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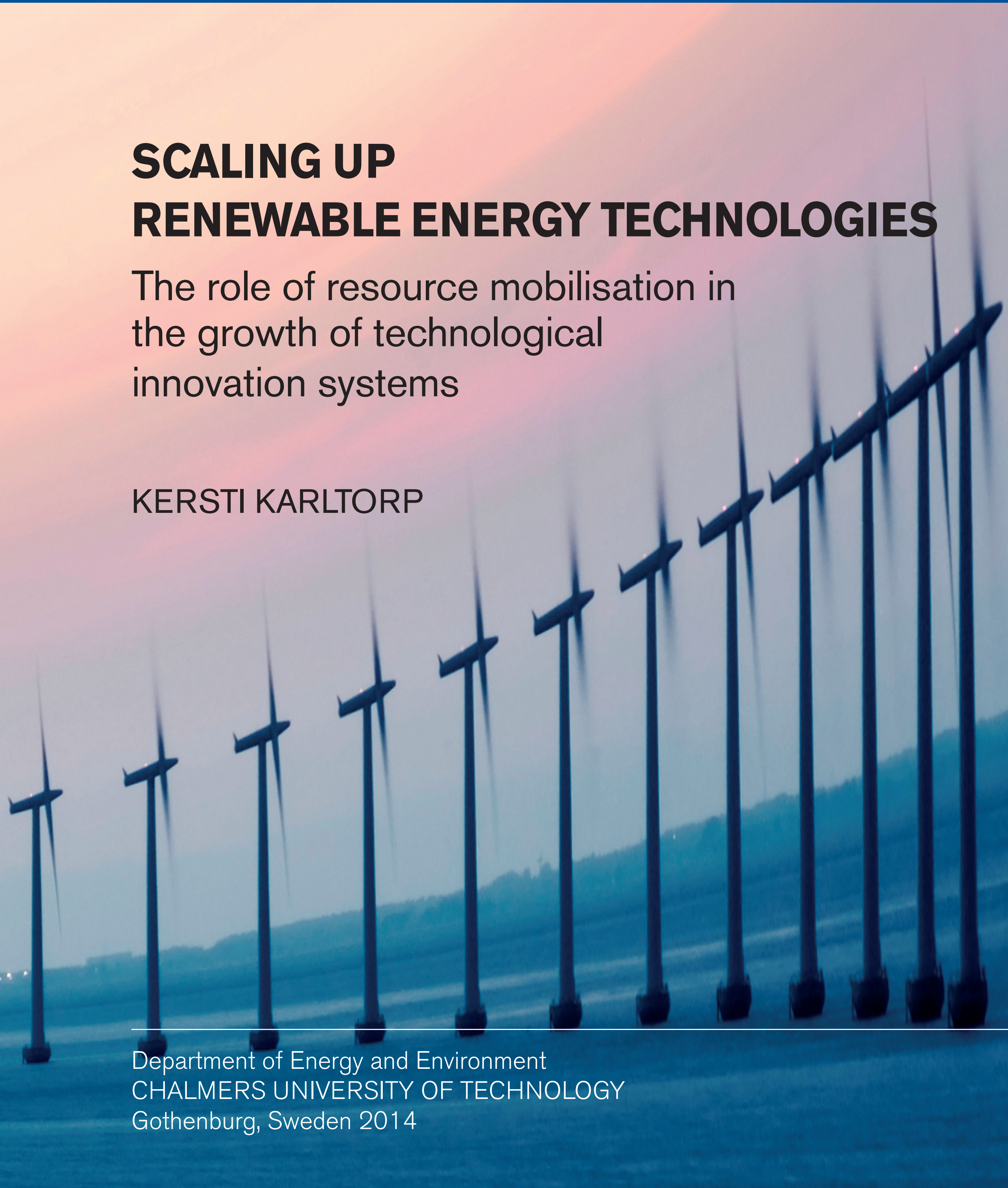

SCALING UP
RENEWABLE ENERGY TECHNOLOGIES

The role of resource mobilisation in the growth of technological innovation systems

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THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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This thesis is based on work conducted within the interdisciplinary graduate school Energy Systems. The national Energy Systems Programme aims at creating competence in solving complex energy problems by combining technical and social sciences. The research programme analyses processes for the conversion, transmission and utilisation of energy, combined together in order to fulfil specific needs.

PROGRAM ENERGISYSTEM

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The research groups that constitute the Energy Systems Programme are the Department of Engineering Sciences at Uppsala University, the Division of Energy Systems at Linköping Institute of Technology, the Research Theme Technology and Social Change at Linköping University, the Division of Heat and Power Technology at Chalmers University of Technology in Gothenburg as well as the Division of Energy Processes at the Royal Institute of Technology in Stockholm. Associated research groups are the Division of Environmental Systems Analysis at Chalmers University of Technology in Gothenburg as well as the Division of Electric Power Systems at the Royal Institute of Technology in Stockholm.

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Abstract

Rapid and large-scale diffusion of renewable energy technologies is needed to avoid severe climate changes that would dramatically affect the conditions for human life on Earth. To scale up these technologies involves technological development, but also the alteration of structures that are locked-in to established socio-technical systems. As the scale of this transition is enormous and the timeframe is short, policy intervention is essential to assist the industrialisation and building up of new socio-technical systems. In this thesis, the technological innovation system (TIS) framework is used to analyse the challenge of scaling up renewable energy technologies. The TIS framework is effective for capturing dynamics in emerging technologies and industries, defining mechanisms that are blocking or inducing development and suggesting where policy could intervene.

Mobilisation of resources such as human and financial capital, and of complementary assets such as transmission grids, raw materials and the space needed for construction and operation, are essential for the growth of novel energy technologies, as substantially more resources are needed when the systems expand. Understanding what is constraining resource mobilisation and how this can be overcome is therefore key for understanding how up-scaling of renewable energy technologies can be achieved. Thus, the purpose of this thesis is to increase the understanding of system up-scaling, by applying the TIS framework, with an emphasis on the role of resource mobilisation.

Empirically, the thesis concentrates on two cases of renewable energy technologies: wind power and biorefineries. It includes analyses with different geographical scopes, ranging from a small country to large countries and regions.

The theoretical contribution of the thesis is a conceptualisation of the TIS's context that enables analyses of the resource mobilisation needed for up-scaling of renewable energy technologies. The empirical contributions include observations of what characterises a TIS in the growth phase. The empirical contributions also include findings on resource mobilisation challenges, for example the scale and quality of human capital needed for large-scale diffusion of offshore wind power in Europe, and suggestions for how these can be overcome.

To effectively address some resource mobilisation challenges, strategic action or policy intervention is required. A suggestion for policy intervention, if this is not done by industry actors, is to coordinate activities within the TIS. For actors involved in development and diffusion of the technology, one way to ease resource mobilisation challenges is to communicate their need for resources, in terms of quantity and quality, to policymakers, academia, the financial sector and incumbent industry actors. Academia and the financial sector can facilitate resource mobilisation by evaluating the need for resources for renewable energy technologies and possibly initiate targeted programmes for education and investments.

Keywords: Wind power, biorefineries, scaling up technologies, technological innovation system, resource mobilisation.

Appended papers

I. Jacobsson, S. and K. Karltorp, 2013, Mechanisms blocking the dynamics of the European offshore wind energy innovation system - Challenges for policy intervention. *Energy Policy*, 63 pp. 1182-1195.

II. Karltorp, K., S. Guo and B. A. Sandén, The dynamics of Chinese wind power industry – understanding causes of financial constraints, submitted to a journal.

III. Karltorp, K., Challenges in mobilising financial resources for renewable energy, submitted to a journal.

IV. Jacobsson, S. and K. Karltorp, 2012, Formation of competences to realize the potential of offshore wind power in the European Union. *Energy Policy*, 44 pp. 374-384.

V. Karltorp, K. and B. A. Sandén, 2012, Explaining regime destabilisation in the pulp and paper industry. *Environmental Innovation and Societal Transitions*, 2 pp. 66-81.

The division of labour in the appended papers has been as follows. In all papers research design has been done in an interactive process involving Kersti Karltorp, Staffan Jacobsson, Björn Sandén and Wiktoria Glad. However, for Paper II, III and V Kersti Karltorp took the main responsibility for this process. In Paper I, data collection, analysis and writing were shared between the authors. In Paper II, Kersti Karltorp and Siping Guo carried out the data collection, Kersti Karltorp analysed the data and Kersti Karltorp and Björn Sandén wrote the article. In Paper III, data collection, analysis and writing were done by the author, but constructive comments were received from Staffan Jacobsson, Björn Sandén and Wiktoria Glad. In Paper IV, the work of data collection, analysis and writing was shared between Staffan Jacobsson and Kersti Karltorp. In Paper V, Kersti Karltorp did the data collection and analysis, while the article was written together with Björn Sandén.

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Contents

1 Introduction

The latest reports by the Intergovernmental Panel on Climate Change (IPCC 2007, 2014) leave no doubt that human activities are causing climate change which in the long term may dramatically change the conditions for human life on Earth. Since the start of industrialisation in the late 18th century, emissions of greenhouse gases have increased, raising the concentration of these gases in the atmosphere and causing a rise in the average global surface temperature. Emissions increased more between 1970 and 2010 than in any previous period, and the highest emission level ever was reached during the last decade of this period (IPCC 2014). The primary source of greenhouse gases is fossil fuel emissions, and the secondary source is emissions from changes in land use.

To avoid severe changes in the climate system, greenhouse gas emission levels need to be radically reduced by 2050. [1] This requires, amongst other measures such as increased energy efficiency, a rapid shift to energy technologies with low emissions of greenhouse gases, such as renewable energy technologies. This is a challenging prospect, as the size of the shift required is considerable: in 2010 fossil fuels accounted for 80 per cent of global primary energy supplies and renewables (including hydro) only 13 per cent (IEA 2012). In addition to the need to replace current energy supply, it is expected that the demand for energy will increase.[2] Hence, to reduce emissions from fossil fuel requires an enormous scaling up of renewable energy technologies.

To go from technological invention to large-scale diffusion takes many decades as it involves not just technological development, but also changes in social practice (Grübler 1996). One reason for the long timeframe is that obstacles caused by lock-in to existing systems must be overcome (Unruh 2002). For example, forming new markets can be arduous, as emerging energy technologies are seldom cost-competitive compared to incumbent technologies (Jacobsson and Bergek 2004). However, mitigating climate change requires that up-scaling is reached within a short time – just a few decades. The International Energy Agency (IEA 2012) has produced an estimate that illustrates how

[1] To limit the increase in global mean surface temperature to 2°C above pre-industrial levels, the atmospheric concentration of greenhouse gases must be kept to about 450 ppm in 2100. This means that global greenhouse gas emission levels must be 40–70 per cent lower in 2050 than in 2010 (IPCC 2014).
[2] In the last decade, global primary energy demand grew by 30 per cent, fossil fuels representing the main part of this (IEA 2012, BP 2013). This has mainly been driven by economic growth and population growth in emerging economies and has resulted in increased living standards for a vast number of people. The increase is expected to continue: in China alone, energy demand is expected to increase by 60 per cent by 2035 (IEA 2012).

rapid this transformation must be. This estimate shows that the existing energy supply infrastructure will produce a large part (about 80 per cent) of the emissions that are permitted under the '2°C temperature target'. If construction continues in the way it is at present, the energy supply infrastructure that will emit all the emissions that can be allowed under this target will have been built by 2017. It is therefore vital that we rapidly change the type of energy supply infrastructure that is being constructed. Policy intervention is needed to radically speed up the construction of renewable energy technologies in order to reduce emissions of greenhouse gases and mitigate climate change.

Policy measures are needed to assist technologies that are in a formative phase, that involves research, development and diffusion on a limited scale. Policy measures are also needed for a technology to enter a growth phase, during which the technology becomes diffused on a large scale. A growth phase implies full industrialisation and the build-up of a socio-technical system around the technology, including, for example, developing knowledge, creating legitimacy and forming markets. The technological innovation system (TIS) framework (Hekkert et al. 2007b, Bergek et al. 2008a), with its roots in industrial dynamics (see e.g. Abernathy and Clark (1985) and Utterback (1994)), is the analytical tool applied in this thesis. The TIS is a suitable framework because it was developed to analyse emerging technologies and industries in order to identify mechanisms that are either blocking or driving development and diffusion and suggest where policy could intervene to support further diffusion. Many studies applying the TIS framework have focused on the formative phase (see for example Bergek et al. (2008b), Meijer (2008), Suurs (2009) and Hellsmark (2010)); few have focused on the growth phase that may follow (some exceptions are Jacobsson and Bergek (2004), Hekkert et al. (2007a) and Huang and Wu (2009)). Hence, this thesis makes a theoretical contribution by conceptualising a TIS in the growth phase.

Mobilisation of resources, such as human capital, financial capital, infrastructure and natural resources, is an essential function of the TIS in the growth phase, as substantially more resources than previously are needed within the system when it expands. The importance of resources has also been acknowledged in the literature of other fields of research. For example, in neoclassical economics, production factors – i.e. labour and capital – are seen as essential for growth (Solow 1956). Another example is the resource-based view (see for example Penrose (1959) and Barney (1991)), in which resources are seen as an explanation of firms' competitive advantages. Because resources are accorded this importance in literature, and because substantial amounts of tangible resources are needed to bring a technology into being on a large scale, this thesis focuses particularly on what constrains the mobilisation of resources, and on how the constraints can be overcome to enable the growth of a TIS.

1.1 Purpose of the thesis and research questions

The purpose of this thesis is to increase the understanding of the up-scaling of renewable energy technologies by applying the TIS framework, with an emphasis on the role of resource mobilisation. Three research questions are specified.

1. What characterises the growth phase of a technological innovation system?
2. What challenges in the mobilisation of resources may hinder the growth of a TIS?
3. How can policymakers, firms and other actors intervene to overcome these resource mobilisation challenges?

1.2 Scope of the thesis

The normative point of departure of this thesis lies in the political targets set up to mitigate climate change. For example, in the EU there are targets for increasing the share of renewable energy to 20 per cent of energy use by 2020 (European Commission 2009). The intention of this thesis, therefore, is to increase our understanding of how the diffusion of technology can be speeded up so that targets like this can be reached.

The thesis focuses on the role of resource mobilisation in the growth of a TIS. *Resources* are defined as human resources, financial resources and complementary assets (Bergek et al. 2008a). In this thesis, complementary assets include infrastructure (such as transmission grids), raw materials (such as biomass), and the space needed for the construction and operation of renewable energy technologies. *Mobilisation of resources* means existing resources being made available to the TIS, or resources being formed to become available to the TIS. However, a 'resource' is not a clearly defined concept in the literature, and different definitions exist. The importance of resources was recognised by Penrose as early as 1959, and others have followed in the field of literature known as 'the resource-based view' (see for example Wernerfelt (1984), Barney (1991) and Grant

(1991)). Within this field, a resource is defined as *'anything which could be thought of as a strength or weakness of a given firm'* (Wernerfelt 1984 p. 172). In the sustainability transition literature, several approaches to resources are found (Farla et al. 2012). For example, Musiolik et al. (2012) suggest that the resource-based view, with its broad view of resources, and the TIS framework can be combined in order to capture how networks contribute to the creation of resources within a system. For the present thesis, however, a narrower definition is needed, as the focus is on the mobilisation of tangible resources for the innovation system from its context. This narrower definition is also in line with the notion of 'resource mobilisation' found in the TIS literature, as one of several functions or processes that need to be fulfilled for a system to evolve.

This thesis includes two cases of renewable energy technologies: wind power and biorefineries. Both these technologies have the potential to supply large amounts of renewable energy, but are still being applied on a scale far below their potential. Wind power technology for onshore application is a proven technology, supplied by a global capital goods industry equipped with substantial resources. Development took off in Europe and the USA, but has also spread to emerging economies and China is now the largest market (GWEC 2014). The offshore application has emerged as a distinct segment that has recently started to grow more rapidly, especially in the North Sea (Figure 1). Offshore wind power technology builds on onshore wind power technology, but needs further development to adjust it to the harsh environment of the sea.

Figure 1 Examples of wind turbines placed offshore. Source: Shutterstock

The concept of a biorefinery is analogous to that of an oil refinery, which processes crude oil to make a range of products. The biorefinery incorporates technologies for processing biomass into chemicals, materials and energy. The development of technologies that can be integrated in a biorefinery has been going on for decades (Hellsmark 2010). These technologies can be roughly classified as gasification technologies (Figure 2) and technologies for separation and refining. Through gasification, biomass is processed into an energy-rich gas that can be used for different purposes, e.g. biofuels. The separation and refining category includes a wide range of technologies that can be used to separate basic components of biomass, such as cellulose, hemicelluloses, lignin and extractives. An example of a final product is ethanol.

Figure 2 An example of a biorefinery technology, the GoBiGas biomass gasification plant in Gothenburg. Source: www.goteborgenergi.se/Om_oss/Pressrum/Bilder/GoBiGas

The papers appended to the thesis have different geographical scopes, ranging from a small country (Sweden) to large countries and regions (European Union (EU) and China). The timeframe for the analyses is the current state of technology development and diffusion. An overview of the appended papers, including the case technologies, resources in focus, geographical scope and actor perspectives, is given in Table 1.

Table 1 Summary of appended papers.

	Title	Technology(ies)	Resource(s)	Geographical scope	Perspective(s)	Main findings
Paper I	Mechanisms blocking the dynamics of the European offshore wind energy innovation system	Offshore wind power	Human and financial resources and complementary assets	European Union	TIS and policy	An analysis of the northern EU innovation system for offshore wind power shows that it faces challenges in the areas of resource mobilisation, market formation and legitimation. Several policy measures are needed to overcome these challenges.
Paper II	Financial challenges in the Chinese wind power industry	Wind power (onshore and offshore)	Financial resources	China	TIS and policy	After about a decade of rapid growth, the Chinese wind power industry is now entering a new phase in which the industry faces several financial challenges. Some of these challenges are shared by the whole industry, while others are specific to turbine manufacturers or utilities.
Paper III	Challenges in mobilising financial resources for renewable energy	Offshore wind power and biomass gasification	Financial resources	European Union	TIS, financial sector and policy	Biomass gasification and offshore wind power face challenges with mobilisation of financial resources. Developers of the technologies lack the capital to scale up. Other investors hesitate due to high risks and uncertain or low return.
Paper IV	Formation of competences to realise the potential of offshore wind power in the European Union	Offshore wind power	Human resources	European Union	TIS, academia and policy	The paper assesses the types and numbers of engineers required to achieve large-scale expansion of offshore wind energy in the EU. This indicates a need for more than 10 000 new engineers by 2020. A variety of competences is required.
Paper V	Explaining regime destabilisation in the pulp and paper industry	Biorefineries	Resources controlled by incumbents, e. g. natural resources	Sweden	Established industrial sector	Adoption of biorefinery technologies has been modest so far. Development along two technological trajectories has been initiated. External pressure is needed to change incumbents' strategies.

2 Conceptual framework

This chapter first presents and compares several theoretical frameworks that can be used to analyse socio-technical change. The conceptual framework developed for this thesis is then presented. This framework draws mainly on the TIS (technological innovations system) approach, but also integrates concepts from other frameworks.

2.1 Conceptual framework for studies of socio-technical change

A system consists of components and relations between these components; together the components form an entirety (Ingelstam 2002). The frameworks presented here all apply a systems perspective to socio-technical change. The benefit of applying a systems perspective is that a distinction is made between the components that are inside the boundaries of the system and the context within which the system exists. Using a systems perspective it becomes possible to analyse both processes within the system and the interplay between the system and its context. Another feature common to the frameworks presented here is that in them the technological and the social dimensions of a technology are intertwined (Hughes 1988, Summerton 1994).

Large technical system

Within the field of science and technology studies, there are several examples of frameworks that can be applied to study the process of innovation and technological change, such as the 'social construction of technology', 'actor-network theory', the 'large technical system' (LTS) framework and 'feminist studies of technology' (Bijker and Pinch 2012). For the present thesis, the LTS seems most relevant. The LTS has evolved from the pioneering work by Hughes (1983), a historian of technology, but has also inspired and been inspired by researchers working in the field of the sociology of technology.

The LTS framework is used to describe the historical evolution of a system in order to understand why and how technical change is achieved and what the power structures are that enable this. Less attention is given to the structures of systems that need to be changed in order for the technical change to happen. As components of a large technical system, Hughes (1987) includes artefacts, organisations, legislative artefacts and natural resources. The components are linked to each other and support a system goal.

Attention is also given to system builders; these are individuals who have the capacity to transform components so that a system is built up. As a larger system is built up over time, it acquires momentum (ibid.).

Multi-level perspective and strategic niche management

The multi-level perspective (MLP), with its roots in social constructivism and evolutionary economics, is another framework for the analysis of technological transitions (Rip and Kemp 1998, Geels 2002, Geels and Schot 2007). The MLP framework differentiates between three levels of system: the niche, the regime and the landscape. A niche is an incubator space in which a radical innovation (new technology) is protected from mainstream market selection, since the selection criteria differ between the niche and its environment. Within the niche, three key processes for technical change can take place: learning, the building of social networks and the articulation of expectations (Verbong et al. 2008). The next analytical level, the regime, is defined as '*the rule-set or grammar embedded in a complex of engineering practices, production process technologies, product characteristics, skills and procedures, ways of handling relevant artefacts and persons, ways of defining problems; all of them embedded in institutions and infrastructures*' (Rip and Kemp 1998 p. 340). These rules guide innovation activities towards incremental improvements of established socio-technical systems and create stability (Geels and Schot 2007). Both niches and regimes are embedded in the third analytical level, the socio-technical landscape that forms the external macro-level. The landscape consists of factors that influence the development and diffusion of the technology, but without being influenced by the outcome of this process (Markard and Truffer 2008).

The initial development of a radical innovation can be supported by strategic management of one or several niches in which the technology is applied (Kemp et al. 1998). For wider diffusion of the technology, one or more regimes will be affected; or rather, for a technology to diffuse on a large scale, changes in regimes are needed. Technological change and the interaction between niches and regimes can be affected by changes in the landscape; an example of landscape changes in the field of renewable energy is the accident with the nuclear power plant in Fukushima. Analyses applying the MLP framework show a broad picture of how long-term interaction of the three analytical levels can lead to technological change, but also how existing regimes are destabilised in order to allow for this. This historical and descriptive view provides an understanding of the past that can be used for lessons for the future.

Innovation systems

The innovation system frameworks are inspired by an evolutionary view of economics. In this view an economy is seen as a complex and varied system that evolves over time as new options (i.e. innovations) emerge and disappear in a process of creative destruction (Schumpeter 1942, Rosenberg 1994). Innovations can be described as incremental or radical (Rogers 2003). The magnitude of innovation needed to address climate change calls for radical innovations, which means fundamental changes in the structure of society.

There are several innovation system models that differ in terms of the system boundaries, but that originate from the same assumption that a systemic interplay between actors (and networks of actors) and institutions is essential to understanding innovation. The national system of innovation (NIS) emerged as part of the debate over industrial policy in Europe in the late 1980s (Sharif 2006). An innovation system is defined as '*constituted by elements and relationships which interact in the production, diffusion and use of new, and economically useful, knowledge…'* (Lundvall 2010, p.2). Furthermore, a national system of innovation '*encompasses elements and relationships, either located inside or rooted inside the borders of a nation state'* (ibid). In a NIS, the system boundary is defined from a spatial dimension, which is practical as the unit of analysis is the same as the unit for many decisions, policies and strategies that aim at governing innovation processes. Other spatial delimitations, such as a regional innovation system (RIS; e.g. European Union or the region of Västra Götaland), are also possible. In this case the system boundaries are chosen according to the degree of autonomy of policymaking and cultural base (Cooke et al. 1997).

The system boundary can also be defined by the type of product that is the focus of the analysis. An example is sectoral systems of innovation and production (SSI), defined as '*a set of new and established products for specific uses and the set of agents carrying out market and non-market interactions for the creation, production and sale of those products'* (Malerba 2002 p. 248). A fourth delimitation of an innovation system is the technological innovation system (TIS), in which technology or knowledge base is used to define the system border. The definition of this framework has evolved from the definition by Carlsson and Stankiewicz (1991 p. 111) of a technological system '*as a dynamic network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure or set of infrastructures and involved in the generation, diffusion, and utilization of technology*'. However, these innovation systems often also include a spatial dimension, for example a nation. In the same way, an analysis of a national or regional innovation system can be limited to a specific knowledge base or product category. The different innovation systems frameworks share common roots and characteristics, but define system boundaries and content differently (Figure 3).

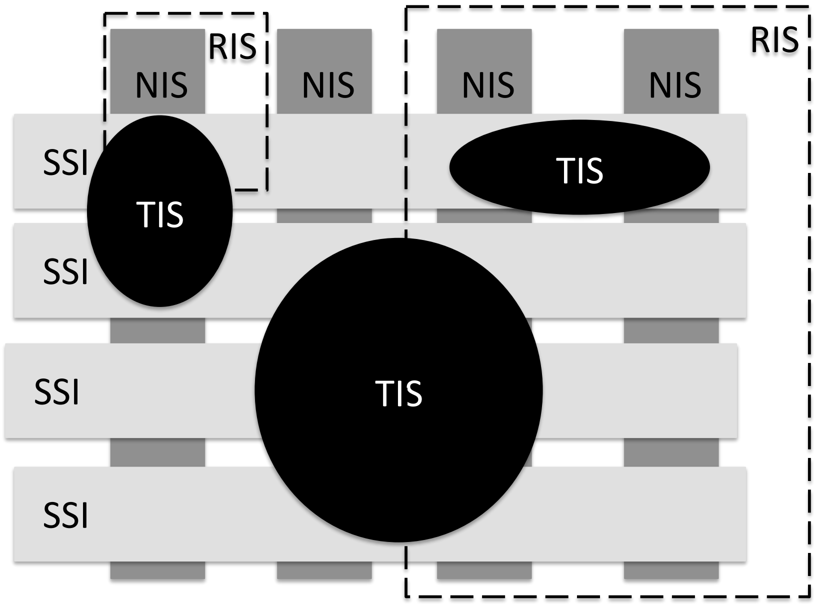

Figure 3 How system boundaries are drawn in different models of innovation systems. Adapted from Markard and Truffer (2008)

Rationale for the choice of conceptual framework

The framework developed in this thesis largely relies on the TIS framework, but also draws on the MLP to define a socio-technical system with different levels and on the LTS framework to underline the importance of artefacts and natural resources for the growth of large systems.[3]

One reason that an innovation system framework is chosen as the point of departure is that it is suitable for analysing the current development of a technology and suggesting

[3] Several suggestions for how to integrate these frameworks have been presented before. For example, Markard and Truffer (2008) integrate TIS and MLP, and Hellsmark (2010) uses the LTS concept of system builders in the TIS framework.

policy interventions for how future changes can be achieved. This fits well with the climate change challenge that requires analyses of renewable energy technologies at today's state of development in order to suggest how these technologies could become widely diffused. In contrast to this, both the LTS and the MLP frameworks have a more descriptive, historical approach to technical change. This is useful for providing lessons for the future from the past, but provides no explicit guidance for policy interventions to support the development and diffusion of specific technologies.

Since the frameworks have different origins, the analyses they produce tend to have different focuses. The innovation system frameworks have their roots in evolutionary economics, and hence much attention is given to economic aspects. The LTS and the MLP frameworks have their roots in science and technology studies, and with them more attention is given to social constructions and power. This illustrates both a strength of using an innovation system framework (economic aspects are included) and a weakness (analysis of power and social constructions is played down).

Similarities can be found between different innovation system frameworks and analytical levels of the MLP. For example, there are many similarities between a SSI and the regime. The same applies for a niche and a TIS in an early formative phase. However, there are differences in how these concepts deal with different phases of technology development. Strategic management of a niche is mainly applicable to the initial phase of technology development, i.e. to the early formative phase of a TIS, while an analysis of a TIS, and what drives or blocks development and diffusion of a technology, can also be applied to a growth phase (see e.g. Jacobsson and Bergek (2004)). Thus, the TIS framework is a more suitable point of departure for the research questions in the present thesis.[4]

As described above, the innovation system frameworks differ in how system boundaries are defined and in the unit of analysis. Both the SSI and the TIS are defined in terms of type of innovation rather than a spatial dimension, but there are essential differences. The structure of the SSI system is regarded as relatively stable and the focus is on novelty emerging within this structure (Coenen and Díaz López 2010). In the TIS, the

[4] In Paper V the MLP framework is used because the focus of this analysis is on the regime and how it is affected by changes in society.

focus on novelty is not limited to the innovative technology, but also includes novel ways of structuring components of the system around it (Markard and Hekkert 2013). For this reason, the TIS is more suitable than the SSI for the purposes of the present thesis. The TIS framework is the most commonly applied innovation system framework within the field of energy and clean-tech (Truffer et al. 2012), but most of these studies focus on the formative phase. In this thesis the focus is switched to the growth phase.

2.2 Conceptual framework for studies of growth of a TIS

The conceptual framework for this thesis takes its point of departure from the TIS. A TIS is defined by the system boundary and the components of the system. Deciding where to draw the system boundary involves choosing the focus (e.g. a knowledge field or product), the depth or breadth of the analysis, and a spatial restriction (Bergek et al. 2008a). If the TIS expands, it will become more and more challenging to decide what is inside the system and what is not, as the system gradually becomes integrated into many parts of society.

The structural components of a TIS include *actors,* both individuals and organisations, and *networks of actors*. Actors and networks of actors are the source of agency and can formulate strategies and take action that affect the development of the TIS (Wirth and Markard 2011). The other structural elements are passive. Examples of important actors are firms along the value chain, universities, research institutes, public bodies, non-governmental organisations and standards organisations (Bergek et al. 2008a). For resource mobilisation, actors that can control or affect resources are central, such as banks that can direct their investments to certain areas, and universities that can affect the formation of educational programs and, thus, the type of competences that are made available.

Another part of the structure is *institutions*, which are humanly devised constraints that structure human interaction (North 1994). Examples of institutions are norms, laws, culture, guidelines, values, regulations and policies that govern how the TIS can evolve. Some institutions are embedded in actors, such as culture and norms. Other institutions, such as regulations and policies, are more exogenous to actors.

As in some definitions (see for example Bergek et al. (2008b) and Suurs et al. (2010)), in this thesis *technology* is also seen as part of the structure. Technology comprises both physical artefacts and knowledge. Knowledge may be formalised in text, as in articles, manuals and patents, or embodied in artefacts, in organisational procedures or carried as tacit knowledge by actors (Bergek et al. 2008b).

The process of development and diffusion of renewable energy technologies is influenced by the established energy *infrastructure* (e.g. transmission lines) and available *natural resources*. Infrastructure is included in the terminology of the TIS, but natural resources are not. However, it has been included in other systems approaches. For example, Hughes (1987) includes artefacts and natural resources as components in the LTS. For a TIS to grow, energy infrastructure and natural resources can be seen as system components, as the diffusion of a new technology to a large extent involves alignment of the system and these components. Wirth and Markard (2011) have provided a good example of how the fact that a natural resource (biomass) is bound to established industries and technology (wood to energy) hinders the development of an emerging technology (biomethane technology).

To evaluate the performance in a TIS, a set of key processes or functions has been identified (Johnson and Jacobsson 2001, Jacobsson and Bergek 2004, Hekkert et al. 2007b, Bergek et al. 2008a) (Table 2).[5]

[5] Slightly different definitions of the functions exist; in addition to the set of functions presented here, more functions have been suggested, for example *creation of value chains* (Musiolik and Markard 2011), *materialisation* (Bergek et al. 2008b) and *social capital development* (Jacobsson et al. 2014).

Table 2 The key functions involved in a TIS.

Key process	Definition	Examples of indicators
Knowledge development and diffusion	The breadth and depth of the knowledge base and how that knowledge is developed, diffused and combined in the system.	R&D projects, number of involved actors, number and size of workshops and conferences, number of patents.
Entrepreneurial experimentation	The testing of new technologies, applications and markets whereby new opportunities are created and a learning process is unfolded.	Number of new entrants, number of diversification activities by incumbents, number of experiments and different types of applications.
Influence on the direction of search	The incentives and/or pressures for organisations to enter the technological field. These may come in the form of visions, expectations of growth potential, regulation, articulation of demand from leading customers, crises in current business, etc.	Visions and beliefs in growth potential, targets set by the government, changes in regulatory framework.
Resource mobilisation	The extent to which actors within the TIS are able to mobilise human and financial capital as well as complementary assets such as network infrastructure.	Availability of human capital, financial capital and complementary assets.
Market formation	The factors driving market formation. These include the articulation of demand from customers, institutional change, changes in price/performance. Market formation often runs through various stages, i.e. 'nursing' or niche markets.	Number of niche markets, how demand is articulated, tax regimes and regulations.
Legitimation	Social acceptance and compliance with relevant institutions. Legitimacy is not given but is formed through conscious actions by organisations and individuals.	Rise and growth of interest groups, public opinion expressed in e.g. new articles and social media.
Development of positive externalities	The collective dimension of the innovation and diffusion process, e.g. how investments by one firm may benefit other firms 'free of charge'. It also indicates the dynamics of the system since externalities magnify the strength of the other functions.	Emergence of pooled labour market, intermediate goods and service providers, information flows and knowledge spill-over.

Source: Bergek et al. (2008a), Jacobsson and Bergek (2011) and Truffer et al. (2012).

The functions capture the dynamics of the system, and by evaluating whether they are strong or weak, conclusions can be drawn about what is driving or blocking the growth of a TIS and in what way policy measures could be introduced to make it easier to overcome obstacles to growth. The functions are not independent, and changes in one function may lead to changes in another function.

Technology development and diffusion

The development and diffusion of novel technology and the growth of the associated TIS is a complex process troubled by uncertainty (Meijer and Hekkert 2007). In successful cases, the development and diffusion of a novel technology can be described with an S-shaped curve (Grübler 1998) (Figure 4). [6]

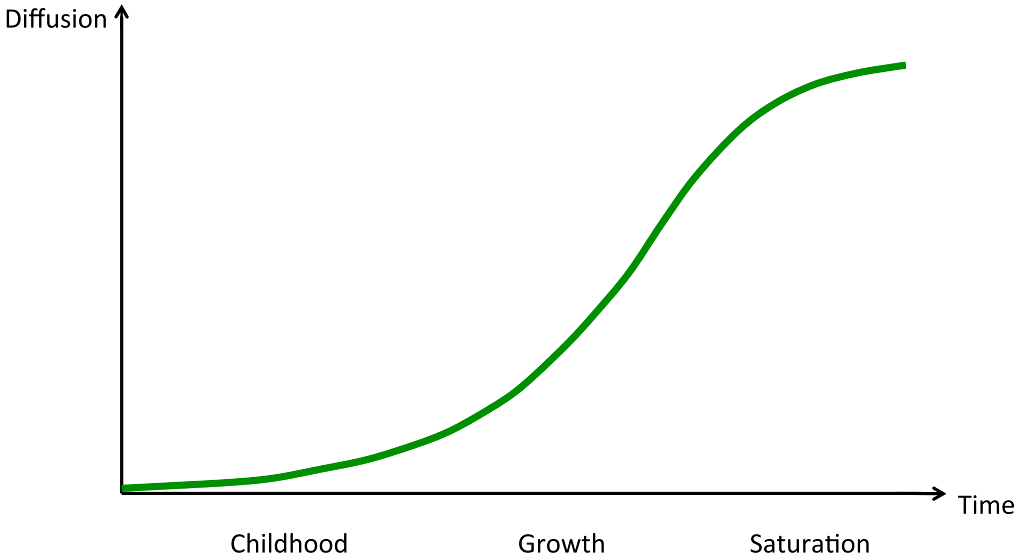

Figure 4 A successful process of development and diffusion of technology can be shown as an S-curve and described in terms of childhood, growth and saturation.

The progress of a TIS can be described as an initial formative phase, a growth phase and possibly a saturation phase. However, there is no guarantee that a TIS will enter the growth phase just because it has come into being in a formative phase (see Jacobsson and Bergek (2004), Huang and Wu (2009)). The formative phase is characterised by high uncertainty, wide technical diversity and limited installations (in terms of both numbers and scale). This phase can last for several decades (Wilson 2012), enabling important knowledge development and diffusion as well as entrepreneurial experimentation in order to show the viability of the technology (Grübler 1998). Legitimation is another important function in this phase, as the technology must become socially accepted and compliant with relevant institutions (Bergek et al. 2008b).

[6] There are several alternative terminologies for the phases of technology development, for example, Kaijser et al. (1988) suggest establishment, expansion, maturity and stagnation.

In the present thesis the focus is on the growth phase of the TIS, in which diffusion of the technology is scaled up. As suggested in Figure 4, if up-scaling once starts, it can happen in a relatively short time. Growth of a TIS can be indicated in several ways, for example by increased strength of the functions (see Table 2), by increased installed capacity or generated output (for example in terawatt hours of electricity) or by assessing whether the development of the technology has gone from build-up of capacity alone to including the transformation of established sectors.

Resource mobilisation is particularly important in the growth phase (Jacobsson and Bergek 2004), as substantially more resources than before are needed for the system to expand. Market formation is another key aspect (Bergek 2014), and as a result one characteristic of this phase is increased standardisation, which often results in the choice of a dominant design, reduced technical uncertainty and falling cost and price (Utterback 1994, Grübler 1998). Another characteristic of this phase is that it is important to strengthen advocacy coalitions in order to overcome opposition from incumbents and align policy with the emerging technology (Jacobsson and Bergek 2004).

System context

The context of a TIS affects its development as it can have an impact on both the pace and the direction (Wirth and Markard 2011). This is especially important in the growth phase when interaction between the TIS and its context increases. To be able to analyse the TIS–context interaction, a description of the context is needed. The context of a TIS can be variously defined depending on the research question. It can, for example, be defined as several mature TIS that can be both competing and complementary (Markard and Truffer 2008), or a NIS, or a SSI (Figure 3).

In this thesis, the TIS context is defined as established industrial sectors, policymakers and resource sectors, such as academia and the financial sector, which control the flow of different resources (Figure 5). Within established industrial sectors, one or more mature TIS could be incorporated. The resource sectors and the established industrial sectors are aligned with each other, but an emerging TIS might not be aligned with either of them or with policy. Actors within established industrial sectors and resource sectors focus on incremental innovation within prevailing technological paradigms and are often reluctant to pursue radical innovations (Dosi 1982). These actors can try to maintain the current system by, for example, affecting how policy is shaped and what technical standards are set (Smink et al. 2013). Due to the lock-in that the rigidity of these sectors creates, some kind of inducement from an overarching societal level might be needed to destabilise them. Policy can be part of this inducement mechanism, but it can also include, for example, broad societal trends or crises (compare with the landscape concept of MLP).

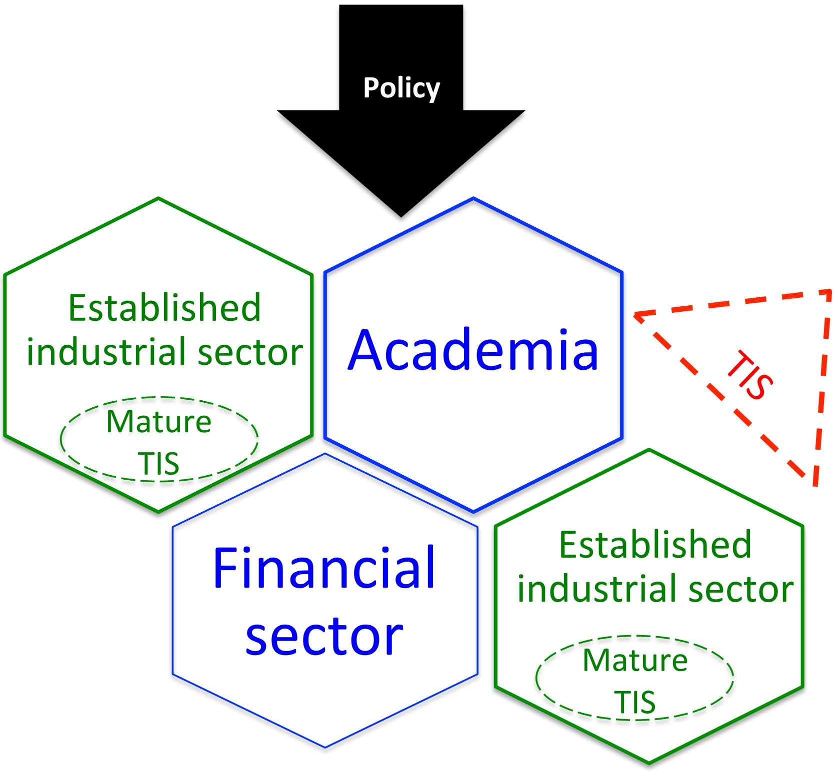

Figure 5 The context of a TIS consists of established industrial sectors (other mature TIS), and resource sectors that control or affect the flow of resources, such as academia and the financial sector, as well as policy.

TIS–context interaction is conceptualised in the TIS literature, and parallels can also be found in the MLP. Sandén and Hillman (2011) describe the interaction between two emerging TIS with six different modes, including for example competition, symbiosis and parasitism. Raven (2007) describes regime–regime interaction in similar terms (competition, symbiosis, integration and spill-over). Binz et al. (2012) conceptualise different types of interaction between two TIS in the same knowledge field but with different spatial boundaries. These diverging boundaries could, for example, be local and global (Binz et al. 2014). This approach is useful for analyses of TIS in developing or emerging economies compared to international TIS (see for example Gosens and Lu (2013)). Interaction between a TIS and established industrial sectors and resource sectors can also take different forms and will differ depending on the phase of development of the TIS.

As the TIS expands, the interaction between the TIS and its context will increase. For large-scale growth of the TIS, mutual alignment of the TIS and its context is necessary (Figure 6). However, making the context adjust to the TIS is challenging as it involves changing structures that have already been built up and have acquired momentum. Resource mobilisation is essential for growth of the TIS, but is structured according to the needs of established industrial sectors and resource sectors. It is therefore important to analyse resource mobilisation from different perspectives to see how it can be better aligned with the TIS.

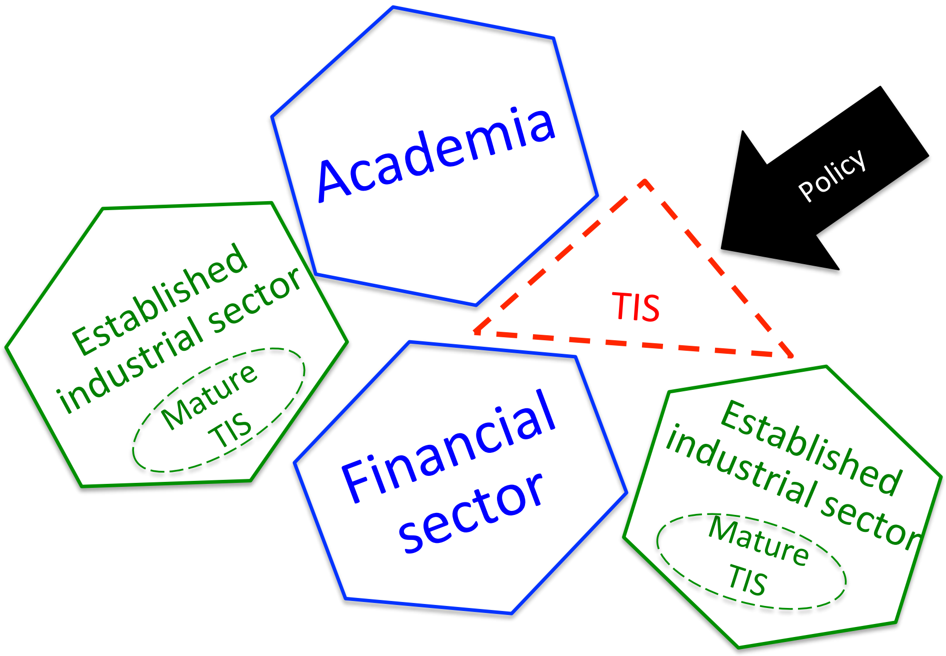

Figure 6 Growth of the TIS will require alignment between the TIS and sectors in its context; policy support may be needed to enable this.

Three perspectives on resource mobilisation

As has already been said, for a TIS to grow requires the mobilisation of sizeable amounts of different resources. Academia, the financial sector and established industrial sectors control resources or are able to affect how they are formed (formation of competences, for example). For this reason, resource mobilisation is an important form of interaction between the TIS and its context during the growth phase, and the mobilisation of large amounts of resources requires the TIS to align with its context and vice versa. To learn more about this, resource mobilisation can be analysed from different points of view – from the perspective and logic of the growing TIS, and from the perspective and logic of actors and sectors resident in what is here referred to as the TIS context. Moreover, established industrial sectors, such as the pulp and paper industry, and resources sectors, such as academia and the financial sector, are likely to take very different positions towards an emerging TIS, established industrial sectors being more competitive and resource sectors having a more neutral view.

Perspective 1: The perspective from the growing TIS

The first perspective is that of the TIS and includes an analysis of the resources that need to be mobilised from resource sectors and established industrial sectors in order for the technology to become widely diffused. To conduct this type of analysis, it may be necessary to combine a systems framework with concepts from complementary literature specific to resource mobilisation.

An example from Paper III will be used to show how an outline of different types of investors is useful to better understand the challenges and constraints that can be faced by actors within the TIS in mobilising financial resources.[7] The types of investor vary with the phases of development of a technology. There are two stages in which financing is particular problematic; these stages are called *valleys of death* (Figure 7). In the formative phase, the public sector is an important source of funding of research, development and demonstration (RD&D) (Berk and DeMarzo 2007). After this phase, funding from this sector often declines abruptly, as investment in commercialisation is expected to come from the private sector. However, in many cases the technology is not yet economically competitive at this point, and the private sector perceives the risks as high and is cautious about investing. To go from public to private finance is, therefore, challenging. This is called the first *valley of death* (Murphy and Edwards 2003, BNEF 2010).

Venture capitalists and private equity funds are often important private investors during early commercialisation. These investors target high returns and can accept high risk (De Jager et al. 2011). However, their investment horizon is usually short, around 3–

[7] For an outline of the heterogeneous investors in renewable energy technology see Bergek et al. (2013).

7 years. Moreover, in comparison with the investment needs of the renewable energy technologies studied here, the size of investment from these firms is small (De Jager et al. 2011). Thus, venture capitalists and private equity firms can invest in high-risk and high-return options, but seek options where a fairly small investment over a few years is sufficient.

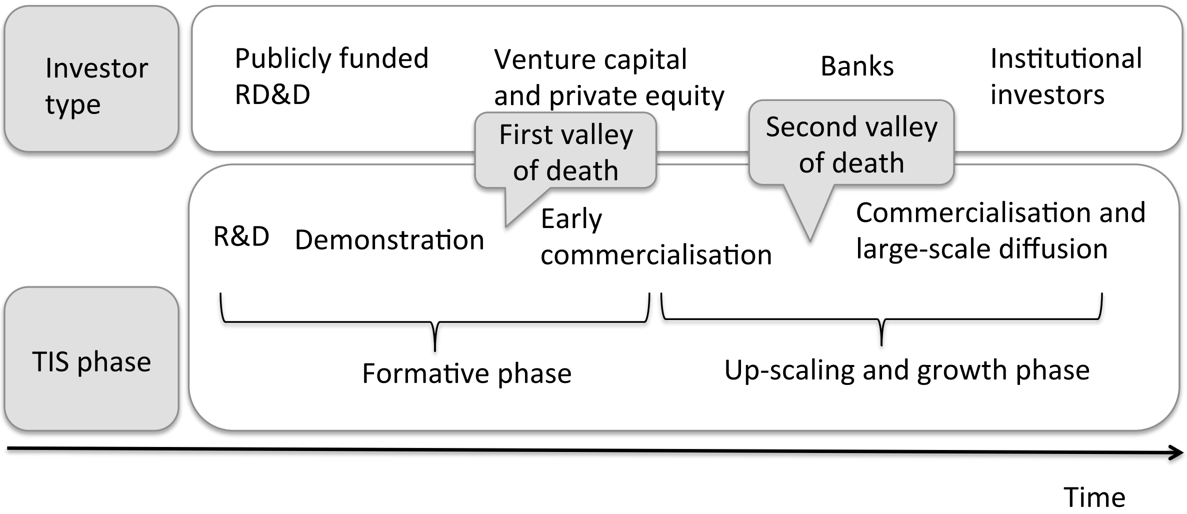

Figure 7 The types of investor vary with the phases of development of the TIS. There are two *valleys of death* when financing is particularly problematic. The first is when the step has to be taken from public to private financing and the second is when substantial sums are needed for commercial up-scaling.

For more developed technologies, important external investors are public and commercial banks. Publicly governed banks can play a role by providing debt when commercial banks do not, or by providing a guarantee (e.g. the public bank guarantees to assume the debt if the borrower defaults). Commercial banks are mainly interested in lending money to more mature technologies and large projects. This is due to the lower risk related to more mature technology and to the fact that the cost of assessing a project is about the same irrespective of the project's size (Mills and Taylor 1994). Banks can provide senior debt and project finance, which means that only the project itself is used as security for the loan (De Jager et al. 2011, Rajgor 2011).

Institutional investors – for example pension funds, insurance companies and foundations – are also interested in more mature technologies (Berk and DeMarzo 2007). These investors manage large assets and buy listed stocks, bonds, funds and real estate. Institutional investors typically invest in options that are characterised by low risk and low return.

A second *valley of death* occurs when substantial capital is needed for large-scale diffusion of the technology (Figure 7). Up until this point, technology developers and utilities can often finance parts of the commercialisation themselves. However, for a scale-up of the industry emerging around the technology, the size of capital needed increases and the technology developer and utilities cannot provide finance to the same extent when several projects are to be developed in parallel. The reason for this is both that the required capital for several projects is too large and that investing too much in only one technology increases risk.

This example outlines a framework for analyses of interaction between TIS and external investors. Similarly, frameworks can be outlined for analysing interactions for the purpose of mobilising other types of resources, for example human resources, where the interactions are largely with academia (Paper IV).

Perspective 2: The perspective from established industrial sectors

The second perspective is that of established industrial sectors and incumbent actors in these sectors. Analysing resource mobilisation from their point of view can increase understanding of how incumbents regard the emerging technology and what resources could possibly be mobilised to the TIS.

For this perspective, too, complementary literature can be used to gain a more nuanced analysis. For example, strategic management literature can be helpful for analysing why and in what way firms in an established industrial sector respond to change. An example is Porter's five-force model (1985), which can be used to explain a firm's competitive strategy by analysing the attractiveness of the industry and the competitive position of the firm within this industry. In this model, the industry's profitability is seen as affected by five competitive forces: the bargaining power of buyers, the bargaining power of suppliers, the threat of new entrants, the threat of substitutes, and rivalry among existing firms (ibid.). To be profitable, a firm should seek to engage in an attractive industry, and within this industry it should strive to create a unique and valuable position through low-cost production or differentiation. Depending on how firms are positioned, they will be more or less exposed to external pressures.

There are, however, other models that (unlike the five-force model) suggest that decision making and strategy formulation are not perfectly informed and rational.

Instead, they say, managers – like all human beings – are guided by mental models which they use as filters to simplify reality and enable decision making (Foster and Kaplan 2001). These models are based on successes and failures of previous actions, but are seldom explicit. Hence, less tangible things such as company culture, which is moulded by the unique history of every firm, also affect how firms response to technical change.

The aim of adopting this perspective is to learn more about existing incumbents and the strategies they adopt in response to an emerging technology.

Perspective 3: The perspective from resource sectors

The third perspective adopts a standpoint within the resource sector in order to compare the flow of resources to established industrial sectors with the mobilisation of resources that would be needed for the TIS.

For analyses of financial resource mobilisation, a relevant complementary body of literature is that dealing with how investment decisions are made. Key to understanding what makes actors in the financial sector decide whether or not to invest in an emerging technology is the risk:return ratio (Gross et al. 2010). Several categories of risk linked to a technology can be assessed for an investment decision (Miller and Lessard 2008, Blyth et al. 2007, De Jager et al. 2011, Fulton et al. 2011). To stimulate investment in renewable energy technologies, policies are used to adjust the risk:return ratio (Wüstenhagen and Menichetti 2012). However, the introduction of a policy can also lead to political risk (Mitchell et al. 2006).

The investment return depends on cost and income. For the investment decision, both the total cost of the investment and the cost per unit of output are important. Cost per unit of output is expected to decrease over time, as a result of economies of scale and learning, which can be described as progress along an experience curve (Neij 2008). It is difficult to assess the income from long-term investments, such as power or fuel production plants, as prices (e.g. electricity and fuel prices) vary over time.

From the perspective of the financial sector, investments with a combination of high risk and high return or low risk and low return are more likely to be financed (BNEF 2010). Many renewable energy technologies have an unfavourable risk:return ratio, primarily due to the high risks involved, and it is therefore challenging to attract investment to these technologies.

In this section, a framework that conceptualises the TIS context has been presented. By applying the three perspectives of this framework to the TIS–context interaction in relation to resource mobilisation, a better understanding of this process can be reached.

3 Research design and method

This chapter presents the research design and methods applied in the thesis. The research design is qualitative and takes an abductive approach to case studies, which means that the work with theory and empirical work evolve in an interlinked process (Dubois and Gadde 2002). In more practical terms, this means that the work has followed a cyclical process, repeated for each paper included in the thesis. This cycle consists of the following steps: research design (including the choice of conceptual framework), data collection, analysis, the outcome in terms of result and theory contribution and, finally, taking the experience (in terms of knowledge of the case technologies and applied theories as well as methodological know-how) gained from one study on to the next one (Marshall and Rossman 2011) (Figure 8).[8] The rationale for the choice of the technologies included as case studies (case technologies) will now be presented, followed by the method for data collection, analysis and verification.

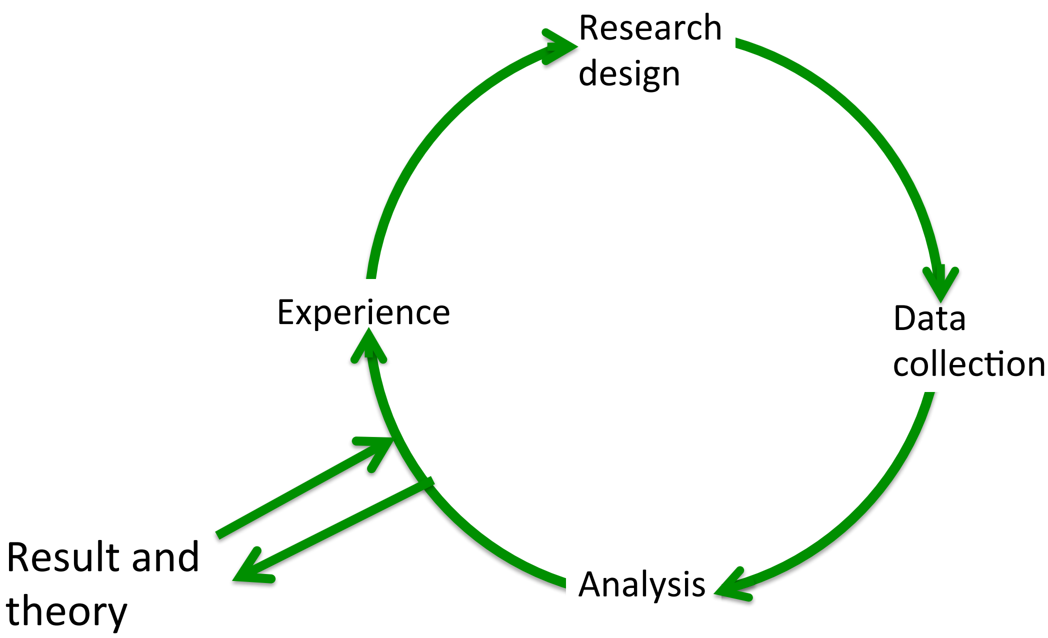

Figure 8 For each of the five papers, the qualitative research process applied represents a loop. Source: Marshall and Rossman (2011).

[8] Note that the appended papers are presented not in chronological order, but as governed by the research questions.

3.1 *Rationale for the choice of case technologies*

A case study can be described as a detailed examination of a specific phenomenon (Merriam 1994). Case studies of two technologies, wind power and biorefineries, have been included in this thesis in order to gain an in-depth understanding of the challenges in a possible growth phase of renewable energy technologies and how these can be overcome. The case technologies have been chosen on the basis that they have the potential to contribute a significant supply of renewable energy, but are not yet diffused on a large scale.

The case technologies are not in the same phase. Most biorefinery technologies (Papers III and V) are at an early stage of commercialisation, i.e. they are still in the formative phase. Offshore wind power in the EU, however (Papers I, III and IV), is entering a growth phase, and onshore wind power in China (Paper II) is in the middle of a growth phase. This enables analyses both of technologies that could be entering the growth phase, if current challenges are overcome, and of the challenges faced by technologies that are already in the growth phase. Thus, challenges both for entry into a growth phase and those encountered in the growth phase are captured.

It could be argued that studying a historical case instead (i.e. a technology that has already gone through growth phases) would have allowed conclusions to be drawn not only about what constitute the challenges to technology development and diffusion today, but also what has helped in overcoming them. However, choosing to study technologies that are currently under development allows conclusions to be drawn that have implications for today's policies. This would not apply to historical cases, as the technology concerned is now either already widely diffused or has failed to do so.

3.2 Data collection

In case studies several methods, such as interviews, observation, document analysis and surveys are combined for data collection (Marshall and Rossman 2011). Stake (1995) emphasises observation as a method as it gives the researchers the ability to see and experience things themselves. However, the cases included in this thesis are difficult to study by observation, since the growth of a technology and the surrounding socio-technical system happens simultaneously in many places, influenced by actions taken by many organisations and persons over a long time. Of course, the mere act of studying a particular technology means that the researcher becomes more observant of actions or events that are part of the innovation system's dynamics. This could be seen as a type of observation, but not in the sense suggested by Stake (1995).

For this thesis, data were collected from documents and semi-structured interviews. The types of documents analysed were scientific articles, news articles, trade journals, reports (for example from non-governmental organisations and consultants), webpages, databases and government documents. To understand the potential of the case technologies, scenarios that estimate future capacity were used. Different scenarios and their underlying assumptions were compared in order to gain an understanding of how the scenarios are constructed.

The documents used in the thesis were critically evaluated. For this thesis it was particularly important to evaluate any tendencies or biases in the data, i.e. who was providing the information and for what purposes (Esaiasson et al. 2009).[9] This is because the development of novel technology is often linked to politics and many actors have an interest in the development – or lack of development – of the technology. For example, several scenarios are used in the thesis. To do this, it has been important to understand the source of each scenario: for what purpose was it produced, and what is its message in the political debate? Thus, to use a document it was critical to identify the author of the document and uncover what the purpose of producing the document might have been. In the work for Paper II on wind power in China, it was more challenging than in previous studies to evaluate the data, e.g. to verify that the same story or fact was told by at least two independent sources (Esaiasson et al. 2009). As a result, some of the collected data was not judged to be valid and was therefore not used in the analysis.

The interview work followed the seven phases described by Kvale and Brinkmann (2009): defining the aim of the study, planning the study, interview, transcription, analysis, verification and writing. To prepare for the interviews, a list was made of questions that the study aimed to answer. These questions were then translated into interview questions that strove to be free from academic concepts and easy for the interviewees to understand (Kvale and Brinkmann 2009). An interview guide was

[9] Esaiasson et al. (2009) describe four aspects of critically evaluating a document: is the document authentic, and is the data it provides independent, current and unbiased.

prepared by grouping these questions into topics to be covered during the interview (an example of an interview guide is provided in Appendix A). The exact phrasing of the questions was adjusted for each interview situation and the interview guide was developed during the study as more knowledge of the topic was acquired. Interviews lasted for 1–2 hours and most of the interviews were carried out face to face, but a few were done on the telephone. Interviews were conducted in Swedish, English and, on a few occasions for Paper II, in Chinese (with Siping Guo, one of the authors of Paper II, translating into English). The interviews were recorded and then transcribed. As the focus is on content and information rather than the way in which things were said, the transcription excluded repetition and small interjections such as *hm*. However, strong reactions, such as laughter, obvious hesitation, anger, etc., were noted in the transcription.

For this thesis, a total of 87 interviews were conducted in the following countries: Sweden, Denmark, Germany, the Netherlands, the UK, Finland, Norway and China.[10] Many interviews were conducted together with co-authors, which enabled a detailed and careful way of interviewing.[11] The number of interviews conducted for each paper was not decided on beforehand. Instead the interviewing continued until a coherent picture of the topic emerged and it was considered that the knowledge to be gained from another interview was low (Kvale and Brinkmann 2009).

The author(s) selected most of the interviewees, but some were selected in dialogue with the organisation. The interviewees represented firms working in technology development, the manufacturing of technology and components, utility firms, grid operators, universities, research institutes, actors in the financial sector, non-governmental organisations, industry associations, governmental bodies and firms in industries affected by the development of the new technology or in control of resources needed for its development. The authors' preferred choice of whom to interview was often persons with a long background in the firm and a position fairly high up in the organisation, as these individuals can often give detailed descriptions and still keep a distance to the topic. These persons are often what Marshall and Rossman (2011)

[10] Paper I is based on 36 interviews, but some of these were initially conducted for Papers III or IV. Fourteen interviews were conducted exclusively for Paper III.
[11] For Papers I and IV, some interviews were conducted by only one of the authors. As a result, the thesis author did not participate in 19 of the interviews included in the appended papers.

describe as *elites* and were sometimes been demanding to interview as it was difficult to gain access to them.

Like providers of documents, interviewees can have a vested interest in the technology and it is therefore important to triangulate statements in the interviews with other sources, such as documents.[12] However, not all interview statements could be verified from other sources. Another way to verify interview data was to give all interviewees the opportunity to comment on a draft of the paper. Interviewees were specifically asked to review how the material from their interview was used. Most interviewees agreed with the interpretation and use of the material; some suggested minor changes and corrections.[13]

3.3 Data analysis

A qualitative approach was used to analyse documents and interview transcriptions in relation to the research questions and conceptual framework. This means that the texts were read in a systematic manner and the arguments presented in the text were sorted according to a logical structure, given by the conceptual framework (Esaiasson et al. 2009). For example, for Paper I the logical structure was given by the seven functions in the TIS framework. The functions each represented a category and most functions had several different themes or sub-categories (Figure 9).

[12] Triangulation can have a wider meaning implying using multiple sources, multiple methods, multiple theoretical frameworks and discussing results with critical colleagues in order to ensure that the analysis is grounded in the data (Marshall and Rossman 2011).
[13] On a few occasions, drafts of the papers needed approval from the firms' communications offices in order to guarantee that a quote was in line with the firm's communications policy.

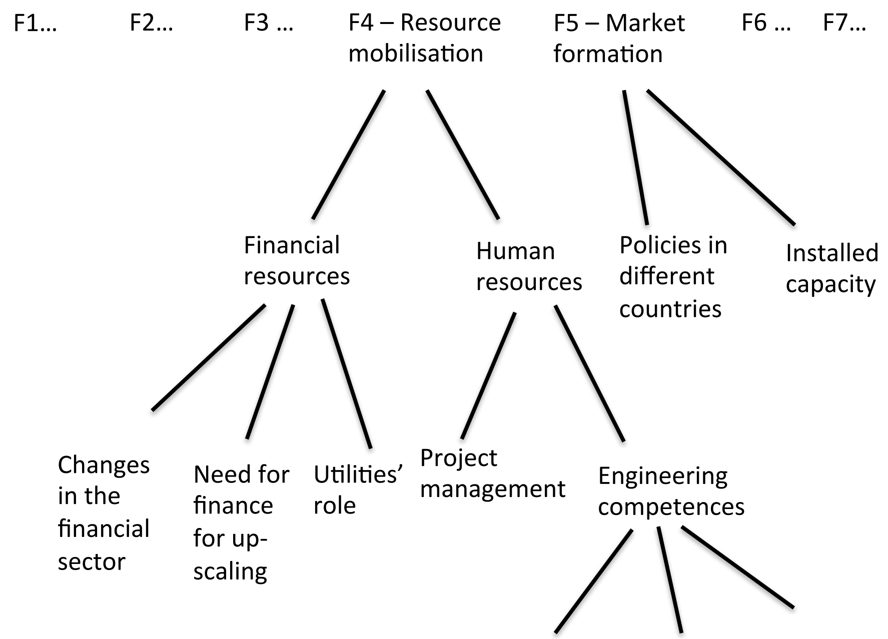

Figure 9 An example of the type of structure with different categories and sub-categories used to analyse documents and interview transcripts.

For Papers I, III, IV and V the material was structured into different categories and sub-categories 'by hand'. In the process of analysing data and writing a first draft of an article, new sub-categories were often identified. This resulted in re-sorting of the data according to these new sub-categories. In Paper IV, interview data was also used to calculate the need for engineers (see Method section in that paper). For Paper II data was coded and sorted into categories and sub-categories with the software MAXQDA.[14] Using software like MAXQDA made it easier to structure the material according to categories and, particularly, to re-structure the material.

3.4 Reliability and validity

Reliability and validity can be discussed in many different ways depending on the research design. For example, Kvale and Brinkmann (2009) emphasise that when using interviews for data collection, providing a valid result requires not just evaluating the end product, but also considering the validity of each step of the interview procedure. In this section, these aspects will be discussed in terms of *construct validity*, i.e. how the theoretical framework and the operational level fit, and *reliability*, i.e. can the work be repeated or are there unsystematic or random errors (Esaiasson et al. 2009). Good construct validity and high reliability will provide validity of the results (ibid.).

[14] www.maxqda.com.

The validity of the results has also been assessed continuously throughout the work on the papers and the thesis, by presenting the results both internally at Chalmers University of Technology and externally. Internally, the presentations have focused on research design and preliminary results. Externally, the results of the papers have been presented at several national and international conferences, both industry conferences and scientific conferences (Table 3).

Table 3 Overview of presentations of the papers and thesis.

Conference	Type of conference	Place and year	Paper presented
Vind 2010	Industry conference	Gothenburg 2010	Paper IV
EWEA conference	Industry conference	Brussels 2011	Paper IV
World Renewable Energy Congress	Scientific conference	Linköping 2011	Paper V
Power Cluster conference	Conference for an EU funded project	Bremerhaven 2011	Paper V
2nd International Conference on Sustainability Transitions	Scientific conference	Lund 2011	Paper IV
Utrecht University	Scientific workshop	Utrecht 2011	Paper I
Nationella vindkraftskonferensen	Industry conference	Kalmar 2013	Paper V and paper III
4th International Conference on Sustainability Transitions	Scientific conference	Zürich 2013	Paper III
ETH PhD academy	Scientific workshop	Appenzell 2014	Paper II
Final seminar	Scientific workshop	Gothenburg 2014	PhD thesis

Construct validity

A concern for construct validity is whether the two case technologies are suitable for drawing theoretical conclusions about TIS in the growth phase. The two technology fields illustrate different phases of development and diffusion. One of these, biorefinery technologies are still in their formative phase. Thus, it could be argued that a weakness of the thesis is that one of the case technologies is not yet in a growth phase and that the operational level of studies of this case does not fit with the theoretical concepts. On the other hand, developments of biorefinery technologies have been going on for a long time, which provides good opportunities to study obstructions to up-scaling. Thus, the two case technologies enable analyses both of what hinders technologies from entering a growth phase and, when a technology has entered a growth phase, what hinders further growth. In addition, biorefinery technologies will face competition for natural resources (biomass) earlier than other renewable energy technologies as these resources are to a large extent locked in to established industrial sectors (described by Pavitt (1984) as 'scale barriers'). Therefore, biorefinery technologies constitute a suitable case for studies of resource mobilisation challenges.

Drawing the boundary of a system is a demanding task that also affects how the operational level corresponds to the theoretical concepts. As part of the analytical tools applied in this thesis, three perspectives on resource mobilisation have been presented (see Chapter 2). However, a weakness of this approach is that at the operational level some actors can appear to be both endogenous and exogenous to the system. Investors, for example, are conceptualised as part of the financial sector, which is seen as something separate from the TIS. This conceptualisation is not problematic for investors who do not finance the technology, as they are outside the TIS, but for investors who do finance the technology it is, as they can be seen as part of the TIS. Hence, some investors are conceptualised both as part of the TIS and as part of a sector separate from the TIS. The same applies to universities engaged in education that generates competences needed within the TIS, and to utility firms that can be seen as part of an established energy sector, but also part of the TIS if involved in development or construction of the technology concerned. However, conceptual distinction between the TIS and the resources sectors is needed to analyse what it is in the structure or organisation of these sectors that hinders resource mobilisation. Thus, the strength of making a clear analytical separation is that it facilitates analyses of interactions between entities that are more or less completely aligned with the system goal of the TIS (growth of the technology) and entities that might or might not support TIS development, i.e. what is here referred to as TIS–context interaction.

Reliability

The discussion on reliability focuses on methodological challenges that could be sources of errors. One challenge is that doing a qualitative analysis of a growing socio-technical system implies that the system under study becomes larger and larger and therefore more difficult to fully understand. Furthermore, system–context interaction becomes more important, meaning that this interaction, too, must be addressed in the analysis. Thus, a source of error can be that the whole system is not captured, but it is not clear what part is missing. In some studies, the scope of the analysis is limited to one function (resource mobilisation) out of a set of seven, which allows a deeper analysis of this function and how it is affected by TIS–context interactions. Another way that the large system has been handled is by doing many interviews with careful verification of the data (Kvale and Brinkmann 2009).

Taking the step of studying system–context interaction can also mean a methodological challenge in terms of studying topics that, for the targeted actors, are sensitive matters. For example, Paper V involved interviewing firms not currently involved in development of the technologies under study, but which might be close to their strategic research work. Thus, interviewees were often restricted in what they could say owing to confidentiality issues, but the interviews were still informative as they could cover aspects of research projects and collaborations that were communicated publicly, and this provided a data set large enough for the analysis. A less successful experience came out of the work with Paper III, where an attempt was made to interview investors that were not investing in renewable energy technologies. The outcome was that the interviewee had very little to say as the topic was considered out of scope of the firm's business. Fortunately, interviews with investors currently financing these technologies provided very detailed descriptions of how the technologies are evaluated and of the critical aspects in this process. If interviewees admit that they cannot discuss an issue for some reason, it is often less of a problem. The real source of unsystematic errors is when an issue is not brought up at all (because the interviewee is not allowed to speak about it). The interviewer may then come to the conclusion that the interviewee does not know anything about a certain issue, when that is not in fact the case. To avoid this, it was important to be as well prepared as possible for the interviews and to know as much as possible about the interviewee and the organisation they represented (Kvale and Brinkmann 2009).

4 Results and conclusions

The presentation of results in this chapter follows the structure of the three research questions. For research questions 2 and 3, the results are structured according to the three perspectives on resource mobilisation (see Chapter 2). An overview of the papers' links to the research questions is given in Table 4.

Table 4 Overview of the appended papers' links to the research questions and the three perspectives presented in the conceptual framework.

Research question	Paper I	Paper II	Paper III	Paper IV	Paper V
1. What characterises the growth phase of a technological innovation system?	X	X	X		
2. What challenges in the mobilisation of resources may hinder the growth of a TIS?	X Perspective 1	X Perspective 1	X Perspectives 1 and 3	X Perspectives 1 and 3	X Perspectives 1 and 2
3. How can policymakers, firms and other actors intervene to overcome these resource mobilisation challenges?	X Perspective 1	X Perspective 1	X Perspectives 1 and 3	X Perspectives 1 and 3	X Perspectives 1 and 2

4.1 Characteristics of the growth phase of a TIS

The first research question is: *What characterises the growth phase of a technological innovation system?* This question is addressed in Papers I, II and III.

Paper I analyses the innovation system for offshore wind power in the EU, identifying both strong and weak functions. Resource mobilisation is one of the weak functions. If offshore wind turbines are to be deployed on a large scale, mobilisation of resources needs to be strengthened significantly. Market formation and legitimation are also considered weak, at least in some countries. The countries in which market formation is strong cannot compensate for weak market formation in other countries. Thus, at the EU level this function is weak. Three functions are strong: influence on the direction of search, entrepreneurial experimentation and the development and diffusion of knowledge.

Market formation, legitimation and resource mobilisation are interlinked; one of them – for example, resource mobilisation – cannot be strong if the others – market formation and legitimation – are not also strengthened. One reason for this is that the same mechanisms contribute to the blocking of several functions. For example, contrary to expectations the cost of offshore wind has increased, which has led to a discussion of the affordability of this technology, weakening its legitimation. Consequently, although Germany and the UK have strong regulatory frameworks that support the development of offshore wind, in many other countries with weak or uncertain policies the expectations of offshore wind are low, market formation is slow, and investors hesitate to invest (mobilisation of financial resources).

Mobilisation of resources can be troublesome in all phases of technological development and diffusion, but growth of a TIS requires a scale-up in the mobilisation of resources. This indicates that resource mobilisation can be more challenging in the growth phase than in the previous phase, as it is sensitive to scale. For example, Paper III demonstrates that mobilisation of financial resources can be particularly problematic in two phases of a technology's development: the step from public to private finance, and the step to the scale-up of financing needed for large-scale commercialisation. A survey by BNEF (2010) confirms that the second step is considered more intractable than the previous as the size of the investment needed is now substantially larger than before. Moreover, in the growth phase both resource mobilisation and market formation mean increased competition for exclusive assets, which is another reason why these functions are challenging in this phase. Resource mobilisation implies that actors within the TIS have to compete for resources with actors external to the TIS. Strengthening other weak functions – for example, legitimation – does not imply competition for exclusive assets in the same way.

The following conclusions can be drawn: the case of offshore wind power in Europe demonstrates that growth of this TIS requires strengthening of three functions: resource mobilisation, market formation and legitimation. These are interlinked, and large-scale technological diffusion necessitates that all three be strengthened. Resource mobilisation is, furthermore, more challenging in the growth phase than in the previous phase, as it is sensitive to scale. Another challenge in this phase is that both resource mobilisation and market formation imply competition for exclusive assets.

Papers I, II and III describe the challenges in mobilising resources for two wind power innovation systems placed in different geographical contexts: Europe and China. These regions have different points of departure for technology development and diffusion. While Europe (together with the US) has driven the development of the technology from early R&D, China has to a large extent been able to rely on technology transfer. This means that the development has been going on for longer time in Europe, whereas China has managed to quickly develop a domestic manufacturing capacity and scale up installations. However, to adjust products to domestic conditions (for example, foundations for offshore wind turbines in China's intertidal zones) requires national R&D. Thus, while the rapidly growing offshore wind TIS in Europe is struggling with resource mobilisation, market formation and legitimation, the rapidly growing wind power TIS in China needs to focus on knowledge development and diffusion and entrepreneurial experimentation – functions that are often key in the formative phase of a TIS.

Thus, in the case of wind power in China, further growth of this TIS requires strengthening of functions that are often important in the formative phase, such as knowledge development and diffusion. Hence, what seem to be the key functions in the growth phase in one region (Europe) might not be the same in another (China), as regions can take different routes for innovation systems to grow.

Papers I and II point to another characteristic of the growth phase: the need for coordination of activities both within the TIS and between the TIS and its context. Paper II shows that wind power deployment in China has resulted in a large installed capacity but also in large-scale problems. These include, for example, insufficient transmission capacity, resulting in major problems with curtailed power (see Section 4.2). For continued deployment of wind turbines in China, there is a need for activities within the TIS – such as R&D, wind farm development, construction of transmission grids, and policies at local and central level – to be coordinated if a slow-down in the diffusion of the technology is to be avoided. Paper I points to the need for coordinating conflicting interests in use of the sea. For offshore wind power to become more widely diffused, there is a need for maritime spatial planning at the EU level to coordinate the interests of TIS actors with the interests of other actors.

Hence, another characteristic of the growth phase is the need for coordination. Within the TIS, coordination is needed to avoid unbalanced growth that could slow down diffusion of the technology. Coordination of, for example, conflicting interests is also needed between the TIS and its context in order to enable wide technological diffusion.

4.2 Resource mobilisation challenges for growth of a TIS

In this section, the three perspectives on resource mobilisation (presented in Chapter 2) are used to structure the answers to the second research question: *What challenges in the mobilisation of resources may hinder the growth of a TIS?*

Perspective 1: The perspective from the growing TIS

The papers appended to this thesis demonstrate the scale of resource mobilisation needed for growth of a TIS. Paper IV presents the case of human resources needed for large-scale diffusion of offshore wind power and includes both quantitative and qualitative analysis. It is estimated that 10 000 new engineers are needed to achieve the targets set for 2020. Most (7000) of these engineers are needed in turbine manufacturers for the supply of both onshore and offshore wind turbines. About 2000 more engineers are needed at the utility companies for activities in offshore wind power. Engineers are also needed in other types of firms along the supply chain, for example in power grid suppliers, component suppliers and consultants.

An obstacle to growth of a TIS might be that the need for competence is specific to the technology and the specific competence required is not available. The analysis in Paper IV shows that engineers are needed with a variety of competences, including 1) deep competences in many fields (such as electrical and mechanical engineering, but also engineering physics and civil engineering) and 2) integrative competences within engineering (for example, mechanical and electrical engineering) and between engineering and non-engineering fields (for example, meteorology and logistics).

Paper IV also points to another aspect that can constrain resource mobilisation: there is a time lag between when a need for new competences is identified and when these competences are formed. This is because it takes some time to develop new educational programmes, and then a number of years for students to follow in these programmes. In addition, before any of the above can be done it may be necessary to educate teachers for the programmes – which also takes time. Thus, to form competences according to the need of emerging technologies takes time, which risks slowing down the development and diffusion of the technology.

Paper III shows the size of financial resources needed for up-scaling of biomass gasification and offshore wind power. If biomass gasification were to contribute to the EU biofuel market in 2030 at a production level equal to 10 per cent of total consumption in 2008 (i.e. 30 Mtoe), it would require investment of €60–120 billion (Hellsmark and Jacobsson 2012). For offshore wind, the member states' target for 2020 is an installed capacity of 44 GW (Beurskens et al. 2011), requiring investment of €130–140 billion (KPMG 2010, Rabobank 2011). In addition, it is important to emphasise that technology developers and utilities that have financed most of the development until now cannot continue to finance all the projects as more projects are developed in parallel.

For financial resources, quality relates to the terms and conditions of the financial deals (Paper III). Emerging technologies are often linked to high risks and long pay-back times, making the risk:return ratio unattractive for many types of investor. The challenge is not only in the size of investments needed, but also how to attract investors to this type of investment.

Lack of access to infrastructure (grids, for example) can hinder the growth of a TIS. As infrastructure is closely linked to existing socio-technical systems, changes to infrastructure can be very complex. An example of this is provided in Paper II, on the wind power industry in China, which after about a decade of rapid development is showing signs of growing pains. One of the main challenges for the industry is that wind farms are being curtailed due to insufficient grid capacity. In 2012, 100 TWh electricity produced by wind power was fed into the grid; another 20 TWh were produced but were lost due to insufficient grids (GWEC 2013). Another reason why wind power can be curtailed is that coal can generate both power and heat, and so in the winter, when heat is needed, power from coal is prioritised over wind power. Here, it is not just the capacity of the grid that is preventing wind power from being connected, but also the fact that the existing energy system is more adapted to coal than to wind power.

Space on land or at sea and the associated natural resources can be viewed as a resource needed for a growing TIS, and consequently the lack of this resource could hinder growth. Papers I and V bring up the issue of conflicting interests in the use of space on land or at sea as well as use of the natural resources available in this space (for example, wind or biomass), which might hinder a TIS in the growth phase. For example, the shipping and fishing industries and persons and organisations wishing to use the sea for recreational purposes are all competing for the same space, which could hinder the development of offshore wind power. Another example is that the established pulp and paper industry largely controls the biomass that is the raw material for biorefinery technologies.

To conclude, the amount of resources needed in the growth phase of a TIS is much larger than that required in the formative phase and can therefore constitute a substantial barrier to further development in this phase. Several types of resources must be mobilised, including human resources, financial capital, infrastructure and space on land or at sea and associated natural resources. Resource mobilisation includes challenges linked to both the quantity and the quality of resources. Another challenge is that there is a time lag between when a need is identified and when the resource becomes available to fill the need; for example, it may take many years to form competences.

Perspective 2: The perspective from established industrial sectors

The substantial amounts of resources needed for up-scaling of a TIS mean that the TIS will be competing for resources with established industrial sectors that are in control of many of these resources. Paper V provides an analysis of an established industrial sector, the Swedish pulp and paper industry, that controls resources, such as production facilities (pulp and paper mills), raw material and competence, that could contribute to the development of biorefinery technologies. The industry is locked in to existing technologies and was for a long time reluctant to develop biorefinery technologies. A transformation of the industry was initiated by the combined effect of several broad trends in society that put the industry under strong pressure to cut costs and find new business opportunities.

After coming under strong external pressure, the pulp and paper industry has now shown a modest interest in assigning resources to the development of biorefinery technologies. Analysing how this has been done reveals that the firms in this established industrial sector have different technological preferences, which can be explained by the different prerequisites that the companies already have for development of the technologies. These include, for example, the technical systems, e.g. the type of mill that they have. Firms with chemical mills use only about half of their biomass for their final product, so for them by-products could be used as raw material in new processes. Another factor affecting firms' strategies is their own research and development work; for example, firms with a history of fibre research tend to be more interested in technologies that use the potential of fibre.

To conclude: as more resources are needed for the growth of a TIS, one challenge will be competition from established industrial sectors for several types of exclusive resources. As these sectors are often locked in to existing technologies, strong external pressure may be needed before resources are made available for the novel TIS. Moreover, even under strong pressure, firms in established industrial sectors will be cautious about devoting their resources, and will do so in a way that fits with their existing system, for example in terms of their existing production facilities and knowledge base.

Perspective 3: The perspective from resource sectors

This thesis includes two examples of resource sectors: academia and the financial sector. The specific need for competences for offshore wind power (described above) indicates that current educational programmes are not enough, and hence there is a need for the formation of new educational programmes to enable the growth of this technology. Paper IV shows that it is academia rather than industry that is initiating formation of competence, even though industry actors are the ones experiencing the lack of competences. This means that, even though the development of university curricula is linked to research, unless there is sufficient communication between industry and academia, the curriculum developments may not be aligned to the need for competences in an emerging industry. Thus, one challenge for mobilisation of human resources can be that industry does not make its needs known, which can impede or delay academia's formation of human resources to meet this need.

Paper III contains analyses of the challenges of financing the development and large-scale diffusion of biomass gasification and offshore wind power in Europe. The analysis shows that mobilisation of financial resources to these technologies is hindered by the fact that the technologies do not fit the investment models of many investors. Development of biomass gasification has up until now (when demonstration plants are under construction) been financed by public funds, technology developers and utilities. To take the next step and build plants on a commercial scale will require funding from private investors. However, venture capitalists (investors of the type that take high risks) are unlikely to invest because biomass gasification requires larger investment over a longer time horizon than they are accustomed to.

For offshore wind power the case is that despite having a history of more than 20 years it still is associated with high risk. Moreover, the return level is very much dependent on policy measures in different countries. Currently, utilities are responsible for a majority of the investments, but this cannot continue when more projects are being developed in parallel. Hence, there is a need for external finance from investors who are willing to accept long pay-back times and average rates of return. Institutional investors, such as pension funds, manage large assets and could be part of the solution for this need for finance. However, they are not used to investing directly in emerging technologies and lack the necessary knowledge to evaluate this type of investment. Thus, this type of investor will not search for this type of investment nor be able to evaluate it.

It can be concluded that one challenge for resource mobilisation is that the need for resources in the TIS does not fit the models for resource mobilisation that have already been built up between resource sectors and established industrial sectors. This includes, for example, university curricula that direct the formation of competences, and the way in which investors decide what types of investment options to evaluate and how these options are evaluated. Lack of knowledge of renewable energy technologies in resource sectors can be one reason for constrained mobilisation of resources for the growing TIS.

4.3 Overcoming resource mobilisation challenges

The third research question is: *How can policymakers, firms and other actors intervene to overcome these resource mobilisation challenges?* In this section the answers to this question are presented according to the three perspectives, but also according to the type of actor that should take action: policymakers, actors in the TIS or actors in other sectors.

Perspective 1: The perspective from the growing TIS

The type of actions needed to overcome resource mobilisation challenges depends to some extent on the type of resource that is to be mobilised. In the case of human resources, an important action that actors within the TIS can take is to communicate their need for these resources to resource sectors, e.g. academia, which to some extent control the formation of the resources (Paper IV). This includes communicating both the type (quality) of resources and the scale (quantity) that is needed. One suggestion for how to organise this type of communication is to form TIS actor–academia networks in order to discuss how university curricula could be developed to suit the competence needs of the industry. There is an example of this in Bremerhaven, where an agency was set up to organise the offshore wind power industry, including the coordination needed for research and education. Communicating needs is also important in relation to other types of resources.

Policy can make it easier to overcome resource mobilisation challenges by applying a systems perspective to emerging technologies. This means that policymakers could acquire information about the need for resources or make their own assessment of this need (in terms of quantity and quality) so as to be able to introduce policies that can facilitate mobilisation of these resources.

Another action that policy can take is to coordinate and manage conflicting interests. Since few resources are free and easily transferred to a novel TIS, resources often are locked in to established industrial sectors, and therefore increasing need for resources within the TIS means increased competition for resources between TIS actors and incumbent firms. An example of this (Paper I) is how the development of offshore wind power in Europe is hindered by conflicting interests in the use of the sea (see Section 4.1 of the present thesis). Policymakers can help to overcome this resource mobilisation challenge by taking on the role of managing these conflicting interests if this is not done by the industry actors themselves. Policy can also take on the role of coordinating activities within the TIS in order to avoid unbalanced growth (see 4.1 of the present thesis). Bergek (2014, p. 17) also draws a conclusion along these lines, stating that '…*policy needs to take on the role of innovation intermediary to facilitate coordination and knowledge integration within the innovation system*.'

To conclude: to facilitate resource mobilisation, ***TIS actors*** *can communicate their need for resources in terms of quality and quantity, for example in networks formed between TIS actors and actors from resource sectors such as academia.* ***Policymakers*** *can apply a systems perspective in analyses of emerging technologies and include assessments of the need for resources in policy design. Moreover, if not done by TIS actors,* ***policymakers*** *have an important role to fill in coordinating interests between TIS actors and actors in established industrial sectors in order to enable resource mobilisation in the TIS.*

Perspective 2: The perspective from established industrial sectors

Strong external pressure may be needed to make actors in established industrial sectors become interested in innovative technologies (Paper V). Policymakers can intervene in order to contribute to this external pressure and stimulate actors in the established industrial sectors to enter the TIS or devote resources to the TIS. However, policy measures may not be enough to motivate actors in established industrial sectors to search for new options. Some type of crisis may be needed to increase the pressure.

Actors in established industrial sectors can enter a TIS in several ways and for several reasons. However, these actors often search for innovative options along existing technological trajectories. Therefore, actors within the TIS that aim at mobilising resources from established industrial sectors might be able to do this more easily by analysing the firms in established industrial sectors in order to see where there could be some type of connection. This connection could, for example, be in terms of a common knowledge base, production facilities, business model, or types of products or strategies. For example, for firms within the pulp and paper industry, the development of gasification technology requires the existence of a by-product that can be used as raw material in the gasification process. Thus, technical features of the production facility affect whether firms can develop this technology or not. Development of technologies for separation and refining of high-value products can build on the firms' knowledge base, but require a modified business model. TIS actors should consider these types of aspects (for example, shared knowledge base) as they try to initiate collaborations that enable resource mobilisation with actors in established industrial sectors.

To conclude, ***policymakers*** *can facilitate mobilisation of resources from established industrial sectors by introducing policy measures that increase the external pressure on* *the actors in these sectors.* ***Actors within the TIS*** *can try to initiate collaborations with actors in established industrial sectors by identifying areas of mutual interest and understanding.*

Perspective 3: The perspective from resource sectors

Actors in resource sectors – for example in the financial sector – can be reluctant to mobilise large amounts of resources to a TIS if these actors lack knowledge of the emerging technology. This might, for example, be the case with some investors (Paper III) who hesitate to invest in renewable energy technologies because they have not invested in them before. One way to overcome this is to increase knowledge about the technologies, so as to enable investors to evaluate these types of investments more correctly. Actors within the TIS can be an important source of knowledge, and cooperation with, for example, utilities developing offshore wind power could be a way for financial actors to increase their competence.

Academia may also need to increase its knowledge in order to be able to adjust curricula and develop competences adapted to the TIS. Paper IV discusses how academia can respond to the need for engineering competences in the offshore wind sector. There are some educational programmes in the countries around the North Sea, but to support a large-scale diffusion of offshore wind turbines, universities must ensure that competences are built in appropriate variety and volume as well as in a timely fashion. This increases the need for teachers (researchers) to design and implement curricula in this field. Thus, universities must not only conduct research, but also educate teachers with the ability to develop educational programmes in accordance with the need of the TIS.

Paper III analyses the financial sector and presents some examples where the model for mobilisation of financial resources is not aligned with the actors in the TIS. A suggestion for overcoming this is to develop new models for resource mobilisation that fit both the actors in the TIS and the actors in the resource sector. This can be initiated both by actors in the TIS and by actors in the resource sectors. One example that involves a TIS actor is in Denmark, where the utility Dong persuaded institutional investors to invest in offshore wind power by finding a new model for risk sharing and by working closely with the investors. Another example – in this case initiated by the financial sector – is financial options specifically directed towards renewable energy technologies, such as green bonds, which were initially set up by the UN, but which have now been replicated at local level, for example in the city of Gothenburg.

*Resource sectors are often strongly aligned with established industrial sectors. Therefore, two means to enable mobilisation of resources for a growing TIS are suggested here: to increase knowledge of the technologies in resource sectors, and to develop innovative models for resource mobilisation that are aligned with the TIS. These measures can be initiated by **actors in the resource sectors**, **actors in the TIS** and **policymakers.***

The results for research questions 2 and 3 are summarised in Figure 10.

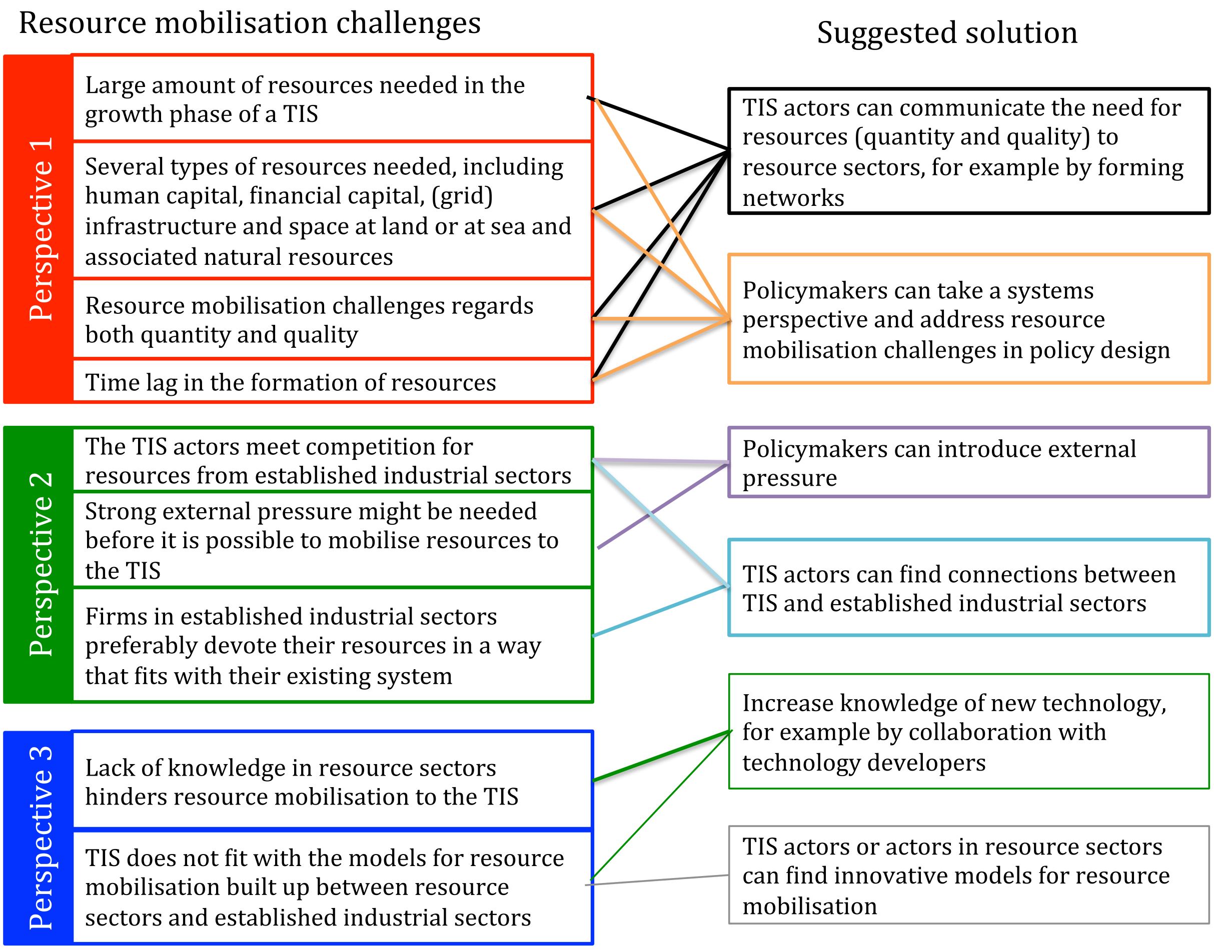

Figure 10 Summary of results for research questions 2 and 3.

5 Reflections on the results

This chapter presents some reflections on the results. For a discussion of validity and reliability, see Chapter 3.

The first of these reflections is on generalisation. It is sometimes argued that a drawback of case studies is that they are interpretations of the specific situation(s) studied and therefore difficult to generalise. Against this, Flybjerg (2006 p. 231) argues that *'one can generalize on the basis of a single case, and the case study may be central to scientific development via generalization as supplement or alternative to other methods. But formal generalization is overvalued as a source of scientific development, whereas "the force of example" is underestimated'.* While the empirical findings in this thesis give detailed descriptions of resource mobilisation challenges for wide diffusion of the case technologies, some generalisations could widen the usefulness of the work. The use of a theoretical framework that in itself is based on a much larger set of empirical studies and theoretical considerations should increase the value and validity of such generalisations, and, hence, some conclusions should also be applicable to other renewable energy technologies and perhaps to other technologies in general. However, since few studies have focused on the growth phase of a TIS, some caution is warranted.

The second reflection regards the use of the results from the thesis. The TIS framework was developed to help advise policymakers on how to support the development and diffusion of a specific technology. However, this does not imply that the advice is straightforward to implement. One reason for this is that the conclusion from a TIS analysis does not normally indicate exactly how policy should be designed. This means there is a risk that the result of the TIS analysis cannot be translated into suggestions for specific policy measures and that the results are therefore not used. Another risk is that the result is contradictive to the discourse in the political environment, which may imply that the result is not understood or not even considered and for that reason is not used. An example of a discourse to which it can be difficult to introduce results from a TIS analysis is the one based on a strong belief that the market should decide what technologies to develop. The same can, of course, also apply to decision makers in firms, academia and the financial sector. For example, Furrer et al. (2012) show that many banks (55% of the sample) are hesitant to implementing strategies for climate change mitigation that affects their value creating processes.

According to the latest reports by the IPCC (2014), immediate action is needed to avoid severe climate change effects in the future. However, the long timespans involved introduce an additional difficulty for policymakers. The time lag between the introduction of a policy and its results in terms of substantial changes in the energy system and emission levels could be several decades. This is longer than the period of office for most policymakers, meaning that a policymaker introducing these types of policies cannot expect to see the result of them while she or he is still in office. Besides, in parallel to the need for policies supporting renewable energy technologies there are many other issues that require political intervention and will generate positive feedback in the coming years. Another aspect is that policies that create change at the same time disturb established interests, which policymakers must be prepared to handle (Meadowcroft 2011).[15]

Laestadius (2013) states that technological development and deployment have been very rapid in times of war. This raises the question of whether development of technologies needed to mitigate climate change could be more rapid if climate change was perceived to be as threatening as a war. To compare climate change with a war might be incorrect, but what such a comparison would suggest is that the way a threat is perceived affects the speed at which technologies are developed that can be used to avoid the threat. Thus, if climate change was perceived as more threatening, it might be easier to introduce policies that stimulate large, rapid scale-up of renewable energy technologies. There are, of course, also positive signals to read from the fact that climate change is not perceived to be as threatening as a war. Another view on the speed of technology development and diffusion is that of co-evolution of policies introduced to support the formation of a TIS and advocacy coalitions formed by actors in this TIS, as described, for example, by Jacobsson and Bergek (2004). Feedback mechanisms between policies and advocacy coalitions, in favour of these policies, can over time result in scaling up of renewable energy technologies.

[15] This does not mean that policymakers should abstain from intervening. For example, Mazzucato (2011) analyses the USA and the UK and discusses the role of the state. She concludes that in order to stimulate innovation and foster new technological revolutions, states have an important role to fill even though the private sector may not always realise this.

6 Contributions

This chapter summarises the main theoretical, methodological and empirical contributions of the present thesis.

6.1 Theoretical contribution

The theoretical contribution of this thesis is a conceptualisation of the TIS's context, which involves different sectors that control resources needed for the system to grow. This conceptualisation enables analyses of TIS–context interaction that are needed for resource mobilisation. From these analyses, conclusions can be drawn about how to increase the alignment of the TIS and its context.

6.2 Methodological contribution

Methodologically, this thesis makes a contribution by combining different scopes of analysis in the appended papers. Papers I, II and V have a broader system perspective, while the Papers III and IV focus on the function resource mobilisation (one out of the seven functions included in the functional analysis of the TIS). The broader systems perspective provides valuable insights into the characteristics of a TIS in a growth phase. The narrower focus allows a deeper analysis of what structures in the TIS and its context are hindering resource mobilisation and system growth.

6.3 Empirical contribution

The empirical contributions can be divided into two parts. The first are findings about the characteristics of a TIS in the growth phase. Three functions are shown to be key in this phase: resource mobilisation, market formation and legitimation. These three functions are linked and large-scale technological diffusion requires that all three be strengthened. Resource mobilisation differs from the other two functions in being more sensitive to scale. However, it is also shown that in another region that has initiated TIS growth by technology transfer, other functions need to be strengthened. Thus, what seem to be the key functions in the growth phase in one region (Europe) may not be the same in another (China), as regions can take different routes for an innovation system to expand.

Another characteristic of the growth phase is the need for coordination within the TIS in order to avoid unbalanced growth that could slow down diffusion of the technology. Coordination is also needed between the TIS and its context.

The second part of the findings is the description of challenges to resource mobilisation that may hinder growth of a TIS, and suggestions for how these can be overcome within the technological fields of wind power and biorefinery technologies. These findings are summarised in Figure 10 and include a wide range of specific challenges and suggested solutions.

7 Further research

This chapter presents some suggestions for further research. This thesis provides empirical findings on characteristics of a TIS in a growth phase. However, additional studies of technologies in this phase, or on the verge of entering this phase, are needed to further deepen our understanding. In addition, further theoretical work is needed to verify and further develop the suggested framework for studies of TIS in this phase.

Another suggestion for further research is to analyse the growth of a socio-technical system around renewable energy technologies with another methodological approach. This could involve taking a quantitative approach and aiming to increase understanding of why different actors are involved or not involved in the development of a technology. For example, it would be useful to study why investors do not invest in renewable energy technologies. These investors could be studied, for example, by a survey which would allow a larger sample (than interviews) and the ability to reply anonymously. Another methodological approach could be to study one organisation more deeply to understand why they have or have not been involved in the development and diffusion of a technology. This could be done through working closely with the organisation in order to learn about its internal processes of, for example, decision making, vision creation and implementing change in the organisation.

This thesis has analysed resource mobilisation challenges for the growth of a TIS and suggested how these challenges can be overcome. The reflections in Chapter 5 point to some difficulties that could be faced in introducing policies in line with these conclusions. A proposal for further research would be to take this further and examine the linkages and possibilities for integration of technology policies and policies in other domains (for example, environment and trade). An example along this line of thought is the framework presented by Weber and Rohracher (2012) that integrates insights from TIS analysis and MLP to form policies for transformative change. However, much remains to be done to verify this empirically.

As renewable energy industries become larger in different regions, they can become a cause of bilateral (or multilateral) conflicts. For example, Chinese manufacturers of solar photovoltaics have been accused of selling at dumping prices in the European and US markets. Policy measures that have been effective in supporting technology development and diffusion in a formative phase might be seen as too supportive (to a national industry) and as violating international trade agreements if they are applied in the growth phase. Even though increased diffusion of renewable energy technologies can be seen as a common good, conflicts like this could hinder the development and diffusion of the technology. Thus, another suggestion for further research is to study conflicts caused by national policies supporting wide diffusion of renewable energy technologies and how these can be mitigated so that the transformation of the energy system can continue.

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Appendix A – Example of an interview guide

Background – the interviewee

1. Can you briefly describe your current role at the firm or NGO or university or authority etc. (the organisation)?

Background – the organisation

2. How does your organisation prioritize between different sectors, including renewable energy?
3. What is your organisation's motivation (or lack of motivation) for going into renewable energy?
    a. Particularly the technology in focus in this study (the technology)?
4. In what way is your organisation different from other organisations?

Finance of large-scale renewable energy technologies

5. What different models of financing does your organisation offer to renewable energy?
6. What are your requirements in these models?
    a. What is a good profile in order to get finance? What is a sufficient one?
    b. To what kind of sponsors?
7. What conditions are offered to the sponsor?
    a. Timeframe?
    b. Interest rate?
8. What different models of financing are offer specifically to the technology?
    a. Can you give some examples? How many projects have been financed?
    b. Has it worked as planned? Challenges?
    c. If no project has been financed, have projects been evaluated? Why or why not?
    d. What must be achieved in order to make the technology considered?
9. What risks do you perceive with the technology?
    a. What can project developers do to make projects more attractive?

Challenges for the future

10. What challenges do you see with finance for the technology in the next 10 years?
11. When it comes to financing renewable energy, what is the role of your organisation in the next 10 years?

Competence

12. What assets (in terms of number of people and competences) are allocated to renewable energy?
    a. What competences do you have to evaluate the development of these technologies?
    b. Do you feel you lack competence(s)?

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Rapid and large-scale diffusion of renewable energy technologies is necessary to avoid severe climate change. This thesis centres on one of the key challenges for scaling up renewable energy technologies: provision of the enormous resources required, such as human capital, financial capital and infrastructure.

The work includes studies of wind power and biorefineries in the geographical contexts of Sweden, the European Union and China. The findings indicate the magnitude and quality of the resources need for scaling up these technologies, but also point to obstacles with lock-in of resources to incumbent actors. Actors involved with the development and diffusion of technology can contribute to overcoming these obstacles by initiating targeted ways for allocating the resources – for example, new investment models. Policymakers can also play an important role, for example by managing conflicting interests of the use of resources.

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