across the seven research areas. Table 3 shows a summary of the structural level analysis.

The clear differences are in whether a network has a focal actor or a constellation of actors driving the network. DTI, DTU and SBi seem to be especially actors important across different focus areas with DTI involved in almost all networks and SBi acting as the focal actor in more building-related areas (*Buildings* and *Behaviour*). There also seems to be differences in the arrangement of supporting groups to whether there are different application areas within a focus area, which for instance is the case with *Cooling*, or whether there are competing groups connected to different part of the main constellation, as is the case with *Ventilation*.

Table 3 - Overview of the characteristics of each focus area

	Lighting	**Behaviour**	**Power elec.**	**Industrial pro.**	**Cooling**	**Ventilation**	**Buildings**
Driver type	Focal actor	Constellation	Constellation	Focal actor	Constellation	Constellation	Focal actor
Driver (s)	DTU – Photonics	DTI, Three energy companies and SBi	DTI, Grundfos and AAU	DTI	DTI, DTU and Danfoss	DTU, DTI and ALECTIA	SBi
Driver characteristics	Scientific-, Application- and organisational-knowledge driver	Large constellation with no distinct driver.	Scientific-, application- and organisational-knowledge driver	Application- and organisational-knowledge driver	Scientific-, application- and organisational-knowledge driver with very strong supporters	Application- and organisational-knowledge driver - a competitive constellation	Scientific-, application- and organisational-knowledge driver
Support groups	#1 Two producers and an energy company #2 SBi and a lighting consultant	#1 DTU Photonics #2 Social science research institutions	#1 Large group of producers, users and energy companies	#1 Five producers and a user #2 Isolated group of producers, a user and a consultant	#1 Producer and user involved with all in the constellation #2 Two technological consultants #3 University, producer and user	#1 A producer and a consultant (supporting DTI) #2 Two producers, a consultant and an energy company (supporting DTU)	#1 DTI #2 DTU & Building consultant #3 Architectural consultant and producer #4 Architectural consultants
Distant actors (*Others*)	Involved through focal actor	Involved by multiple actors	Rarely involved	Involved through focal actor	Involved by multiple actors	Involved by multiple actors	Involved through focal actor
Avg. Degree	3,8	5,1	3,6	3,8	6,0	4,2	4,0
Density	1,3	0,7	0,9	1,3	1,0	0,8	0,8

5 DISCUSSION

The findings cover seven distinct research and development areas in energy efficiency all with their own structural characteristics and distinct actor composition. Certain patterns appear across the seven areas with regards to the kind of actors that seem to be driving the networks and the technological maturity.

Network drivers in energy efficiency

Consistent across the seven networks there seems to exist a pattern of certain actors or groupings likely to be acting as drivers in the networks. These actors are primarily knowledge and research institutions as e.g. DTI, DTU or SBI. They are acting as drivers of networks either at as focal actor or as a part of a larger constellation, which illustrates their role as both organisers and knowledge providers in the networks. The role of these institutions therefore appear especially important in the case of energy efficiency where RD&D is more valuable than basic research.

Besides a pattern of network drivers the networks also seem to have a pattern of supporting groups. These groups consist of actors, which complement the focal actor or constellation of actors. Here the differences between the networks are visible in terms of the actors involved. The focus area of *Cooling* has two groupings attached to the main constellation supporting different aspects of the research area. In this case it is interesting to see how the focus area has inherent technological subgroups, which defines the network structure.

Technological maturity

Overall energy efficiency is mostly dealing with proven and mature technologies but the different research areas do include technologies at different maturity levels. An interesting perspective is to determine the maturity of the technologies based on who is involved in the separate networks. If so will the area of *Lighting* be the least mature area by having the strongest connection to basic research in the form of DTU Photonics. The rest of the research areas seem to be dominated by institutions that do not carry out basic research.

Data validity and structure

The data used in this study is aggregated from nine years of RD&D projects, which is a long time without accounting for changes in for instance the prioritization of the funding. In the study this does however not seem important as the focus is on the aggregated network and the data does seem consistent in the time period.

The data does not cover all public funding going into energy efficiency in Denmark but approx. half or more of all projects in the period 2002-2011. This was a deliberate choice as the quality of the data for the rest of projects was insufficient and because it seemed sufficient for the purpose of the research.

As there is no coding or alteration of the data the validity is high although it could be lowered slightly in the aggregation to the organisation-level. These aggregations should however not influence on the overall validity of the study.

6 CONCLUSION

New knowledge on the development and commercialisation of energy efficient technology is created through cooperative structures of multiple organisations, which structural characteristics are dependent mainly on the technological domain. Energy efficiency is often regarded as homogeneous group of initiatives (seen in relation to energy, climate and environmental challenges) classified together because of their similar goal-orientation. This study shows that energy efficiency is very heterogeneous when looking at the different actors and organisations involved in its development. Through the application of network analysis on data from public energy efficiency research projects in Denmark the underlying network structures are revealed and they illustrate some of the fundamental differences between focus areas of energy efficiency RD&D. There are structural differences between the seven focus areas, which highlight the differences in collaboration networks, the actors involved, and the strength of the relations.

Certain organisations appear especially important in establishing and facilitating these network structures. The Danish Technological Institute (DTI) seems very valuable because of their role as network organisers and more importantly because of their role in knowledge integration and diffusion between actors. This role as knowledge integrator of scientific and application-based knowledge into new products and systems seems critical in energy efficiency developments independent of the focus area. There are however focus areas where DTI doesn't seem to play this role and where it is typically a university or other research institution, which act as both knowledge supplier and knowledge integrator – this is seen in the Lighting and Buildings area.

Policy implications

Mismatch in ideal research composition

The seven network diagrams in general show a very wide variety of actors and actor types associated to the projects, a deliberate approach taken by the funding agency. This is rather common in RD&D. There are however areas where important actors seem to be missing.

In the buildings network there are universities, technical consultants and product suppliers present, but users in the form of builders and contractors are not involved. It is quite common for the building sector not to do traditional research and development hence they rarely are involved in public research projects (Gann & Salter 2000). In the network this has great influence on the actual application of the research and whether innovation in the building sector is supported. This point again to the acknowledgement of the diversity in energy efficiency as different innovation dynamics related to market, sector or policy is in play.

Network strategizing and development

Using the perspectives from network analysis the paper is also able to contribute on the overall research strategy. The results generally show how energy efficiency research consists of a very diverse group of actors and that strong brokers are connecting the research networks together. The following strategies offer two ideas on how to develop this further.

The first strategy is about including new knowledge through the involvement of new actors. By including new and more diverse actors in the network it should benefit from new knowledge and more innovative perspectives (Granovetter 1973). This strategy will however strengthen the role of the intermediaries and brokers, as it will be their role to connect distant actors in the network.

The second strategy attempts to induce knowledge flows in the existing networks to enable easier diffusion and less dependence on knowledge brokers. All seven research networks are more or less dependent on a few valuable brokers. Those acting as brokers in the network are very valuable as they connect distant groups of actors. This is however also a vulnerable spot in the network as it will become parted if the broker is removed. Creating more relations between actors which are not important brokers will therefore increase the density of the overall network and in theory allow for knowledge to flow easier (Granovetter 1973).

Further research

The paper increases the understanding of how new knowledge in increased energy efficiency is created and how its diverse nature leads to the involvement of many different actors collaborating in different ways. These results should be investigated and compared by studies in other countries where the networks most probably will look completely different. The availability and quality of such data is however very limited in most countries.

The paper also proposes a new methodology for application in research and with policy-makers that builds on social network analysis. This way of approaching an energy efficiency focus area where the emphasis is on relations and structures of knowledge networks provides a different perspective, which supports a systemic understanding of knowledge and innovation. This data driven methodology is especially useful in cases such as energy efficiency where the network is not well-known or well-established and covers different sectors and industries. Especially in those cases it is important to know who are involved and how collaboration is happening. Further validation and development of the method is however needed and the use of the methodology for strategic purposes in companies and policy settings could also be investigated.

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