Exploring Transition of Large Technological Systems through Relational Data

A Study of The Danish Smart Grid Development

Ph.D. Dissertation

Roman Jurowetzki

Dissertation submitted March, 2016

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Curriculum Vitae

Roman Jurowetzki

Roman Jurowetzki is a Ph.D. Fellow with the Innovation, Knowledge, and Economics Dynamics (IKE) group at the Department of Business and Management, Aalborg University, Denmark. He holds a M.Sc. in Innovation Economics (MIKE-E) from Aalborg University and a B.A. from the University of Passau, Germany in Governance and Public Policy. His research interests are related to understanding of socio-technical change processes. While not being officially part of the Danish strategic research alliance on *Energy Innovation Systems* (EIS), he has been – given the empirical focus of the present thesis – associated with the project and in close contact and collaboration with project partners. Throughout the three years in which he has been working on the present thesis, he aspired to build bridges between the innovation science tradition and the young field of *computational social science*. This is reflected in the adaptation of machine learning methods such as *Natural Language Processing* into the analysis. He believes that especially relational data – constantly growing in quantity, availability, and detail – has to be better utilised in social science.

Since the beginning of his affiliation with Aalborg University, he has also been part of the Secretariat of Globelics, *The Global Network for Economics of Learning, Innovation, and Competence Building Systems*. Globelics is a worldwide, open and diverse community of scholars working on innovation and competence building in the context of economic development. He has been responsible for the relaunch of the network's Working Paper Series, the webpage, and other public communication related tasks. He has also assisted in the preparation of the 2012 and 2013 conferences in Hangzhou, China and Ankara, Turkey. In 2014 and 2015 he has been part of the organising committees for the conferences in Addis Ababa, Ethiopia and Havana, Cuba. Here he has been, among others, coordinating the reviewing process of submitted paper proposals. The work with the Secretariat also led to a collaboration with Bengt-Åke Lundvall and Rasmus Lema in the attempt to bring the Innovation System tradition together with the Global Value Chain literature. This has to date resulted in a joint bibliometric publication and spurred the dialogue between scholars from the two traditions.

Papers written since joining the IKE group have been presented at several international conferences and workshops, and accepted for publication in, among others, the proceedings of the ISS conference 2014 and the conference proceedings for the annual conference on *SocioInformatics*. Other papers have appeared in working series or are under review with journals. A collaboration with the Copenhagen Cleantech Cluster (today part of CLEAN) resulted in a policy report on the developing Smart Energy System in Denmark.

From March until May 2014, he had stayed with RAND Europe, Cambridge and Brussels, where he participated in various projects. Particularly he has been involved in commissioned research evaluation and mapping of collaboration in medical research funded by the Department of Health, UK. He has also participated in a project on technological forecasting, commissioned by DG Connect.

Abstract

The 2013 edition of the European Commission's report "Smart Grid projects in Europe" outlines Denmark's strong leadership position within smart energy research, development and demonstration. The high and constantly growing percentage of wind power in the Danish system, the country's aspiration to become a European Smart Grid laboratory, and the currently achieved strong position in this technological area make Denmark an interesting case to study.

The smart grid relates to the grid not in the same way as the smartphone to the phone. The transformation is characterised by adding components to the existing energy grid(s) rather than replacing them. Consequently this process is characterised by a tension between *the old* and *the new*. The new (e.g. smart meters, advanced transmission monitoring etc.) does not necessarily appear to replace the old (the established transmission and distribution infrastructure) but to integrate with it and upgrade its capacity. The most obvious area of friction is the technology itself – new and old technological components have to be able to interact, which leads to challenges in terms of interdependence and interoperationability. But also the tension between established and new actors in the field, old and new business models, and institutions to support them has significant importance for the transformation of the grid. The overall guiding question of the thesis is therefore formulated as follows:

> **How does the interplay between established and new technologies and actors determine the direction and outcomes of innovation in large technological systems (such as the Danish smart grid)?**

The thesis can be subdivided into 3 parts. The introduction and Chapter A constitute the overall conceptual basis. Chapter B and C take a system-wide view on the subject matter. Both chapters have in common that they approach the focal technology as something that is defined by more than the purely technical delineation. Mapping and identification of implicit structure becomes a central part of the analysis. The scope of Chapter D and E is focused on more narrow conceptual aspects. The former aims at exploring actor behaviour within technological niches, while the latter – looking at a different technology than smart grid – proposes a more general computational method for understanding technological evolution.

The contributions of the thesis can be divided into (1) subject matter insights, (2) conceptual contributions, and (3) methodological contributions.

Results of several chapters indicate that in the Danish case it might be more appropriate – from an academical and policy point of view – to think in terms of a "smart energy system" rather than a pure electricity smart grid. This insight should be considered in policy development, research funding, and the definition of standards.

Conceptually the thesis aims to combine elements form Science, Technology and Society (STS) tradition with the Technological Innovation System (TIS) framework. Thereby, a more refined analysis of the transforming energy grid system is possible.

Throughout the thesis relational data and network analysis tools are utilised to explore the above-mentioned interplays, thus embracing the complexity of the explored system. This allows gaining a more detailed picture of the composition, structure, and power relations between the elements.

Resumé

EU-Kommissionens rapport „Smart Grid projects in Europe“ (Smart grid projekter i Europa) fra 2013 fremhæver Danmark som førende inden for smart grid forskning, udvikling og demonstration. Den høje og voksende andel af vindenergi i det danske energisystem sammen med landets målsætning om at blive et europæisk smart grid laboratorie og den stærke position på dette teknologiområde gør Danmark til en spændende case at analysere nærmere.

Smart grid forholder sig ikke til elnettet på den samme måde som smartphones til traditionelle telefoner. Transformationen af energisystemet sker ved, at komponenter bliver tilføjet til de nuværende energisystemer i stedet for helt at erstatte dem. Som konsekvens heraf opstår en indbygget spænding mellem det etablerede og det nye. Det nye (f.eks. intelligente elmålere, avanceret transmissionsovervågning osv.) udvikles således ikke nødvendigvis for at erstatte det nuværende (det eksisterende energitransmissions- og distributionssystem) men for at integrere med det og for at opgradere dets kapacitet.

Det mest åbenlyse spændingsfelt opstår omkring selve teknologien – nye og gamle teknologielementer skal kunne spille sammen, hvilket tit giver udfordringer i forhold til interdependens og kompatibilitet. Også spændingen mellem de etablerede og nye aktører på området, gamle og nye forretningsmodeller, og understøttende reguleringer og institutioner har en betydelig indflydelse på systemets transformation. Den overordnede problemformulering af denne afhandling er således:

> **På hvilken måde bestemmer samspillet mellem etablerede og nye teknologier og aktører retningen og resultatet af innovationsaktiviteter i store teknologiske systemer (som f.eks. det danske smart grid)?**

Afhandlingen består af 3 hoveddele. Indledningen og Kapitel A udgør første del og etablerer det overordnede konceptuelle grundlag. Kapitel B og C (anden del) tager en systemanalytisk tilgangsvinkel til problemfeltet. Begge kapitler tager udgangspunkt i en definition af den konkrete teknologi, som er bredere afgrænset end ud fra en ren teknisk forståelse. Kortlægning og identifikation af implicitte strukturer er en central bestanddel i analyserne. I Kapitlerne D og E (tredje del) er der sat fokus på mere afgrænsede og udvalgte konceptuelle elementer. Det første af de to kapitler ser på aktøradfærd i teknologiske nicher. Det andet foreslår en mere generel computerbaseret metode til at forestå teknologisk udvikling. Casen her er dog en anden teknologi end smart grid.

Det videnskablige bidrag i afhandlingen kan inddeles i (1) ny viden om selve caseområdet smart grid, (2) konceptuelt relaterede bidrag og (3) metodologisk bidrag.

Afhandlingen indikerer, at i en dansk kontekst kan det fra både en analytisk og en politisk synsvinkel være mere hensigtsmæssigt at tale om et „intelligent energisystem“ i stedet for et smart grid elnet. En sådan bredere tilgang og forståelse bør indgå i forbindelse med lovgivningen, i forskningsfinansieringsøjemed og ved formuleringen af standarder.

Afhandling integrerer elementer fra Videnskabs- og Teknologistudier (STS-studier) og Teknologiske Innovationssystemer (TIS). Dermed opnås en mere nuanceret analyse af transformationen af energinetsystemet.

Der bruges relationel data og netværksanalysemetoder gennem hele afhandlingen for at kunne udforske de ovennævnte interaktioner. På den måde forsøges kompleksiteten af det analyserede system fanget. Disse metoder gør det muligt at tegne et mere detaljeret billede af sammensætningen, strukturen og magtforhold mellem elementerne.

Zusammenfassung

Der im Jahre 2013 herausgegebene Bericht der Europäischen Kommission „Smart Grid projects in Europe“ (Smart Grid Projekte in Europa) betont die führende Position Dänemarks in Forschung, Entwicklung und Demonstration intelligenter Energiesysteme. Der hohe und beständig wachsende Anteil der Windkraft im dänischen Netz, die nationalen Bestrebungen zum europäischen Smart Grid-Labor zu avancieren und die bereits heute erreichte starke Stellung in diesem Technologiefeld machen Dänemark zu einem interessanten Fall.

Das Smart Grid – oder das entstehende intelligente Energienetz – verhält sich zum etablierten Netz nicht wie das Smartphone zum Telefon. Die Transformation ist dadurch gekennzeichnet, dass Komponenten zu den bestehenden Energiesystemen hinzugefügt werden, anstatt diese zu ersetzen. Folglich ist dieser Prozess durch eine Spannung zwischen dem Bestehenden und dem Neuen gekennzeichnet. Das Neue (z.B. Smart Meter, fortschrittliche Leitungsüberwachung usw.) soll das Bestehende (die etablierten Hochspannungsleitungen und Verteilungssysteme) nicht verdrängen, sondern sich in dieses integrieren und dessen Kapazität erweitern. Die Technologie an sich stellt die vorrangige Konfrontationsfläche dar – hinzukommende und etablierte technologische Komponenten müssen interagieren können, was im Hinblick auf wechselseitige Abhängigkeiten und funktionelle Kompatibilität Herausforderungen schafft. Doch auch die Spannungen zwischen etablierten und neuen Akteuren im Technologiefeld, althergebrachten und neuen Geschäftsmodellen und den Institutionen die diese jeweils unterstützen, haben beträchtliche Bedeutung für die Umwandlung des Netzes. Die übergeordnete Leitfrage dieser Dissertation formuliert sich daher wie folgt:

> **Wie beeinflusst das Wechselspiel von etablierten und neuen Technologien und Akteuren die Richtung sowie die Resultate von Innovationen in großen technologischen Systemen (wie dem dänischen Smart Grid)?**

Die Dissertation ist in drei Teile gegliedert: Die Einleitung und Kapitel A bilden die übergeordnete konzeptuelle Grundlage der Dissertation. Kapitel B und C beleuchten die Fragestellung aus einer systemischen Perspektive. Beide haben gemein, dass sie sich der zentralen Technologie, also dem Smart Grid, in einer Weise annähern, die nicht ausschließlich von der technischen Definition ausgeht, sondern auch andere Faktoren berücksichtigt. Mapping und Identifikation von impliziten Strukturen sind zentrale Bestandteile der Analyse. Kapitel D und E schließlich haben einen mehr spezifischen Fokus auf bestimmte konzeptuelle Elemente. D studiert das Verhalten von Akteuren in technologischen Nischen, während E eine mehr generelle computerbasierte Methodologie zur Erforschung von technologischer Evolution erarbeitet. Das letzte Kapitel betrachtet dabei nicht das Smart Grid.

Der wissenschaftliche Beitrag dieser Arbeit gliedert sich in folgende drei Kategeorien: (1) Thematische Erkenntnisse im erforschten Technologiebereich, (2) konzeptuelle und (3) methodologische Beiträge.

Im Fazit mehrerer Kapitel zeigt sich, dass es im dänischen Kontext – vom akademischen und politischen Standpunkt aus – angebrachter sein könnte, von einem integrierten „intelligenten Energiesystem“ anstatt lediglich vom Smart Grid zu sprechen. Dies sollte insbesondere in der Gesetzgebung, im Bereich der Forschungsfinanzierung und bei der Definition von Standards berücksichtigt werden.

Konzeptuell gesehen integriert dieses Projekt Elemente aus der Tradition der Wissenschafts- und Technologiestudien (engl. STS) und dem Technologisches Innovationssystem (TIS). Dies ermöglicht eine ausführliche Analyse des sich wandelnden Energienetzes.

In allen Teilen der Dissertation wird von relationalen Daten sowie Analysetechniken Gebrauch gemacht, um die obengenannten Wechselwirkungen zu erforschen. Dadurch wird die Analyse der Komplexität des Systems gerecht und erlangt eine detailliertere Einsicht in dessen Zusammensetzung, Struktur und die Machtverhältnisse zwischen den Elementen.

Contents

Thesis Details

Thesis Title: Exploring Transition of Large Technological Systems through Relational Data: A Study of The Danish Smart Grid Development

Ph.D. Student: Roman Jurowetzki

Supervisors: Assoc. Prof. Birgitte Gregersen, Aalborg University
Assoc. Prof. Jesper Lindgaard Christensen, Aalborg University

The main body of this thesis consist of the following papers/chapters. It is preceded by an introduction.

[A] Roman Jurowetzki, Conceptualizing and Analysing Evolving Technical Systems – A bibliometric review *Working Paper*.

[B] Roman Jurowetzki, Unpacking Big Systems – Natural Language Processing meets Network Analysis. A Study of Smart Grid Development in Denmark. *SPRU Working Paper Series (SWPS)*, 2015-15: 1-36. ISSN 2057-6668. www.sussex.ac.uk/spru/swps2015-15, 2015.

[C] Roman Jurowetzki, The Danish Smart Grid System – Components & Functional Dynamics. *Working Paper*.

[D] Daniel S. Hain & Roman Jurowetzki, Incremental by Design? On the Role of Incumbents in Technology Niches – An Evolutionary Network Analysis. *Accepted (R&R) ISS2014 Springer proceedings*.

[E] Roman Jurowetzki & Daniel S. Hain, Mapping the (R-)Evolution of

Technological Fields – A Semantic Network Approach. *Lecture Notes in Computer Science - Social Informatics*, 8851, pp. 359-383, doi: 10.1007978-3-319-13734-6_27, 2014.

In addition to the main papers, the following publications have also been made.

[1] Jonas Mortensen (Ed.); Roman Jurowetzki; Anders Dyrelund; Lars Hummelmose; Preben Birr-Pedersen; Sune Thorvildsen, *The Smart Energy System: Asset mapping of Danish competencies across the value chain*, Copenhagen Cleantech Cluster, 2014.

[2] Sarah Grams & Roman Jurowetzki, 'Emotions in the Classroom: The Powerful Role of Classroom Relationships', in B. Lund & T. Chemi (eds.) *Dealing with Emotions: A Pedagogical Challenge to Innovative Learning*, pp. 81-98, Creative Education Book Series, vol. 3, Sense Publishers, 2015.

[3] Daniel S. Hain & Roman Jurowetzki, 'The Silicon Savanna – Local Competence Building and International Venture Capital in Low Income Countries The Emergence of Foreign High-Tech Investments in Kenya, *Globelics Working Paper*, 2015.

[4] Roman Jurowetzki, Bengt-Åke Lundvall & Rasmus Lema, 'Overcoming Intellectual Tribalism – A bibliometric mapping of Innovation Systems and Global Value Chain Literatures, *Globelics Working Paper*, 2015.

[5] Simone Franceschini, Lourenco Faria & Roman Jurowetzki, 'Unveiling scientific communities about sustainability and innovation. A bibliometric journey around sustainable terms, *Resubmitted after the first round of reviews to the Journal of Cleaner Production*, 2015.

This thesis has been submitted for assessment in partial fulfilment of the Ph.D. degree. The thesis is based on the submitted or published scientific papers which are listed above. Parts of the papers are used directly or indirectly in the extended summary of the thesis. As part of the assessment, co-author statements have been made available to the assessment committee and are also available at the Faculty. The thesis is not in its present form acceptable for open publication but only in limited and closed circulation as copyright may not be ensured.

Preface

A key concept associated with innovation is uncertainty, the immanent inability to predict the outcome of a creative process that is set out to lead to something new. Does that mean that we shouldn't try to engage in forecasting of where our inquiry might lead us to? Should we just reach out for *the new*, going wherever we feel like? Will an attempt of planning lead to less creative outcomes, as we may cut off potentially fruitful paths because they do not fit a predetermined roadmap? Having finalised this thesis I see that the challenge lies in being able to find a fine balance between planning, having a bit more than a sense of direction, while leaving enough space for experimentation. It is about being open to solutions that might not seem obvious at the onset but may equally lead to a desired outcome. This seems to be true for large technological systems but also for the writing of a dissertation.

Having started out with an empirical focus – the emerging Danish smart grid – I had struggled for some time to produce something interesting, without venturing in qualitative approaches[1]. Almost a year and two discontinued papers later, I was dispirited and realised that my problem was not a conceptual one but mostly methodological in its nature. I approached the smart grid with a very determined understanding of what it had to be instead of asking what it actually is, in the context which I was interested in. I went to a summer school in Utrecht where I met another Ph.D. student from France who has been studying the emerging technology of 3D printing, and he was facing exactly the same challenge as I. And then, inspired by his approach, I took an unforeseen detour into new areas – natural language processing and network analysis – to find one solution for the methodologi-

[1] This should really not be understood as some form of aversion against qualitative research.

cal challenge. Today, I am happy that I went there and grateful that I could do so. I was able to take my initial Ph.D. plan for what it was – a plan with built-in freedoms to adopt, not some kind of computer-program that I had to follow slavishly.

This thesis could have looked very different, may have been more informative about details of the Danish smart grid development in areas that lie outside the current scope. However, I think that the contribution that finally evolved is of greater value. It provides some unexpected results about the features of the smart grid in the Danish context and it has led to the development of several methods that are equally applicable in many other domains. Finally, I believe that having the chance to try out something less conventional, I was able to learn and grow more than I had imagined.

At this point I would like to express my gratitude to a number of people that accompanied me in the past years and some that I encountered on my journey. Without them it would have been impossible for me to finalise this project – at least not in its current form. I will try not to list too many names, as I have noted that most of the people would appear in various contexts.

Above all, I would like to thank my supervisors Birgitte Gregersen and Jesper Lindgaard Christensen for the mentorship that they have given me in all these years. Thanks for being there when I asked for help, for supporting my decisions and ideas, and also for encouraging and pushing me forward when I needed it.

I am indebted to all my colleagues in the IKE group. Not only have they triggered my interest in the subject of innovation and in pursuing an academic career path, they also accepted me in the research environment almost from the very beginning when I came to Aalborg to study in 2010. I wish to thank Christian Richter Østergaard and Bram Timmermans who invited me to work with them on the Global Operations Networks (GONE) project before I commenced as a Ph.D student. I believe that the IKE group offers a rare and beautiful environment to study and work in with fast and informal communication, support, and also joy. I'm particularly thankful to Dorte Baymler and Jeanette Hvarregaard, who are always there and just make everything work.

Although there are many overlaps with the IKE group, I would like to mention the fantastic people in the Globelics Secretariat and the extended

Globelics family. It has been an incredible experience working with you. Admittedly, I might have had (a bit) more free time in the past years, have I not engaged in working with Globelics. But that option stands in no comparison with how challenging and in the same time rewarding the experiences have been that I gained through this work. I consider it an honour having worked with Bengt-Åke Lundvall who lured me into joining the Secretariat during a walk in the forest.

Thanks to the members of the Strategic research alliance for Energy Innovation Systems (EIS) for involving me in its activities.

Throughout the past years I have collaborated with a number of people on different projects, which are all listed in the *thesis details* section on page xvii. I have learned a lot from all of my co-authors for which I would like to express my deepest gratitude.

In early 2014, I spent three months at RAND Europe, Cambridge, UK. This stay has been very valuable for me, as it reminded me of the world outside the University and once again demonstrated me why what I am doing is important – also outside academia. I would like to thank all the great people in the *Innovation & Technology Policy* team and especially Joe Chataway and Rebecca Schindler.

Great support for the progress of this thesis and many other projects have come from the "young generation" of the IKE group, all the current Ph.D. students and those that have already finalised. Particularly, I am glad that I have met my two former office mates, Daniel Hain and Eunkyung Park. Both of you have become some of my closest friends (apart from being co-authors, travel and workout buddies and so much more) and I am happy to have you around now and hopefully in future.

I would like to thank my friends who have been there for me – also as enduring proofreaders – and supported me during my journey.

Finally, I wish to thank my family, my mom, dad, and my sister for believing in me, for allowing me to pursue my ideas, and for all the support and love.

Roman Jurowetzki
Aalborg, March 3, 2016

Part I

Introduction

Studying the emerging smart grid in Denmark: A triple challenge

1 Objectives and Motivation

On July 10th 2015, due to seasonally low energy consumption and strong winds, Danish wind power plants generated the equivalent of 140 percent of the national consumption for two hours (Steel, 2015) – a new record. Much of the harvested energy could not be used in Denmark but was exported to Germany, Norway, and Sweden. At the same time, a smaller amount of electricity from Germany was imported into western Denmark to help balancing the North German grid, which on its own was not able to canalize locally generated wind power surpluses to other regions. To date, the North European electricity transmission grids are managing such events. However, with the increasing amount of intermittent renewables, such situations will become more common and feature stronger peaks which will impact several countries at the same time (Pöyry, 2011). On July 11th, the day after the record was set, the wind was not blowing. Denmark had to import electricity and the national share of wind power was on average at 8 percent. In fact, Denmark is today one of the most dependant countries on energy imports, which is mainly caused by the high share of intermittent wind power in the system. The balancing of the network by transmission of intermittent renewables through a (future) “European Super Grid” is therefore seen as only a partial solution. The development of smart solutions at the distribution level — turning the existing power grid into a *smart grid*, or looking further into the future, to an integrated "smart energy system" – which would allow to absorb and store energy is politically envisioned as the complementary rather than competing development to upgrade the overall transmission infrastructure.

This research project started out in 2012 with the intention to identify and explain innovation dynamics related to the development of the *smart grid* in Denmark. Put as a more direct question the project asks: How do large technological systems (such as the Danish power grid) transform?

The *smart grid* is the common notion for the upcoming electricity grid infrastructure. It has been conceptualised as the result of a merger between the existing electricity grid and a "layer of intelligence" that comprises various digital and advanced components to monitor and manage the electricity flow. It is currently emerging as a way to cope with the challenges imposed by the ongoing changes within the overall energy system. These are, for instance, the decentralization and renewable energy harvesting rather than fossil fuel based energy production, increasing use of electricity as compared to other energy sources, and the emergence of electric mobility (Farhangi, 2010). The Danish case, as several chapters of the present thesis argue, shows that while the challenges mainly emerge in the electricity field, solutions might be also found in other parts of the energy system. Scholars from the area of energy planning asserted that rather than looking at the emerging smart grid in isolation, it should be studied taking in interaction with other energy grid, conversion, and conservation technologies (Lund et al., 2012). The well developed, dense district heating system in Denmark and the gas grid can complement the electricity grid and help reaching greater overall efficiency and higher levels of renewable energy integration. This thesis follows the recommendation and aims at drawing a picture of the smart grid development as a co-evolutionary process with an emphasis on the importance of the technological and socio-economic context into which the different smart grid technologies are integrated.

The greater context of these developments is the aim to reach more environmentally sustainable energy consumption in the future, escaping the carbon lock-in[2] (Unruh, 2000). What makes the development of the smart grid particularly interesting is that new functionality – the bi-directional transmission of energy and data in a decentralized manner – is envisioned to be achieved not by designing a totally new system. The smart grid relates to the grid not in the same way as the smartphone to the phone. Rather it will be done by transforming the established energy grid(s) and, breaking the established technological path dependencies (David, 2007).

Consequently this process is characterised by a tension between *the old* and *the new*. The new (e.g. smart meters, advanced transmission monitoring etc.) does not necessarily appear to replace the old (the established transmission and distribution infrastructure) but to integrate with it and upgrade its capacity. Focusing merely on *new* components to understand this process would be therefore not enough. The perspective taken by the thesis chapters that explicitly explore the development of the smart grid (Chapters B, D, C) is broader and more interested in the complex relation between *the old* and *the new* at different levels. The most obvious area of friction is the technology itself – new and old technological components have to be able to interact, which leads to challenges in terms of interdependence and interoperationability. But also the tension between established and new actors in the field, old and new business models, and institutions to support them has significant importance for the transformation of the grid.

Specifying the above placed question further, the overall guiding question of the thesis could be formulated as:

> **How does the interplay between established and new technologies and actors determine the direction and outcomes of innovation in large technological systems?**

Seen in the light of the sustainability discussion, studying such transformation processes is not only important to inform similar developments in other countries but can also provide valuable insights for the overdue sustainability transformations of other systems (e.g. transportation or agri-food).

[2]The condition of self-perpetuating entrapment in fossil fuel-based energy systems, achieved through a process of technological and institutional co-evolution, that can inhibit public and private efforts to introduce and diffuse carbon-saving technologies (Unruh, 2000).

This thesis represents a collection of articles with each having their own more specific research objective, and each contributing to the understanding of a particular facet of the overall question above. Thus, the different (empirical) chapters have been directly addressing the following sub-questions:

> **SQ1:** How can an emerging systemic and context dependent technology – such as the smart grid – be delineated?

While the technologies that belong to the "layer of intelligence" seem to be well specified (see following section), the particular scope of the systemic technology in a certain context is shaped by many other factors. Thus the Danish smart grid might be significantly different from what is considered to be the smart grid in the UK. The system combines a shifting variety of technologies that are traditionally classified into distinct categories and consequently also the actors involved in the development are difficult to point out. Answering this sub-question becomes therefore key for any further analysis.

> **SQ2:** How does the broader smart grid technology develop in Denmark, transforming the national energy grid infrastructure? Which actors and institutions drive this development and what are the blocking mechanisms?

Having established the scope of the focal technology this sub-question investigates the concrete emperical case, adopting the functionalist TIS framework.

> **SQ3:** Do incumbent actors from the energy field, over time, gain dominance in smart grid research – supposedly an emerging technology in need of shielding from the established selection environment and incumbent influence?

Literature from the TIS tradition and to a higher degree the transition community argue that the established "regime" and its representatives are not likely to contribute to the development of technological solutions that could cannibalise existing structures in which they have ownership. Yet, many Danish smart grid research projects – providing arguably appropriate spaces for the development of new technology – involve incumbent actors as participants and often as leaders. The sub-question aims at understanding the appropriate role of these actors.

> **SQ4:** How can social media and unstructured online available text data be used to identify evolving technological trajectories?

This sub-question is more general and goes beyond the guiding question, aiming at using new types of data to understand technology development.

Sub-questions that directly relate to the smart grid technologies are motivated and elaborate below. The last sub-question and the associated article (Chapter E) are mainly focused on the development of the method and explore a different technological field.

As the project evolved – even considering that the above guiding question had an implicit character initially and only took shape halfway into the project – it became more and more clear that the research ambition comes with a methodological challenge. Apart from the novelty and heterogeneity of the technology and hence a latent insufficiency of *straightforward* quantitative data, the stated aim is to look at interaction.[3] This means that data and methods needed to be used that are able to depict relations between elements of the focal system. Throughout the thesis relational data and network analysis tools are utilised to explore these interplays, thus embracing the complexity of the explored system. This allows us to gain a more detailed picture of the composition, structure, and power distribution[4] between the actors. Here lies also the central methodological contribution of the thesis.

This introduction aims to achieve three objectives: First, to provide an understanding of the focal evolving technology in general and in particular the Danish context. Second, to portray the development of the smart grid as the transformation of a large technical system, which to analyse imposes a conceptual and methodological challenge. Third, to give an overview of the different chapters and contributions of the thesis.

[3]Section 4 elaborates the methodological challenge that emerged as the project developed and how it was addressed.

[4]Here the abstract power not the electrical one is meant.

2 Empirical setting: the need to develop a smart grid

To understand what the smart grid is envisioned to become and which functions it is supposed to fulfil in the overall energy system, it is first essential to recapitulate the developments – particularly within the energy production area – that call for changes in other parts of the energy system. This section outlines in its first three parts these developments mainly in a general fashion, disregarding most of the territorial differences that otherwise have significant implications for the grid. The last part portrays the context of the smart grid emergence in Denmark.

2.1 What are the reasons for building a smart grid?

Overall, there are three major tendencies that challenge the currently established energy grid architecture[5]: (1) Growing energy demand, mainly in the form of electric power, (2) energy production by actors who traditionally have been consumers, and most importantly (3) the shift from fossil fuel based energy production to renewable energy harvesting. On the energy consumption side a noticeable trend is the shift from various energy sources towards electrical power. Not only is electricity increasingly used in applications where it has been one among several energy sources – such as cooking and space heating – but now it also has become a favoured energy source in new fields such as transportation. Electric vehicles are still a niche market but constantly gaining momentum. This trend is associated with a growing load on the power distribution grid and – given that the system remains unchanged – likely to require capacity extension. Traditionally, energy has been produced centrally and then transported through the transmission and distribution system to the consumer. Today, an increasing number of consumers, both private households and industrial units, are generating energy. Energy is, for instance, produced in the form of electricity on rooftop (photovoltaic) PV panels and by small windpower generators. This energy is not necessarily used at site and this means that the grid has to be able to absorb

[5]While the smart grid is a concept that is associated with the electricity system, its antecedents and the implications are important for the whole “energy grid” or “energy system”

and transport it away from these new type of actors entitled "prosumers". Finally, and most importantly, there is an ongoing paradigm shift within energy production that challenges the grid. Traditionally, energy has been largely *produced* in a controlled fashion by burning fossil energy sources such as coal, natural gas and oil. The generation levels have been adjusted to the anticipated demand and could easily be held stable. With respect to this, the generation of renewable energy is different, as it is – most prominently in the cases of wind, solar PV, and wave energy – not generation as such but harvesting of energy. Sunshine and strong wind depend on the weather, which is beyond human control and therefore renewable energy is inherently intermittent. The central challenge thus becomes to balance the supply and demand of power in the grid. Since production cannot be controlled directly, the two available approaches (on the distribution level) to balancing are: (1) demand flexibilisation, (2) energy conversion and storage.

The aim with demand adjustment is to reduce the load on the grid in peak times and shift as much demand as possible to times when much renewable energy is in the grid. In the case of Denmark that would mean, for instance, to run energy intensive appliances such as washing machines, dishwashers and dryers during the night when wind generated power is abundant in the grid, while the overall demand is usually low. The participation of customers in such a network optimization is often referred to as "demand response". Consumer empowerment and consumption flexibilisation have become arguments for the implementation of the smart grid. "Non-engineering" contributions to smart grid research are mostly found in this area. Reducing consumption during certain times by increased awareness in companies and households and through the pricing mechanism which is one important measure currently implemented in many countries. Several approaches to designing the practical implementation of *demand response* have been proposed (Boait et al., 2013). Yet, results from studies exploring the consumer behaviour in demonstration of *demand response* settings are not optimistic. Hargreaves et al. (2013) have analysed how households interact with smart meters and its feedback on their energy consumption, finding that in the long run changes in the consumption behaviour are very limited. The argumentation in He et al. (2013) is similar, suggesting that the incentives to become active are too low and consumers will not be sufficiently motivated by a technological push only. The authors suggest institutional change in the form of new types of contracts between energy suppliers and consumers. Geelen et al. (2013) and Ghanem and Mander (2014) point additionally to the role of product and service designers to facilitate the activation of "real" rather than "ideal" end-users. Alternatively, energy can be stored directly in batteries – as for instance suggested by Tesla with the introduction of their "powerwall" in 2015 – or converted to another energy carrier such as gas or heat and stored for later use. This would require a more limited adaptation in user behaviour but likely demand for greater technical changes in the system. Both approaches (which may be happening simultaneously) would require large scale adjustments of the grid infrastructure.

2.2 The smart grid technology and alternatives

The International Energy Agency (IEA) defined the smart grid as:

> an electricity network that uses digital and other advanced technologies to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands to end-users.

The smart grid is envisioned as a way to address the above listed challenges. The definition explicitly focuses on the electricity grid and the National Institute of Standards and Technology (NIST, 2010) proposes to classify the following eight technology areas as belonging to the new electricity network. These are:

- Wide-area monitoring and control
- Information and communications technology integration
- Renewable and distributed generation integration
- Transmission enhancement applications
- Distribution grid management
- Advanced metering infrastructure (AMI)
- Electric vehicle (EV) charging infrastructure

- Customer-side systems (CS)

While this general classification framework appears comprehensive as it covers all parts of the energy value chain – from generation to transmission and distribution to the end-users – the emphasis is exclusively on the new digital and advanced technology, the so called "layer of intelligence". The smart grid has been also conceptualized as the result of the integration of these new components into the existing grid. New digital components are, after all, not supposed to replace the existing system but rather to upgrade and complement it.Such a synthesis of technologies is not trivial, particularly in an infrastructure area. Therefore, the development of the smart grid is likely to become a process in the course of which old and new components are gradually connected, making adjustments on both sides to achieve compatibility. An alternative to the development of the smart grid is the above briefly mentioned super grid concept (page 3), which is defined as:

> an electricity transmission system, mainly based on direct current, designed to facilitate large-scale sustainable power generation in remote areas for transmission to centres of consumption, one of whose fundamental attributes will be the enhancement of the market in electricity (Friends of the Supergrid, 2010).

While policy often claims that super grid – long distance transmission based solution – and smart grid – distribution based solution – have to evolve as complementary and mutually supporting technologies, Blarke and Jenkins (2013) find that the development of one might jeopardize the feasibility of the other. The authors argue that the super grid will rely on increasing capacity in transmission grids and partly transnational integration of existing national and regional grids. These measures are important, but not necessary contributing to building up an innovative new system. In fact, they claim that the development of the super grid that aims at targeting intermittency by higher capacity and long distance transmission, can threaten the development of innovative technologies at the distribution level – the smart grid.

2.3 Who are involved in the development of the smart grid?

The new actors entering the energy area in the course of the smart grid development are universities involved in R&D, entrepreneurial firms, car manufacturers that diversify into EV-development, and ICT companies that are likely to become the main driving force behind the development of the "layer of intelligence" (Erlinghagen and Markard, 2012). The evolving smart grid is envisioned as a combined network of old and new technologies. The transmission system operators (TSO) and utilities together with the energy producing companies and hardware suppliers can be seen as the established actors that are in charge of the current grid. These actors are facing a trade-off situation. They will have to get involved in the transformation, but they might at the same time be challenged by the new technology. The smart grid is necessary to cope with the different recent developments. Yet, the changes in the network architecture might undermine the incumbents' investments, competences, and business models. One issue is the acceptance of the new technology, both on the side of energy producers but also with consumers. Wolsink (2012) asserts that the assumption that operators of distributed energy production plants will automatically join smart grids, might be too broad. The paper also emphasizes that institutional adaptations, particularly to overcome existing hierarchies[6], are necessary to be made in parallel to the technological decentralization. Corresponding to the required but yet limited acceptance by the end-users, there are also consequences for utility companies. The deployment of the smart grid will help alleviating several of their problems that have emerged in the energy grids. But the participation of new players and the new design of the grid might be challenging for the established business models of the utilities (Shomali and Pinkse, 2015). The uncertainty about new revenue streams in the new system, for instance, exploiting big-data analysis of consumer behaviour, and existing sunk costs into infrastructure are reasons for incumbent firms to approach the smart grid with less enthusiasm (Poudineh and Jamasb, 2014). Another finding by Erlinghagen and Markard (2012) is that incumbent players from the energy sector are reacting by acquiring ICT start-ups. This can be a sign for their

[6]especially the power hierarchies between actors including the dominance of utilities in the system

attempt to expand their competences in areas that haven't been part of their business so far. This can however be also a strategy to prevent competence disrupting innovations (Tushman and Anderson, 1986). Energy networks across territorial areas (e.g. countries) are differently grown structures. Energy sources, the level of decentralization of these, end-users, and many other factors vary and therefore it is likely that the evolving smart grids will be adapted to the particular structures (Verbong et al., 2013). Efficient national and regional adaptations, as well as policies to support and guide these processes are therefore of crucial importance. The role of the state as regulator, investor in, and organiser of R&D is addressed in Ngar-yin Mah et al. (2012) and Mah et al. (2013) for the cases of Korea and Japan. Both papers emphasize the importance of interaction between the state, private companies, and end-users to make progress. Lo Schiavo et al. (2013) explored three emerging areas – smart grid, smart metering, and e-mobility in Italy – concluding that regulation is essential for innovation and diffusion of these technologies. The authors also find that regulation should be harmonized, for such systemic technologies that show strong overlaps and potential for synergies in deployment.

2.4 The Danish case

Denmark is known for the large scale integration of wind power which it has pioneered – without yet having a smart grid in place. The notion of a smart grid entered the Danish public discussion increasingly starting 2009. The point in time when this awareness rose seems related to the percentage of intermittent energy in the grid. The Danish grid in its configuration at that time was able to handle on average around 20% of intermittent renewables utilizing, for instance, fast responding gas plants to balance peak load and established transmission procedures for trading with neighbouring countries.[7] Figure 1 displays the development of renewable energy sources in the Danish

[7] This number is an estimate suggested by colleagues at the Energy Engineering Department. So-called intermittent energy penetration studies for that period could not be found in the literature. For the year 2002 Ackermann (2005) suggest that on average a share of 17% windpower – which is the main source of intermittency – was handled by the Danish grid.

energy mix.[8] That increased awareness of the the intermittency challenge and the related discussion about how to address it emerged around 2009 becomes understandable, against the backdrop of the strong expansion of intermittent electricity sources in the following years that has been planned and anticipated. Most prominently one can point to the jump of the wind power share from 20 to over 30% in the few years after 2010 and the forecast of 50% by 2020.

Another important historical development dates back to the oil crisis in the 1970s. At that time Denmark's energy supply relied almost entirely on the import of fossil fuels and the country virtually did not have an energy policy. The crisis triggered its development since 1976. One consequence was the construction of the district heating system, which today supplies over 63% of Danish households with heat from efficient large scale boilers, but also capturing and redistributing surplus heat from industrial processes. The Natural Gas Supply Act, 1979 laid the foundation for the construction of a natural gas network.

A significant role in this process is played by a dense network of differently scaled efficient CHPs that have been built up in Denmark since the 80s. Producing electricity and heat from primarily indigenous fuels (natural gas, waste, biomass and biogas) simultaneously, these plants represent widely distributed functional links between the electricity, district heat, and gas systems.

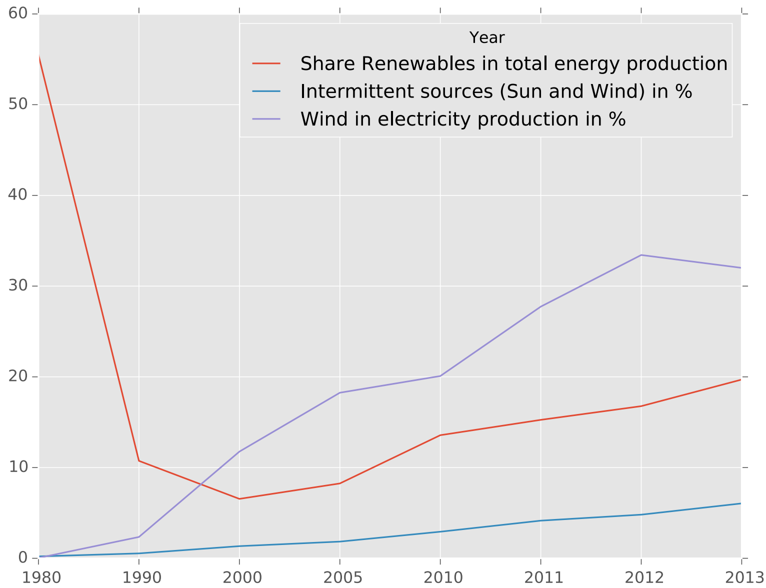
In the case of Denmark the initial context is thus different from the general description. The tight interconnectedness of energy grids is unique and provides a very specific environment for the development of the national smart grid. Given this configuration that already today allows for an intensive interaction between the electricity and the heating grids, restraining the analysis of the evolving smart grid to the electricity networks, as suggested by the technology classification above, might be too restrictive.

Other arguments for why the Danish setting is interesting to explore can be found in the proactive smart grid strategy within policy and companies.

The current energy agreement of the Danish government has been made in March 2012 and presents under the heading "Accelerating Green Energy

[8] A more detailed overview and breakdown of different energy carriers in the production mix can be found in Table 2 in the appendix.

Fig. 1: Renewable energy sources in the Danish energy mix over time (Danish Energy Agency, 2014)



Towards 2020" a multidimensional package of targets and active policy measures.

The four stated main goals for 2020 are: (i) to have more than 35% renewable energy sources in final energy consumption, (ii) to supply more than 50% of the consumed electricity by wind power, (iii) a 7.6% gross energy consumption reduction in relation to 2010, and (iv) a 34% reduction of greenhouse gas emissions in comparison to 1990.

Broadly, the listed policy measures related to smart grid development can be summarized into four interrelated fields of action:

- Incentive creation
- Setting of standards and requirements
- Initiation and support of collaboration at various levels
- Legitimation through information, agenda setting, and lobbying

Among other measures, the "Smart Grid Strategy" – established based on the 2012 energy agreement – lists the roll-out of remotely-read smart meters to be installed at all consumers between 2016 and 2020 (KEMIN, 2013). Prior to that, already in 2013-14, such meters have been installed at 50 percent of the electricity customers that account for 75 percent of the consumption. Further, the required data processing infrastructure that allows settlement of hourly variable electricity prices, as compared to the traditional fixed-price settlement, has been established.

The "Smart Grid Strategy" sees the country as a European laboratory for innovative energy solutions (KEMIN, 2013). This goal was once again highlighted with the launch of 27 new publicly co-founded research projects in 2012, further 15 in 2013, 21 in 2014, 17 in 2015, and already 2 registered projects as of February 2016.

The 2013 edition of the European Commission's report "Smart Grid projects in Europe" (Giordano et al., 2013) outlines Denmark's strong leading position within smart energy research, development and demonstration. Among all European countries Denmark has the highest involvement in R&D projects in terms of demonstration and deployment and the highest research investment per capita and consumed KWh. A third of all national smart energy projects in Europe are conducted in Denmark. Furthermore, Denmark participates in 30 percent of all multinational smart grid projects in Europe. Together with Germany, Denmark is the leading country with projects focusing on consumer engagement.

The imperative to upgrade the grid is more urgent in Denmark than many other places, given the already high share of renewable energy sources in the system as of today. This together with the national support of smart grid technology development make the Danish case promising to study this emerging technological field.

The development of the smart grid is an attempt to radically transform the functionality of a large established system – the power grid – by combining it with various new technological components. This process will naturally lead to tensions between *the established* and *the new* at different levels. The hope of proponents of the concept is that the overall efficiency of the energy system can be raised, allowing for more renewable energy sources, without the need to radically change the established infrastructure. Seen in the light of the sustainability discussion, studying this ongoing transformation is not only important to inform similar developments in other countries but can also provide valuable insights for the overdue sustainability transformations of other systems (e.g. transportation or agri-food).

From an empirical perspective, the present thesis contributes to understanding selected aspects of this process in the Danish context, focusing particularly on the tensions between *the old* and *the new*.

3 The conceptual setting: A transforming large technical system

The power grid can be conceptualized as a *Large Technical System* (LTS) (Hughes, 1987). The concept is mainly rooted in the tradition of sociology of technology. Such a system includes physical artefacts such as hardware components for the transmission and distribution of electricity. In addition, it contains organisations such as manufacturing firms or utility companies. All these elements interact with each other following formal, normative, and cognitive rules. Since energy grids are physically connected to energy producers on the one side and users on the other, the aforementioned components also interact with artefacts and agents external to the system.

The development of the smart grid is associated with the introduction of new physical components, new organisations, and new rules to the established system. A key attribute of LTSs is the high level of *interdependencies* between components, which is among the reasons that make change within LTSs so challenging. The introduction of new components in order to change the overall functionality of an LTS requires adjustments in various parts of the system such as for instance the development of new technical standards. Work from scholars associated with this tradition mainly relies on detailed ethnographic studies of the complex multidimensional set-up around technological systems, and sheds light on the variety of factors that influence and shape its development (Bijker, 1997; Bijker et al., 1987; Hughes, 1987). While the argumentation proposed by this literature is relatively easy to grasp, multidimensionality, the high number of diverse actors and feedback loops make the concepts hard to operationalise. Given this set-up paired with the non-linear nature of innovation processes (Nelson and Winter, 1982), the transformation of such a system is expectedly complex and also difficult to explore. Taking the present case: not only that an infrastructure system has to be transformed, but the aim is to make the system sustainable. In the absence of policy intervention, this type of innovation – *sustainable*, *eco*, *green*, and *environmental* [9] – is regarded as particularly challenging, due to weak (economic) incentives for both, producers and consumers (Rennings, 2000). Even though renewable energy sources have become price-wise competitive over the recent years, in the particular case there is no obvious gain for utilities within their current business models (Shomali and Pinkse, 2015). Yet, ability to upgrade the energy grid is key for being able to integrate more renewable energy sources and thus address the environmental sustainability challenge. On a more conceptual level the thesis thus contributes to understanding how LTSs can change, becoming more sustainable.

A large share of recent research that studies similar system innovation processes (e.g. the emergence of electric vehicles, renewable energy sys-

[9] Although often used synonymously, the terms are associated with different research strands and issues (Franceschini et al., 2015).

tems, changes within the agriculture system) draws either on the Technological Innovation System framework (TIS) (Bergek et al., 2008b; Carlsson and Stankiewicz, 1991; Hekkert et al., 2007) or the Multi Level Perspective (MLP) (Geels, 2002, 2004). Both traditions have made a considerable contribution to the understanding of how technological systems develop and co-evolve with the surrounding socio-economic systems.

3.1 Socio-technical transitions and the Multi Level Perspective

The MLP has been suggested as a framework to understand socio-technical transitions during which – in the standard case – one technology replaces another established one. The framework operates with three analytical structures or levels: (i) the landscape on the macro level, (ii) the socio-technical regime on the meso, and (iii) niches on the micro-meso level. The landscape is conceptualized as the overarching layer, external to the emerging technology and the established system but responsible for the general context and conditions that it is facing. These can be for instance global fluctuations of resource and energy prices or the political attitude towards the focal technology. They can be shaped by recent events such as industry accidents in the established energy system or natural disasters linked to its consequences. The *regime* level is constitutet by a set of (1) routines and institutions together with (2) a network of actors and (3) a set of materials and artefacts (Geels, 2004). With regard to its composition and the tendency to resist systemic change the regime level is similar to the concept of the LTS as defined by Hughes (1987). Niches are located at the lowest level of the model but are central as the spaces which drive change in the overall system. In terms of texture, they are similar to the regime, but all components are less well defined and subject to change. The level of alignment between contained elements is considerably lower in niches as compared to the regime. Favourable landscape conditions and the stronger alignment help the regime generating momentum and power and thus maintaining stability and path dependency. Change is the result of interaction between the three levels and several transition *pathways* have been outlined (Geels and Schot, 2007). In the most "simple" case a novel technology is developed within the protected niche and, once it has gained momentum, it penetrates the established regime, almost instantly replacing the incumbent technology. Another, less abrupt scenario is the gradual hybridization of new niche and established regime technology (Raven, 2007). This happens when the new technologies are not radically different from the existing ones and build on top rather than replacing them. The MLP is very conscious of the context in which new technology is developed. The regime is not an exogenous context with favouring and blocking mechanisms, but a path dependant, stable structure. This stability is the usual point of departure in MLP based analyses.

3.2 The Technological Innovation System

The TIS framework focuses on the functioning of the innovation system around a specified emergent or established technology or technological field (Bergek et al., 2008b; Carlsson and Stankiewicz, 1991; Hekkert et al., 2007). As most other types of innovation systems, the TIS consists of actors, networks, and institutions. Technology is not considered to be an element of the system but rather the output. Generally, the TIS is not limited by territorial borders. However, geography is often an important component in TIS based analyses, as they tend to coincide with national borders (Coenen et al., 2012). The framework became widely used in academic articles and as a tool among policy-makers after the delineation of the TIS functions and the publication of an analytical framework that builds on the evaluation of these functions (Bergek et al., 2008a). Structural differences make it, by and large, difficult to undertake comparisons across innovation systems. With a clearly defined set of essential activities or functions, within the TIS tradition, it became much easier to assess the performance, identify deficient areas, blocking mechanisms, and suggest intervention measures. Markard and Truffer (2008) went on to suggest a combination of the two conceptual strands – bringing together the TIS and MLP traditions –, arguing that such a merger would contribute to cross-fertilization and eventually generate a synthesis with a more holistic perspective. Particularly they were emphasizing the well operationalisable elements of the TIS and the context awareness of the MLP. In the aftermath their article in Research Policy received a high number of citations but there are hardly any studies that explicitly build upon an integrated framework. A recent article by the core authors of the TIS tradition picked up the theme of the context but rather than following up on the synthesis proposal by Markard and Truffer (2008), they argued for a better conceptualization of context interaction within the TIS framework (Bergek et al., 2015):

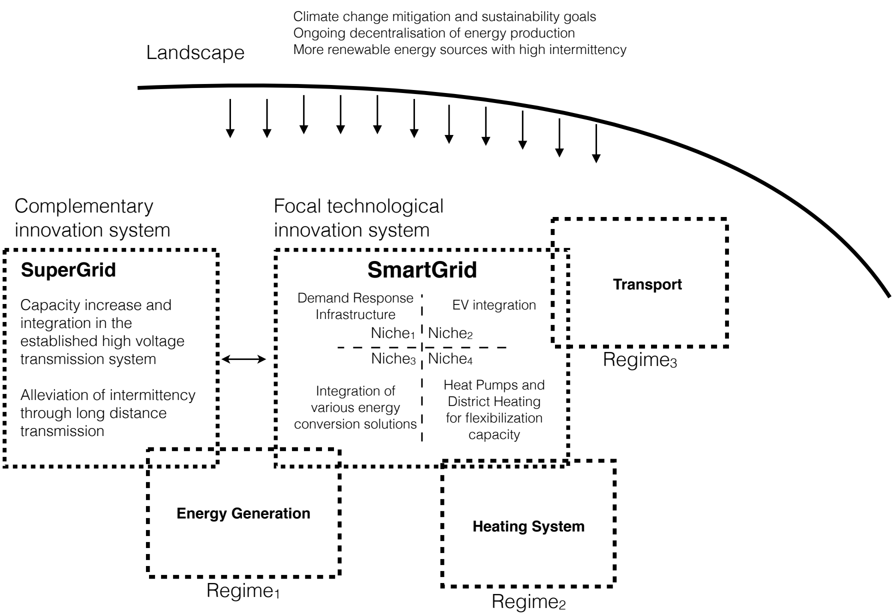
> Structures and processes inside a focal TIS are generally well conceptualized in the literature. [...] what happens outside and across the system boundary has been less systematically worked out.

The interest of the article lies in identifying different types of context structures, specifically what the authors call *structural couplings*, overlapping and shared elements (e.g. physical structures, actors, and networks) between the TIS and other structures that influence its development. These couplings can manifest between the focal TIS and other (complementing/competing) TISs, the pre existing infrastructure and institutions, and system-level assets provision systems as for instance the political, educational or finance system.

In the case that is explored in this thesis a *smart grid TIS* – once analytically constructed – would span across several sectors and come in contact with different established *regimes* as they are conceptualized within the MLP tradition. Furthermore, many of the smart grid components are not developed to replace the existing infrastructure but to upgrade it building on top of the established network. Overall, there might be a transition happening in the area of energy generation and also from the perspective of the functionality of the energy networks, but in terms of the grid structure, the change will more likely resemble a gradual transformation and integration process. In the TIS tradition – as mentioned above – the technology itself is not part of the system but rather an output. Yet, the technical complexity of the explored system, and the interdependence of components, ask for a thorough exploration at the technological level. Already the uncertainty about the proper delineation of the system in the focal context provides enough reasons to do so.

Figure 2 summarises the overall framework, which aims at combining the TIS framework with a stronger focus on the technological (and actor) complexity of the focal system. Also, it highlights the importance of interaction with the surrounding context. The scheme shows the *smart grid TIS* with various niches or sub-systems in the centre surrounded by several connecting established systems (e.g. energy production, heating, transport). Other – perhaps more remote yet adjacent – systems such as for instance construction or manufacturing could have been included. The supergrid is conceptualized as a complementary system, yet with an ambivalent relation to the smart grid. While it can help to address some of the challenges that the energy system is facing in its way, investments into the development of the *supergrid* can drain resources from smart grid development (Blarke and Jenkins, 2013). The landscape, overarching the picture, generates the pressure for change. It summarises various factors, exogenous to the focal system, that demand its adaptation. In the present case these is a technical need to adjust the grid in a way that it allows to integrate more decentralised and renewable power sources. On a non-technical higher level the driving objective is to mitigate climate change, pollution, and resource depletion through a more sustainable energy system.

Fig. 2: Framework (adapted from (Markard and Truffer, 2008))



3.3 Conceptual focus points

The present thesis is a compilation of articles that have addressed specific aspects, within the above depicted framework. The emphasis on the transformation process and the emerging tension between new and old elements led to a more thorough exploration of two aspects: The delineation of the system and the actor interaction.

System delineation and technology interaction

As outlined in the recent work by (Bergek et al., 2015), particularly in the TIS tradition the context of focal emerging systems has remained under-theorised. While the TIS literature, building upon ideas from evolutionary economics, heavily emphasizes the importance of context and technological-multidimensionality, most of the sector case studies tend to explore a relatively limited and *ex ante* defined set of technologies. Such an approach leaves not much space for the inherent uncertainty in emerging technologies and might be particularly problematic when analysing transitions in large infrastructure-related systems.

This might (not necessarily but often) also lead to an understanding of the change processes, which does not account for architectural or modular innovation, i.e. restructuring of existing systems to meet emerging needs or the re-purposing of established components (Henderson and Clark, 1990). The delineation of the technology-focus and the system as such, has been identified as a methodological issue by Carlsson et al. (2002), far ahead of the rapid growth of system innovation studies. Yet, only very few studies have explicitly developed approaches to address this problem utilizing the variety of data sources and methods that have emerged since the publication of Carlsson et al. (2002). A sub-question (SQ1) that emerged in the course of the research project behind this thesis is:

> How can an emerging systemic and context dependent technology – such as the smart grid – be delineated?

Delineating the technology is not only important in order to understand its scope but also to identify the different couplings and overlaps with adjacent systems (Bergek et al., 2015). This technology-focused delineation builds also the foundation for further identification of involved actors, networks, institutions, and the functional dimension.

Chapter B and E approach this challenge, proposing novel methodology compositions.[10] In chapter B a new explorative methodology is developed, which can be used for the detection of dominant technological fields or trajectories in a relatively loosely defined socio-technical context. Combining elements from natural language processing and network analysis, a number of socio-technical fields can be identified, proving the method as a promising novel approach for pre-processing unstructured text data and inform more detailed analysis. The results from this chapter have, for instance, influenced the data collection for the survey that constitutes the empirical foundation of chapter C – the part of the thesis that aims at understanding the evolving Danish smart grid system and the functioning of the related TIS on an aggregated level. Chapter E builds upon this method proposing a computational process, which can map the development of any complex topic, and particularly identify the dynamics of sub-themes from unstructured language data. An important feature of the method is the data-generation, which in itself is a semi-supervised process based on social interaction of identified "expert" Twitter users. While chapter E mainly focuses on the technology dimension, the process also retrieves other "entities"[11] form the text-data, such as locations, organisations, firms and even persons.

Actor interaction: The role of established players

Another issue with (particularly more recent quantitative) research linking to the TIS tradition, is – to some degree – a lack of awareness of actor ambivalence and critical assessment of actor interaction characteristics. Identifying *inducement and blocking* elements is an important stage, suggested by the TIS analysis scheme as proposed by Bergek et al. (2008b). Yet, many studies, while doing an excellent job at mapping the structure of the system and describing its functions, pay less attention to potential blocking mechanisms originating from vested interests of certain actors. An important focus point

[10] See Table 1 for a schematic overview of the thesis chapters.

[11] The term *entity* – not to be confused with actors – originates from natural language processing and describes any kind of objects belonging to a specified class that are identified as such within unstructured text data by a machine learning algorithm.

of the thesis lies therefore in the exploration of the interaction between the new actors within the system and the established ones.

This issue can be seen from three angles. First, the question of niche protection and curation (Smith et al., 2005), second, the incumbent actors' strategies (Bergek et al., 2013; Smink et al., 2013; Tushman and Anderson, 1986) and third, the system interoperability, or put more generally technological inter-relation. Chapter D studies the behaviour of different actors that are involved in the development of the smart grid, starting with the concept of the technological niche as an artificially created and protected space from the competitive and selective forces of the free market. Departing from the question about the "appropriate" level of niche-protection, the chapter uses data on all publicly co-financed R&D projects related the smart grid technology in Denmark. A dynamic network analysis shows that, in fact, large incumbent companies, over time become increasingly dominant in the network of actors that develop the smart grid.

4 Exploring an transforming technical system – A methodological challenge

There are several methodological challenges associated with the analysis of a technological system's transformation. These can be broadly summarised under the following three headings: the novelty of the technology; the heterogeneity of artefacts, their (re)combinations, and actors; the adaptation of the technology to the territory-specific systemic context.

A variety of methodological approaches has been developed to study *emerging technologies* (see Rotolo et al., 2015, for an overview)[12]. The more established techniques are based on patent and publication data with their respective citation structures (Ernst, 1997, 2003). The advantage of using this

[12]Here an emerging technology is defined as *a radically novel and relatively fast growing technology characterised by a certain degree of coherence persisting over time and with the potential to exert a considerable impact on the socio-economic domain(s) which is observed in terms of the composition of actors, institutions and patterns of interactions among those, along with the associated knowledge production processes. Its most prominent impact, however, lies in the future and so in the emergence phase is still somewhat uncertain and ambiguous.*

data lies in the explicit technical character of the data, established classifications, and its comprehensiveness. Based on the seminal work of Dosi (1982) on technological paradigms and trajectories and adapting a methodology suggested by Hummon and Dereian (1989), Verspagen (2007) modelled and analysed the "flow of knowledge" using a patent collection in the field of fuel cells. Patent citation networks were used to study knowledge diffusion (Ho et al., 2014) and small world phenomena (Guan and Shi, 2012). Erdi et al. (2013) constructed dynamic patent citation networks to predict emerging technology clusters. The drawback, given the present research question, is that it is hard to reach an overlay between the global presence of knowledge in a certain domain and the development and diffusion of a technology in a specific territorial space. Compared to the analysis of *emerging technologies*, the exploration of transforming technical systems is broader and has to consider both, the established and the evolving components.

The concept of the smart grid comes with a built in heterogeneity, as it means a set of different technologies. Yet, from a socio-economic and political perspective it is a single term. That manifests itself in, for instance, an explicit "smart grid policy" of the Danish Government (KEMIN, 2013). The first problem to tackle is therefore to delineate the technological scope of the system in the particular context.

The NIST[13] classification specifies a number of new technologies that are supposed to comprise the smart grid and there exist studies that rely on such classifications and patent data to compare the development of the technology across countries (e.g. Chen et al., 2012). But how much can be said about the transformation of a systemic infrastructure technology that is highly dependent on the national context from identifying patent emergence within a technology area that will supposedly constitute the "layer of intelligence"? Suppliers of energy technology are often large multinational companies e.g. Siemens or ABB. The same is true for the software developers. The fact that a technology is developed and patented in a country does not imply that it is used there. And analogously, a technology can be utilized in a country without having been developed there. For example, the "maglev" magnetic levitation train – today connecting the central Shanghai with the international

[13]National Institute of Standards and Technology of the US

airport – was developed but never built in Germany.

One criterion for the utilised data is therefore *spatial specificity* that can reflect the development of the technologies (within the transforming system) in the national context.

Recombination of technology and gradual innovation lead to another challenge. As shown in Chapters B and E, the recombination and integration of technological elements is an important source of innovation for the smart grid. Often new elements are integrated with existing artefacts, or general components specified and enhanced through software elements. This type of technological change is very unlikely to be reflected in patent data.

As demonstrated by Erlinghagen and Markard (2012) but also argued by Shomali and Pinkse (2015), new actors from sectors, that earlier haven't been associated with energy, are becoming part of the grid development. This makes the use of register data that relies on established NACE classifications challenging in order to map and analyse the involved actors.

Thus, the data and methods have to be able to identify which, how, and with which outcome elements – technologies or actors – get involved in the transformation process. The interaction between the new and the old becomes an identifier but also the object of exploration.

This thesis seeks to emphasise interaction on different levels within the analysis. Much of the utilised data and technique come therefore from the field of network analysis. This approach helps to overcome some of the above outlined problems and adds further dimensions of insight to the analysis.

Graph-based methods are combined in several chapters with techniques from natural language processing (NLP). Using text as a data source is becoming increasingly popular in the analysis of emerging technologies (Rotolo et al., 2015) and addresses some of the above presented challenges.

The remainder of this section will provide further detailed justification for the choice of graph related approaches and NLP techniques. Also the specific data sources and methods applied are presented.

4.1 Usage of relational data and networks

The notion of *networks* has been central in the broader field of innovation studies from the very beginning. Within the innovation systems discussion – as later highlighted in chapter A – interaction between different actors such as firms, users, and universities are expected to lead to new recombination of knowledge and innovation. Already the definition of a system implies the presence of actors and links between them (Edquist, 1997). To build strong and dense networks between various actors in order to spur innovation has been consequently a policy recommendation issued by studies standing in this tradition. Increased interaction on different levels is similarly at the centre of studies that prefer to conceptualise clusters without prominently referring to innovation. The framework of the technological innovation system, which this thesis and in particularly chapter C adopt, names networks as one of the three core element types of the system[14], next to actors and institutions. This emphasis on the notion stands in contrast to a rather limited amount of research that has explored the emergence and change of networks directly. The absence of appropriate data for a long time and the fact that sophisticated methods (and tools) for network analysis have been made available relatively recently, may serve as an explanation. The recent five years have seen a noticeable increase in networks research in general and within the innovation studies community. This can be for instance seen in the growing number of related sessions in the research field's central conferences such as DRUID and ISS.[15] Networks are the formal language for representing complex systems and have been used in all chapters of the present thesis. Network analysis allows to draw conclusions about the overall system or certain parts of it. For instance, can community detection help to identify dense sub-structures within a system that has been considered to be homogeneous. Exploring the development of networks beyond the comparison of snapshots of the same network has become possible through recent developments of evolutionary network analysis techniques. The methodology – based on Stochastic Actor-Oriented Models (SAOM) (Snijders, 1996) – helps to understand why systems

[14] Note that technology is not an element of the system but considered the outcome of the system dynamics.

[15] DRUID - Danish Research Unit for Industrial Dynamics; ISS - International Joseph A. Schumpeter Society

evolve as they do and whether certain observable actor attributes determine the development of the system. Chapter D uses this methodology to investigate the development of incumbent players' dominance in smart grid related research projects. Using relational data is also a promising approach in the case of data scarcity or unreliable/undeveloped classifications. Data describing the relations between nodes in the network can be used to infer latent attributes of the nodes. Studies with data from social networks (e.g. Facebook and Twitter) have shown that both "likes" and friendship relations are extremely accurate in revealing characteristics of persons such as religion, political positions, and even sexual orientation (Abbasi et al., 2014; Kosinski et al., 2013). While in the latter case this is due to isomorphy among friends, behaviour such *liking* of, for instance, movies and online sites can be modelled as a bipartite graph and once projected onto the actor mode reveal a similarity-structure between all actors in the network. This property is used in the analyses in chapters A and C. In the former chapter the latent similarity of publications inferred from citation patterns is used to identify relevant discussions and guide the literature review, which the chapter represents. The latter chapter aims at detecting groups of actors, mostly companies, in the broader smart grid field that are similar in terms of technological activities. Here the graph representation is used to draw conclusions about the composition and segmentation of the technological innovation system and the relatedness of the different involved technologies. Chapters B and E also use network representations in their analyses. The graphs model here semantic features of processed natural language and provide a structured map of different discourses. Chapter E also contains another application of network analysis: centrality measures applied to a large twitter "followship network" are used to identify online "experts" on the social network.

4.2 Utilising text data and natural language processing

While patents are a well structured and reliable source of information about theoretically available technology and its development, they do not reflect the application of the technology in a systemic set-up. The main drawback of such invention-focused approaches is their inability to account for many mainly non-technical factors related to the social and institutional framing of technology in a certain space. Value driven policies, technological and institutional path dependencies, or user expectations and routines have major impact on the technological outcomes in a particular context.

Given an appropriate corpus (a collection of text documents) about a technology in such a context, these non-technical influences can be inferred from the emerging discourse, associated with the object of analysis. Technology development can be understood through the numerous texts commenting on it. As trivial as that sounds, it has been not until relatively recently that researchers – especially outside computer science and linguistics departments – have commenced to utilise language data in a more quantitative manner. Especially with the development of IT giants such as Google or Facebook and associated research facilities, methods for the preparation and analysis of relational and unstructured data (e.g. text, imagery, sound) have leaped forward. Two of the chapters of this thesis (B and E) have relied on language data to map technological development. Techniques from language processing and network analysis were combined to detect patterns within large amounts of text documents. These patterns help in identifying boundaries of the explored topics, contained technologies (or as in the case of chapter E dynamic technological trajectories), and the relation of these elements to each other.

4.3 Data used across the chapters of the thesis

The finally used data are: (1) An early 2014 survey with 178 companies operating in the energy sector, (2) Data on the configuration of approximately 100 R&D projects that are attributed to the smart grid development by the Danish Energy Agency and have been funded under respective schemes, (3) The descriptions of the same projects, (4) approximately 500 industrial publications mentioning the smart grid in a national context.

Chapter E that further develops the language processing method – presented in chapter B – uses a different empirical example. It combines data gathered from the micro-blogging platform Twitter with unstructured text data (1,398 documents) that is automatically collected across the internet.

Survey Data: The survey data was collected in collaboration with the Copenhagen Cleantech Cluster (CCC) in the initial months of 2014. It has been sent out to the members of the largest Danish energy related industry organisations including the Confederation of Danish Industry (DI), the Danish Board of District Heating (DBDH), and the Lean Energy Cluster. The 15 question of the survey covered basic company characteristics that were complemented by company register data, technological specialization & competences, innovation & barriers, revenue & exports stemming from *smart energy technologies*, and collaboration patterns including a detailed collaboration partner mapping. 178 companies and organisations responded to the survey[16]. The *smart energy* field is arguably broader than the smart grid area in the traditional understanding. Yet, given the very detailed technology positioning questions and the collaboration mapping – the data provides a good opportunity to explore the smart grid actors.

R&D Project Networks: As source for public funded research projects chapter D utilizes the database provided by `Energiforskning.dk`. The joint database of publicly (co-) funded energy research in Denmark contains detailed information on nearly 2100 projects, classified into 7 broad technology areas. It represents the most comprehensive source for public funded energy research in Denmark, covering projects funded by the *Strategic Research Council, ForskEL, ForskNG, ForskVE, ELFORSK, Green Labs DK, Danish High Technology Foundation* and the *European Union*. For the current analysis records from the "smart grid and systems" category were exported containing information on projects from 2009 to 2012 on yearly basis, overall 75 projects with 277 participants, and 132 single firms. This classification is interesting as such, since it indirectly grounds on the (partly political) decision to fund a particular activity under a certain notion or not. Thus, it can be assumed that this *pre-classified* data implicitly carries information about the technology perception by the public sector. Among those actors we identify 27 incumbent firms, 21 research institutions with the rest being either established diversifier companies or new entrants[17].

[16]Due to the design of the survey, a response rate cannot be provided. The survey and sample are discussed more in detail in Chapter C on page 148.

[17]A detailed description of the applied classification methodology is described in chapter D

R&D Project Descriptions: Initially 102 project descriptions were obtained through `www.energiforskning.dk`. The descriptions were usually 500 words long and briefly outlined the background and purpose of the project, technologies used and, expected outcomes. Project start dates range from 1996 until 2013; however, the distribution is highly skewed towards the latest 5 years. The projects span from basic research to deployment activities which is explicitly indicated in meta-data available for each activity but also can be inferred from the finance mechanism applied.

Smart Grid – Industrial Publications: In order to map out the scope of *smart grid* applications in a national context, 574 non-academic industrial publications have been explored. These were retrieved from the Danish national publications database *infomedia*. A search-string was systematically built up by exploring term frequencies, n-grams, and collocations within the press releases by the Danish Smart Energy Alliance which, since it's initiation in April 2012, informs about the national *smart grid* industry.

The coverage of *smart grid* related themes remains marginal until 2009. The majority of articles before 2009 are published by the engineering journal *Ingenøren*. Only starting in 2009, more practically oriented periodicals take up the topic, indicating the upcoming interest for the *smart grid* outside the engineering community. Overall, articles come from 61 different periodicals largely affiliated with engineering and construction themes. However, 81 percent of the publications relate to 12 journals focusing on the national energy system, appliance installation, computer – and information science, the business part of the engineering, and energy industry. Simple NLP filters (length, language, mentions of Denmark or Danish context rather than reporting about development abroad) have been applied and reduced the number of documents to the final number of 574

5 Contributions of the thesis

Together with this introduction the chapters of the thesis can be subdivided into 3 parts. The introduction and Chapter A constitute the overall conceptual basis. All of the empirical chapters have – as one would expect – their respective specific theory sections. Chapter B and C take a system-wide view on the subject matter. The scope of Chapter D and E is focused on more narrow conceptual aspects. The former aims at exploring actor behaviour within technological niches, while the latter – looking at a different technology than smart grid – proposes a more general computational method for understanding technological evolution.

Table 1: Overview: Chapters of the thesis, aim of the analysis, and contribution

Chapter	Analysis Type	Contribution
	Conceptual part	
Intro	–	–
A	Bibliometric analysis	Conceptutal, Bibliometric method
	Studies with a system-wide perspective	
B	NLP-based mapping of the technical field	Method, Delineation of technological systems
C	TIS analysis of the Danish smart grid	Subject matter: In depth analysis of the focal case
	Focused studies of narrow conceptual aspects	
D	Actor strategies in smart grid R&D: Network evolution analysis	Conceptual, Operationalisation using novel approach
E	Technological trajectory identification using unstructured data and machine learning techniques	Mostly methodological

5.1 Chapter summaries

Chapter A: Conceptualizing and Analysing Evolving Technical Systems – A bibliometric review

This chapter reviews the different strands of conceptual literature that take a systems view on technological change and selected empirical studies that have relied on the respective frameworks. It combines a quantitative bibliometric approach with a traditional reading of the literature. The bibliometric analysis is based on over 7000 records obtained through the Web of Science database. The constructed network of publications is defined by a bibliometric coupling measure that has been proposed in an earlier article by the author (Jurowetzki et al., 2015). It is then segmented using a novel hierarchical clustering approach. The aim of this exercise is to identify relevant conceptual elements that can be helpful to explore the empirical setting. The technological innovation system and the transition literature appear to be two well suited conceptual frameworks, due to their comprehensive perspective and the fact that they are both incorporating elements from several strands of literature within the broader field of innovation studies. While being similar in terms of empirical settings, which scholars explore using the frameworks, the mapping suggests that they have different origins and have initially been developed to address slightly different objectives. This finding questions, to which extent a combination of both frameworks as suggested by Markard and Truffer (2008) is useful. The idea of introducing more context-awareness, elements from the evolutionary tradition, and complexity-thinking into the well operationalised TIS framework is promising and taken up by this thesis. However, a more extensive integration may compromise the practical value of the framework, rendering it challenging to utilise.

The analysis in this chapter highlights several conceptual elements that are later taken up and explored in detail in other chapters of the thesis – also as possible extensions for the technological innovation system approach.

Chapter B: Unpacking Big Systems – Natural Language Processing Meets Network Analysis: A Study of Smart Grid Development in Denmark

In this chapter a new explorative methodology is developed, which can be used for the detection of dominant technological fields or trajectories in a relatively loosely defined socio-technical context. The chapter thus mainly addresses **SQ1** and the *system-delineation challenge*. When studying the development of new technologies, one problem is often the lack of a clear delineation of the technology. While there might be an overarching term such as the *smart grid*, in fact it is not given that it is known which components and functions are part of such a system and which not. Technological trajectories are path dependent, sometimes compatible, often competing and it is therefore appropriate to expect local (spatial) variation in the technical composition of such as system as the (extended) electricity grid.

Accounting for this fact, the proposed methodology uses unstructured text to identify potential technological fields. The understanding of these areas is not merely technological but socio-economic, meaning that the analysis explores how the smart grid is understood by companies, policy makers, funding bodies, and the involved researches in a particular territory. The data used is one corpus with nearly 100 research project descriptions within the Danish *smart grid* research portfolio, and another corpus with 574 industrial publications that mention the *smart grid* as a concept. Combining elements from natural language processing and network analysis, a number of socio-technical fields can be identified, proving the method as a promising novel approach for pre-processing unstructured text data and inform more detailed analysis. Heat pump and district heating technologies seem to play a major role in the Danish smart grid research and the public discussion, which is an interesting finding, as it shows that pre-defined classifications of technology (which usually exclude these technologies) might not necessarily describe these heterogeneous technical systems well. With upcoming change in large systems, mature technologies can get a chance to receive new functions. Quite often these dynamics are not captured by analyses of technological change, which usually focus on new technological components. Algorithmic exploration of large unstructured collections of text can help the researcher to detect interesting patterns.

Chapter C: The Danish Smart Grid System – Components & Functional Dynamics

Chapter C provides a comprehensive analysis of the Danish smart grid technology development adapting the TIS approach, which particularly focusses on the functional elements of the innovation system. The contribution aims at addressing **SQ2**. Being the most recent contribution to this thesis the chapter draws on the findings from the preceding papers. The analysis includes a structural mapping of the central actors, institutions, networks, and technologies but also the functional exploration that is well established in the TIS literature. One of the important insights of this chapter is that a technology such as the smart grid is highly context dependent. Many of the smart grid elements and solutions under development in Denmark seem to be necessary or first possible because of the presence of other complementary technical structures that are absent in other countries. In fact, the extent of functional couplings between different energy technology networks is so high that it becomes essential to look at the emerging Danish smart grid not only as an upgrade of the electricity network but an evolving sub-system that is closely integrated into a developing intelligent energy system. While this is technically feasible, the analysis suggests that intensive institutional alignment is still necessary to support this development. The results also confirm findings and assumptions from chapter D: Some of the established players do in fact apply strategies against innovation that might threaten their technologies.

Chapter D: Incremental by Design? On the Role of Incumbents in Technology Niches – An Evolutionary Network Analysis

Chapter D studies the behaviour of different actors that are involved in the development of the smart grid, starting with the concept of the technological niche as an artificially created and protected space from the competitive and selective forces of the free market. Literature from the TIS tradition and to a higher degree the transition community argue that the established "regime" and its representatives are not likely to contribute to the development of technological solutions that could cannibalise existing structures in which they have ownership. Following this argumentation, niches – such as publicly co-financed research projects – should be protected from the influence of established companies. At the same time, the know-how of these actors, their connections and resources can contribute to the development of new technologies. This analysis targets **SQ3**. Departing from this discussion about the "appropriate" level of niche-protection, the chapter uses data on all publicly co-financed R&D projects related to the smart grid technology in Denmark. A dynamic network analysis shows that, in fact, large incumbent companies, over time become increasingly dominant in the networks of actors that develop the smart grid. On the one hand this can be explained by the infrastructure character of the electric grid, which might demand the involvement of incumbent actors, as they can assure the interoperationability of developed components. On the other hand, one question that comes up is related to the novelty of a technology, which is developed under close guidance of established actors belonging to the "old" regime.

Chapter E: Mapping the (R-)Evolution of Technological Fields – A Semantic Network Approach

The aim of chapter E is to develop a computational process and a method pipeline, which can map the development of any complex topic, and particularly identify the dynamics of sub-themes. It can be seen as a dynamic extension of the method proposed in chapter B and is linked to **SQ4**. An important feature of the method is the data-generation, which in itself is a semi-supervised process based on social interaction of Twitter users. It takes the combination of NLP and network analysis, developed in chapter B, further in a number of ways. First, the corpus generation - as said above - is exploiting the social graph structure of the microblogging service Twitter to identify experts that in their posts point to relevant text documents, which are automatically extracted. Second, rather than using a linguistic approach for term-identification within the documents, algorithmic entity extraction detects technology related concepts in the texts (also other entities such as companies, institutions, locations etc.). Third, overlapping communities are taken into account, by utilising a novel link-clustering approach. Lastly, the analysis is made dynamic, allowing to track persistence and change of identified communities over time. The corpus is split up in several semantic time-slice networks, which are not built up of documents but rather the contained technological terms. This construction generates the over-time node persistence, which is necessary to identify similar clusters in several mutually independent time-slice-networks. The example of "technological singularity" is used, as it has recently received much attention and because it is expected to contain many "sub-technologies" such as robotics, nanotechnology etc. While we can identify the increasing dominance (centrality) of single technological terms, the development of communities remains challenging due to a generic problem of false negatives within the field of artificial intelligence. Language variation, the use of synonyms, which is natural and important for normal human language generates sparsity. While "mobile phone" and "mobile" refers to the same concept and is easily interpreted by humans, computers are not able to make this connection right away. One solution to be tried out in future research could be to use static synonym-dictionaries to reduce linguistic diversity automatically. A perhaps more elegant solution might be the use of neural network based deep learning approaches such as the recently published Google's Word2Vec (2013) or the Stanford NLP Group's GloVe (2014) algorithms that operate with word vectors generated from a specified corpus, accounting for both semantic and syntactic properties of the language. Such word-vectors inherit features from the linguistic structure of the input texts that allow to identify terms, which are used in similar ways or belong to the same entity class without human interaction.

The chapter does not explicitly discuss the results obtained from the "singularity" example analysis. However, it is worth to mention that it showed a growing importance of "smartphones" as platform technologies that are connecting different add-on devises and allowing for increasing numbers of applications. The initial draft of the later published article contains an extensive discussion of this finding making connections to literatures on complex adaptive systems and modularisation.

The method pipeline offers great potentials for mapping the (implicit) interactions of companies, institutions, technologies and even persons that are easily identified using entity extraction (and often avoiding the false negative problem).

5.2 Combined contribution: Approaching system transformations

Three levels have to be considered when talking about the contribution of the thesis as a whole. The project started mostly with a socio-technical problem formulation, associated with a very concrete empirical case – the transformation of the Danish energy grid(s) and the emergence of the smart grid. On a conceptual level, the analysis of emerging systemic technology within established Large Technical Systems – or the transformation and evolution of the latter – calls for refinements of existing frameworks and stronger focus on aspects that were previously less pronounced. The novelty of the technologies involved, the emphasis on interdependence of the elements, and the wish to reflect the non-technological facets of technology development in the analysis contributed to a data and methodology challenge. Thus, the contributions of the thesis can be divided into (1) subject matter insights, (2) conceptual contributions, and (3) methodological contributions.

Understanding the development of the Danish smart grid and the adaptation of the energy system

The guiding research question of the thesis specified two dimensions of the smart grid development: The technological level and the actor dimension. The intention of the analysis was to shed light on the interplays between *new* and *old* in both dimensions and to infer how these determine the direction and outcomes in the focal technological system. Interaction between old and new elements is assumed departing from the basic definition of the smart grid as a layer of intelligent technology on top of the established power grid infrastructure. The question, which emerged consequently was: What is the smart grid in the Danish context?

The results from Chapter B indicate that when talking about the Danish energy grid transformation from a socio-technical point of view, the scope should be set differently from what the purely technical definition of the technology might suggest. In other words, many technologies outside the electricity-field can help to adapt the energy system and thus analysing the smart grid as an isolated sub-system may be too short-sighted. Given the set-up of established energy grids – including district heating and the gas grid – Denmark has the potential to develop a smart energy system. This development calls however for an even stronger interplay between the different technologies. To date, we see vibrant R&D efforts in the different areas each of which proposes potential solutions. Yet, combining the different areas even stronger from the beginning may generate better outcomes.

Chapter C maps the technological innovation system associated with the broader smart grid, evaluating the functional and institutional level. Also here the results point more towards an organisational and institutional challenge rather than a technical. The conclusions drawn at the actor level in this chapter fit well with the dynamic analysis of established research networks.

Incumbent players from the energy sector play a key role in the analysed process. While theory and the survey, used in chapter C indicate that these *old* actors are less likely to favour the emerging technology, the development of this infrastructure area cannot happen without involvement of incumbents. The growing dominance of these firms, as compared to new entrants and companies diversifying into this field, is identified in chapter D. This chapter contributes to the discussion on the architecture of publicly co-funded research – representing niches or protective spaces for experimentation – against the backdrop of evolutionary theory applied to technology development.

These insights are equally relevant for policy-making and academia. Considering the former realm, it is rather obvious that these insights are not entirely new for those areas of the policy machinery that are responsible for the shaping of the smart grid R&D. Yet, a more comprehensive understanding and treatment of the system has to be aimed at, for instance, with regard to energy tax regulations that are clearly designed without considering the energy grid system as a whole. The dynamics observed in Chapter D may trigger a discussion about the role of established companies in this particular and in similar transformation processes. The latter group, scholars working within the area of sustainable and energy innovation might get inspired by the ideas about the role of old technologies and interplay with new components. Most of the research in the area is focusing on *the new* but often neglects the technological contexts within which the new elements are introduced. Bergek et al. (2015) is a recent example that highlights the importance of this point. Future research aiming at understanding transformation of technological systems in the context of sustainability should intend further integration of such relational views and ideas from complexity theory into the analysis.

Contributions to understanding of LTSs transformation

Most of the chapters of this thesis follow the lead-idea of introducing more aspects of the *Science, Technology and Society* STS tradition into the TIS framework. It does not go all the way as proposed by Markard and Truffer (2008), developing a combined framework, but aims at refining the TIS framework and some of its elements. Also, several of the chapters propose quantitative approaches to aspects that yet have been mostly explored qualitatively.

This includes a more context-conscious angle on innovation and technological change within large systems understood as a recombination process of old and new components. Such a view is closer to the evolutionary roots of the innovation science tradition than the mere emphasis on the *new*. Specifically, some of the chapters are referring to the concepts of *technological trajectories* and *paradigms*, modularity as it appears in the complexity tradition, and – also related – architectural innovation. Many of the discussions in the thesis are close to what the key authors of the TIS tradition just suggested in the Bergek et al. (2015) paper. This entails the proposed approach to system delineation, the network-driven matching of actors and technology areas, the analysis of actor dynamics, and also the approach to identifying and mapping evolution of technological trajectories in the last chapter – which is looking at another technological field.

The conceptual refinement is closely related to the data and methodological strategy of the thesis. The STS tradition that initially defined and analysed LTSs has developed extensive conceptual buildings to approach technological transformation and transitions. The MLP represents the best example for that – a framework that draws on the tensions and interactions between the various levels and the elements these levels contain. Operationalising these aspects outside of in-depth qualitative case studies has been yet challenging, but is becoming increasingly available as data – particularly relation data – access grows and new methods to explore it emerge. Thus, the conceptual adjustments across the different chapters should also be seen as a quasi data-driven contribution.

The TIS framework has been over time accepted by many scholars and authors of policy reports as a useful guidance. To be able to compare different TIS is a key feature of the approach with its functionalist focus. Despite overall conceptual and structural agreement, there is no or only little consensus on how to approach the analysis methodologically when moving beyond case study research designs. Quantitative and data-intensive opretaionalisation of concepts that yet have been mostly explored in case studies should therefore be on the agenda of future research in this area.

Methodological contribution: Use of unstructured and relational data and methods

The original methodological contribution of the thesis lies in the suggested combination of utilising unstructured text data and machine learning methods for its processing, and network analysis techniques to identify patterns in discourses.

Given the empirical focus of the project, the method pipeline has been developed and utilised in the context of technological system mapping and technology development. Other fields of application are however feasible, as both central techniques – Natural Language Processing, specifically Latent Semantic Analysis and network analysis – are generic in nature.

Chapters B and E are early attempts – and some of the very few to be found in the field of innovation studies – to use machine learning techniques in order to deploy unstructured data, converting it into a shape which can be explored quantitatively. The ability of thereby *generated* data to capture various levels of elements, features, and interactions has the potential to allow for more detailed and nuanced insights in the field of innovation studies and social science in general. Given the vast amount of steadily growing data, both in terms of quantity and quality, and considering the rapid progress of machine learning methods, further integration of computer science approaches into the study of technological changes and more generally innovation studies appears as a promising path to follow.

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Appendix

Table 2: Danish energy mix 1980-2013

Year	1980	1990	2000	2005	2010	2011	2012	2013
Crude Oil	12724	255959	764526	796224	522733	470447	429140	373365
Waste oil	717	750	602	304	39	41	40	41
Natural Gas	17	115967	310307	392868	307490	246964	216000	179275
Solar power	50	100	335	419	657	789	1254	2889
Wind Power	38	2197	15268	23810	28114	35187	36972	40044
Hydropower	123	101	109	81	74	61	63	48
Geothermics	0	48	58	172	212	166	288	229
Straw	4840	12481	12220	18485	23323	20220	18301	20625
Wood chips	0	1724	2744	6082	11352	11407	12425	11746
Firewood	7621	8757	12432	17667	23779	20469	19660	18851
Wood pellets	0	1575	2984	3262	2407	2418	1749	1778
Wood waste	3710	6191	6895	6500	8500	7810	8791	9111
Biogas, deposit	0	28	613	542	312	213	231	213
Biogas, sludge	123	458	857	913	840	822	898	968
Biogas, div.	61	266	1442	2375	3184	3072	3254	3461
Waste, non-biodegradable	4787	6975	13676	17006	17008	17292	16789	16923
Waste, biodegradable	5851	8524	16715	20786	20788	21135	20520	20683
Biofuel	0	744	49	3393	4824	3748	4061	4175
Heat pumps	306	2462	3585	4058	4714	4798	4906	4917
Total primary energy production in TJ	40968	425307	1165417	1314947	980350	867059	795342	709342
Electricity production	97508	93518	129776	130469	139906	126825	110611	125088
Renewables	22724	45657	76306	108545	133081	132316	133371	139739
Share Renewables in total energy production	55.47%	10.74%	6.55%	8.25%	13.57%	15.26%	16.77%	19.70%
Intermittent sources (Sun and Wind) in %	0.21%	0.54%	1.34%	1.84%	2.93%	4.15%	4.81%	6.05%
Wind in electricity production in %	0.04%	2.35%	11.76%	18.25%	20.09%	27.74%	33.43%	32.01%

Notes: Absolute values of contained energy equivalent in TJ, Source: Danish Energy Agency (2014)

Part II

Papers

Paper A

Conceptualizing and Analysing Evolving Technical Systems – A bibliometric review

Roman Jurowetzki

Abstract

This chapter combines a quantitative bibliometric approach with a qualitative exploration of different strands of literature that have taken a system view on technological change. The aim of this exercise is to identify relevant conceptual elements that can be helpful to understanding the empirical setting of this thesis – the development of the Danish smart grid and related energy systems. This is accomplished by using 7806 records from the Web of Science database and a hierarchical clustering approach that reveals five broad areas of research with a high number of "relevant" sub-discussions. These conceptually related groups have been operationalised as dense communities in a network defined by publications linked though a bibliographic coupling indicator. Results show that most of the research with similar empirical focus points constitutes upon the Technological Innovation System approach or the Multi-Level-Perspective. In addition, the analysis identifies and locates other concepts and discussions that are later taken up in several chapters of this thesis.

Keywords: Technological change, technological systems, bibliometrics

1 Introduction

The environmental sustainability challenge and the associated necessity to transform infrastructure-related sectors have recently received increasing attention by policy and research. It is well understood that systems such as energy or transportation have to undergo comprehensive restructuring to contribute to a sustainable future. The development of the smart grid in order to facilitate the integration of a larger share of renewable energy sources in the overall energy system represents such an episode of system transformation. The evolution of large techno-economic systems[1] has been conceptualized and studied within various scholarly traditions which have set the focus on different aspects and sub-phenomena of the overall change process. Different lineages of research within the Innovation System tradition, industrial dynamics, but also sociology of technology made this broad area their subject of inquiry. While not addressing specifically the systemic setting, Freeman

[1]This notion is used here without referring to any particular framework

(1994) provides a comprehensive overview of the variety of approaches that have been taken to understand technological change in general – already at that time. The concepts vary in terms of system composition or context in which technology/ies evolve, the understanding of innovation, the notion of *technology*, interaction between components – and more generally – the functional characteristics.

A large share of recent research that studies such innovation processes that happen within or against established systems (e.g. the emergence of electric vehicles, renewable energy systems, changes within the agriculture system) draws either on the technological innovation system framework (TIS) (Bergek et al., 2008b; Carlsson and Stankiewicz, 1991; Hekkert et al., 2007) or the Multi Level Perspective (MLP) (Geels, 2002, 2004). Both traditions have made a considerable contribution to the understanding of how technological systems develop and co-evolve with their surrounding socio-economic systems.

Markard and Truffer (2008) went on to suggest a combination of the two conceptual strands, arguing that such a merger would contribute to cross-fertilization and eventually generate a synthesis with a more holistic perspective. Particularly they were emphasizing the well operationalisable elements of the TIS and the context awareness of the MLP.

A recent article by the core authors of the TIS tradition picked up the theme of the context-importance but rather than following up on the synthesis proposal by Markard and Truffer (2008), they argued for a better conceptualization of context interaction within the TIS framework (Bergek et al., 2015). The interest of the article lies in identifying different types of context structures around the focal TIS, specifically what Bergek et al. (2015) calls *structural couplings*, overlapping and shared elements (e.g. physical structures, actors, and networks) between the TIS and other structures that influence its development. These couplings can manifest between the focal TIS and other (complementing/competing) TISs, the pre existing infrastructure and institutions, and system-level assets provision systems – as for instance – the political, educational or finance system.

This is only one example showing that, although both TIS and MLP build on a large number of insights from the broader innovation studies field, there are many opportunities to extend and adjust them, and thus, incorporating new or refining existing elements of the frameworks. Also, this points to the relevance of studies that take up and explore single building blocks of these general frameworks.

The present chapter reviews the different strands of literature that take a systems view on technological change and selected energy system related empirical studies that have relied on the respective frameworks. It combines a quantitative bibliometric approach with a qualitative exploration of the literature to identify relevant conceptual elements that can be helpful to explore the empirical setting of the Danish smart grid development. Networks are used here as a tool to model and identify latent relationships between single publications. The bibliometric analysis builds on the representation of conceptual similarity between publications as links in the network.

The remainder of the chapter is composed as follows. The following section introduces the data and explains the bibliometric approach utilized in the "quantitative" part. Section 3 presents the overall results from this analysis. It depicts the topology of the resulting network map and discusses single strands of literature that were identified within the constructed network with regard to their relevance to the scope of the thesis. Section 4 summarizes the findings relating to the two general frameworks – MLP and TIS, points out potential Its final part links the discussed concepts and research fields to the chapters of this thesis.

2 Bibliometric foundation

This review builds on a bibliometric analysis, which should not be taken at face value, but rather, understood in its function as a guiding tool to support a traditional literature review. The results from the quantitative analysis support the author with the identification of relevant literature, the delineation of single discussions, and central contributions on which these constitute. Such an approach makes the review more systematic, as it reveals the scope of particular research traditions and can identify less prominent (but relevant) contributions or highlight smaller discussions. The following subsections describe the data, its preparation, and the hierarchical clustering approach used in this study.

Data

The dataset used for the bibliometric analysis is extracted from Thomson Reuters Web of Science (WOS). This database was chosen, as the analysis is building on the citation structure of extracted publications for which WOS provides a perfectly suited input. Compared to other (often more extensive) bibliographic databases WOS, routinely normalizes references in all listed publications – making the construction of citation networks straightforward and reliable.

Instead of using a search string, a "bibliographic snowballing" approach was chosen to extract records from WOS. The reason for selecting this approach is related to the *ex ante* uncertainty over the scope of literature that can be regarded as relevant. Technological change in systems has been addressed by various streams of research under many different headings. A search for `Large Technical System*` would return literature related to a particular traditions (here STS) and thus be restrictive from the beginning. Although "snowballing" is likely to gather much unrelated literature it should be helpful to extract records that belong to discussions that are thematically related but less known or using a very particular terminology and wouldn't be matched by a pre-determinde search string. "Snowballing" builds on WOS's function of "related records". This function is based on the basic implementation of bibliographic coupling within the database. For each publication selected in the database it is possible to display other "related records" that share at least one reference with the selected publication. These appear in descending order, starting with the most similar – i.e. those sharing many references. Data gathering trough reference relations has been chosen for at least two further reasons. (1) Broader selection: as compared to more traditional search-string based approaches, relevant publications will be detected even if they do not explicitly contain some "pre-selected" keywords in their title or abstract. Even if some publication is not relying on a framework that this chapter is aiming to uncover, it is likely that the literature review section of the particular publication will refer to the framework or related literature. (2) Limitation to social science: The reference based extraction is expected to lead to a lower number of false positives without having to rely on WOS's filtering, as referencing across larger scientific domains (even within social sciences) is very seldom (Jurowetzki et al., 2015).

Reference patterns are commonly also reflecting a *time affiliation*. Since references of a publication are by their nature older than the publication itself, similar publications (closely related research sharing many citations) are likely to be also temporally closely located. This however, also reflects the feature of scholarly discussions, belonging to particular periods of time. If the initial corpus has to contain a variety of discussions it has to be initiated through "seed publications" that are sufficiently diverse in terms of research discussions to which they belong, but also with regard to the temporal diversity.

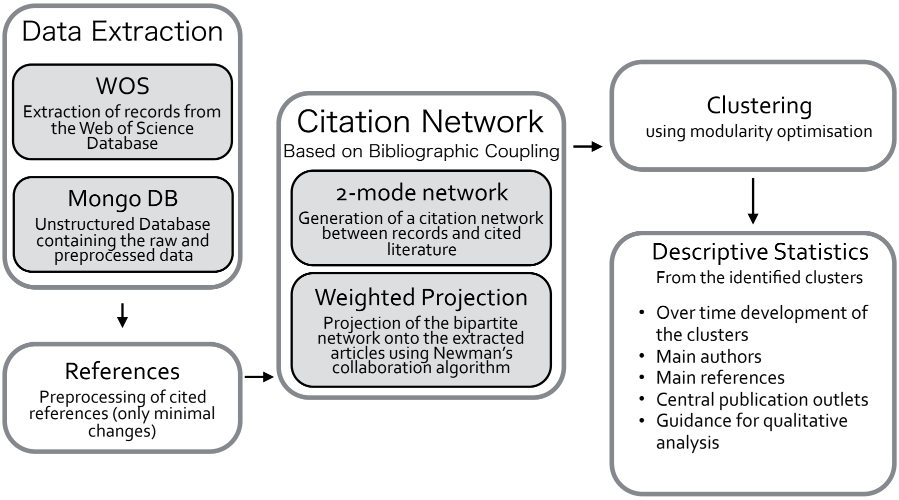
Accounting for that, the initial input consists of several publications from the past three decades that relate to a variety of research traditions. As the central "seed" for the data gathering, the Markard and Truffer (2008) article was chosen, as it aims to bring together two frameworks that are often utilized for the analysis of evolving large techno-economic systems. The paper was among the first to suggest this combination and is extremely well cited in publications that can be related to both traditions. Being a conceptual paper with an extensive literature review it contains many diverse references, which qualifies it to be a suited "seed publication" for the data gathering. Records of the first 5000 related publications were extracted for this "seed publication". In addition, 5 other central and highly cited papers in the context of technological development were added, and for each article 1000 related records were extracted. These are Dosi (1982) on technological paradigms and trajectories, Malerba (2002) on Sectoral Innovation Systems, Carlsson et al. (2002)[2] and Hekkert et al. (2007) on Technological Systems and Geels (2002) describing the Multi Level Perspective. The final set of gathered records contains 7.806 papers (with 243.028 unique references), suggesting some overlap between the different extracted groups.

Bibliographic coupling

The usage of bibliographic coupling (BC) as a measure of thematic relatedness of research is well established in scientometrics and has proven to

[2]This article was chosen, since the Carlsson and Stankiewicz (1991) paper that is usually associated with the first conceptualisation of the TIS is not listed on WOS.

Fig. A.1: Method pipeline



produce good results for cluster identification when compared to other relatedness measures (Boyack and Klavans, 2010). The underlying assumption is that the more publications share references, the more they are conceptually related. Traditionally, pairwise BC is computed as

$$w_{ij} = \frac{n_{ij}}{\sqrt{n_i * n_j}} \tag{A.1}$$

where n_{ij} is the number of shared references, and n_i (resp n_j) the number of references of publication i (resp j). The present paper proposes a slight modification of the index in order to account for the "popularity" of the jointly cited papers. It is based on an argument that has been suggested by Newman (2001) for co-authorship induced relations, implicating that the bond between researchers decreases as the number of collaborators on one study goes up. Applied to bibliometrics the logic translates as follows: One shared reference to a study k_m with overall few citations is likely to indicate a stronger thematic connection between the two papers i and j than one shared citation of a highly cited seminal publication k_l. Thus n_{ij} is replaced by

$$\sum_k \frac{\delta_i^k \delta_j^k}{n_k - 1} \tag{A.2}$$

n_k is the number of citations that publication k receives overall[3] while $\delta_i^k \delta_j^k$ is 1 if papers i and j both cite paper k.

Computing pairwise BC measures for all publications in the database generates a dissimilarity matrix, which can also be interpreted as a network of papers, connected by a measure of thematic similarity.

Hierarchical clustering

To identify communities of articles that belong to particular discussions, the modularity optimization method (Blondel et al., 2008) is used. The algorithm identifies a not-predetermined number of clusters - groups of strongly connected articles - in the network and assigns each node (publication) to one of these clusters. For a relatively large number of nodes as in this case, identified clusters can contain several thousands of publications and represent research fields rather than discussions.[4] Therefore the clustering is applied once more for 5 selected clusters (containing 7070 publication records)[5]. This process is repeated a third time on each sub-cluster to generate sub-sub-communities.

Interpretation of the bibliometric analysis

Figure A.1 represents the practical workflow of the bibliometric analysis. The extracted records from WOS are stored as a MongoDB collection, processed, and the resulting partition is used to extract information about the single discussions. The hierarchical structure as such contains already interesting information about the number and size of sub-groups within larger communities. For all groups at the different levels, the analysis allows to find core references, main contributors, central journals, and the most relevant time period at which the discussion has taken place. Keywords are synthesized from the abstracts of gathered WOS records thus allowing for queick identi-

[3]Only citations within the corpus are considered.

[4]The terms *field* and *area* are used synonymously in the analysis to describe a larger group of publications that has been identified as such by the algorithm. They do not necessarily share an empirical focus but rather tend to refer to the same theoretical concepts and frameworks. *Discussions* are more narrowly focused groups of publications that are more homogeneous in terms of shared citations and tend to share empirical aims and/or the conceptual foundation.

[5]A number of small clusters and one large group of 627 articles from natural sciences, mostly nanotechnology, were dropped after the first partition

fication of the subject matter of particular discussions. Core references and central keywords are not only ranked by their frequency within the groups but also accounting for their specificity, using $TF - IDF$ scaling [6]. Given that two sub-communities are contained by the same larger communities, what are the respective specific core references that are not, the generally, often cited publications in the broader research area? Being able to answer such questions supports the identification of relevant literature and also allows for the linking of discussions to one another.

3 Overall results from the bibliometric anlaysis

3.1 Network overview and hierarchical classification

The result of the above described process is a hierarchical 3-level structure with 5 (selected) large communities on the first level, 91 on the second, and 447 on the third level.

Figure A.2 provides an example of the identified structure. Departing from these 5 communities, the remainder of the section below explores the sub-discussions in the communities on level 2 and level 3.

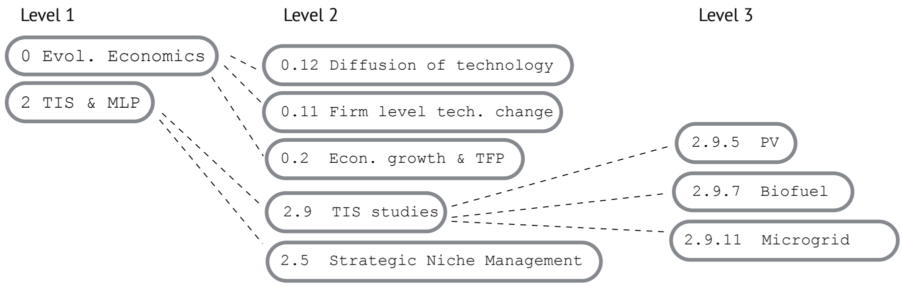
Figure A.3 presents a visualization of the first level network with 7070 publications and the identified 5 relevant communities. The labels in the network are not direct results of the bibliometric analysis, but rather, the result of manual review of the grouped literature. The borders drawn into the visualisation are only approximate delineations of the areas and do not suggest isolation of the single communities. In fact, the identified communities are well interconnected. Yet, the network layout may be interpreted as a two-dimensional map where increasing distance is paralleled by growing conceptual difference.

[6] $TFIDF[t_i^d] = TF[t_i^d] \cdot IDF[t_i]$ Where TF is the ranked element (keyword / reference), t_i its frequency in a group d divided by the number of elements in the group and IDF the logarithm of the number of all publications in the corpus divided by the number of publications, containing the element i.

Table A.1: Level 1 Communities – Indicators

Community (N)	Community ID	Top Journals	Top References	Max. Year
Evolutionary Economics (1138)	0	RESEARCH POLICY JOURNAL OF EVOLUTIONARY ECONOMICS TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE CAMBRIDGE JOURNAL OF ECONOMICS JOURNAL OF ECONOMIC BEHAVIOR & ORGANIZATION	NELSON RR, 1982, EVOLUTIONARY THEORY SCHMOOKLER J., 1966, INVENTION EC GROWTH ROSENBERG N., 1976, PERSPECTIVES TECHNOL NELSON R. R., 1982, EVOLUTIONARY THEORY DOSI G., 1988, TECHNICAL CHANGE EC	2001
Technological Systems & Transitions (1673)	2	ENERGY POLICY TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE TECHNOLOGY ANALYSIS & STRATEGIC MANAGEMENT JOURNAL OF CLEANER PRODUCTION RESEARCH POLICY	GEELS FW, 2002, RES POLICY, V31 KEMP R, 1998, TECHNOL ANAL STRATEG GEELS FW, 2007, RES POLICY, V36 SMITH A, 2005, RES POLICY, V34 RIP A., 1998, HUMAN CHOICE CLIMATE, V2	2014
Innovation Systems (1662)	3	RESEARCH POLICY EUROPEAN PLANNING STUDIES REGIONAL STUDIES INTERNATIONAL JOURNAL OF TECHNOLOGY MANAGEME TECHNOVATION	PORTER ME, 1990, COMPETITIVE ADVANTAG LUNDVALL B.-A., 1992, NATL SYSTEMS INNOVAT SAXENIAN A, 1994, REGIONAL ADVANTAGE C FREEMAN C., 1987, TECHNOLOGY POLICY EC EDQUIST C., 1997, SYSTEMS INNOVATION T	2012
Industrial Dynamics & Innovation Management (1963)	4	RESEARCH POLICY STRATEGIC MANAGEMENT JOURNAL INDUSTRIAL AND CORPORATE CHANGE TECHNOVATION INTERNATIONAL JOURNAL OF TECHNOLOGY MANAGEMENT	NELSON RR, 1982, EVOLUTIONARY THEORY COHEN WM, 1990, ADMIN SCI QUART, V35 TEECE DJ, 1997, STRATEGIC MANAGE J, V18 HENDERSON RM, 1990, ADMIN SCI QUART, V35 BARNEY J, 1991, J MANAGE, V17	2012
Science and Technology Studies (634)	5	RESEARCH POLICY SOCIAL STUDIES OF SCIENCE TECHNOLOGY ANALYSIS & STRATEGIC MANAGEMENT SCIENCE TECHNOLOGY & HUMAN VALUES SCIENTOMETRICS	KUHN T.S., 1962, STRUCTURE SCI REVOLU FEYERABEND P., 1975, METHOD LAKATOS I., 1978, METHODOLOGY SCI RES HUGHES T., 1987, SOCIAL CONSTRUCTION KUHN TS, 1970, STRUCTURE SCI REVOLU, VII	2013

Fig. A.2: Hierarchical structure of the identified strands of literature



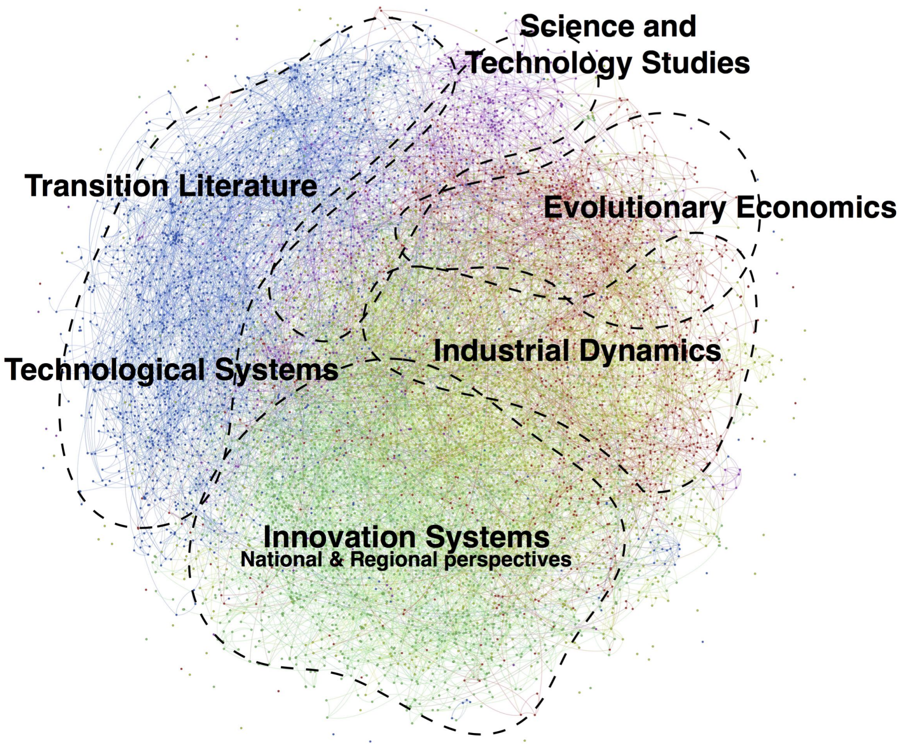
Note: The figure represents only a fragment of the identified structure. The captions of the groups are based on the

3.2 Top level communities

The top level communities reflect the different strands of research in the broader innovation studies field. However, it is obvious that the data extraction (as intended) generated a bias towards research focused on technology development. The share of publications relating to entrepreneurship and innovation management is, for instance, relatively small and they have been for the most classified as a sub-groups under *Industrial Dynamics*. The other groups are Technological Systems and Transition Literature, Innovation Systems, Science and Technology Studies, and Evolutionary Economics. While still classified as one community, the prolonged shape of the Technological Systems and Transition Literature cluster already suggests a strong conceptual division within the group. In fact, while the upper part – closer to STS literature and Evolutionary Economics – contains publications clearly relating to transition literature and the Multi Level Perspective, the lower part – adjacent to the Innovation Systems cluster – is comprised of studies standing in the technological innovation system tradition. Table A.1 summarises key indicators for the 5 groups, including their size, core references, and main publication outlets.

The remainder of the section will discuss the 5 research traditions – highlighting *relevant* sub-discussions closely related to systemic technology development. Overview tables of the generally mostly cited publications that are part of the corpus can be found in the appendix. It is important to highlight here that all statements about the size of particular publication traditions approximated by the clusters or the reported time frames relate to the explored corpus and are subject to limitations associated with the features of the sample.

Fig. A.3: Publication network with Level 1 partition



Note: Labels determined through the detailed analysis of the publications in the cluster, central references, journals and keywords.

Evolutionary Economics, `com.0`

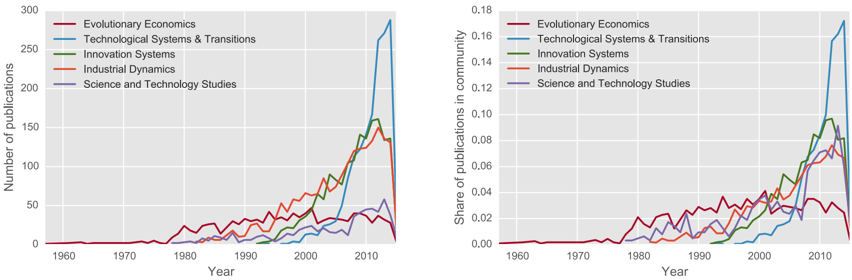
This community is the "oldest" among the five explored with papers from the late 50s and early 60s, but with 1138 papers not the largest. While the other 4 communities show strong growth of publications in the past decade or even

Table A.2: Discussed sub communities and their properties

ID	Size	Level	Peak(s)	Theme/Tradition
0.0	55	2	-	Economic history and technological change
0.6	132	2	1994	Evolutionary economics seminal
0.6.9	20	3	-	Evolutionary economics 80s
0.6.6	13	3	-	Evolutionary economics 90s
0.12	46	2	1995, 99, 2010	Diffusion and adoption
2.9	354	2	2012, 2014	TIS tradition analyses
2.3	233	2	2014	Niches as development spaces
2.5	93	2	2013	Energy technology transitions
2.0	129	2	2014	Electric and hydrogen based mobility
2.2	118	2	2013	Sustainable technology management
4.2	238	2	2011	Firm capabilities and evolution of technology
4.2.0	36	3	-	Standards and network externalities
4.4	351	2	2014	Complexity in corporate processes
4.4.6	23	3	-	Complexity, recombination, and invention
4.0	244	2	2013	Sectoral perspective
4.0.5	16	3	-	Technological regime and learning
3.6	153	2	2007	National Innovation System
3.0	260	2	2003	Economic geography and innovation systems
3.5	232	2	2011	Industrial clusters
3.7	174	2	2013	Industrial clusters knowledge perspective
3.2	202	2	2011	University-industry collaboration
5.5	40	2	-	Triple Helix related research
5.1	153	2	2010	Social construction of technology

Note: Peaks not reported for level 3 communities and in cases with comparably even over time distribution of publications.

Fig. A.4: Publications per year by identified community



(a) Absolute numbers of publications **(b)** Relative numbers of publications

Note: The visualisations show a general growth trend that is present in nearly all of social science disciplines.

the last few years, this community has a consistent number of publications since the early 80s with a peak in the early 2000s. Most important outlets are Research Policy and the Journal of Evolutionary Economics. Among the most central 15 references, only Nelson (1995) was published in the 90s. Most of the other key publications are from the 80s and earlier. The main citations are – perhaps not surprisingly – the seminal book by Nelson and Winter (1982), Schmookler (1966), and Rosenberg (1976), while the central abstract-keywords are: *model, innovation, firm, technology* (ordered after descending centrality).

Relevant discussions: Sub-Community `0.0` is of certain interest, as it looks on technological change from a economic history perspective, analysing the big transitions from sail to stem ships, industrial revolutions in England and Germany, and their interplay with new technologies. The MLP framework by Geels (2002) builds, for instance, on such historical examples. Some of these studies are relatively recent (e.g. Cohn, 2005) and might contribute to refining concepts within currently widely used frameworks.

Sub-Community `0.6` and 2 level-3 clusters (`0.6.9, 0.6.6`) contain a number of interesting discussions related to technological change. `0.6.9` contains papers that prominently refer to the seminal work by Pavitt (1984) on the sectoral patterns of technical change and the book by Nathan Rosenberg collecting papers from 10 years of research on the role of technology in economic growth (Rosenberg, 1976). Most of the papers aggregated in this subcluster are well-cited publications from the late 80s. For instance, Freeman (1994), which provides an excellent overview of the different conceptualizations of technological change; or Dosi (1988), connecting his earlier developed concepts of technological paradigms and trajectories with innovation and its macroeconomics effects. `0.6.6` contains several papers from the early 90s that utilize concepts from Dosi (1982).

Diffusion and adoption of technology is discussed in `0.12` with reference to work by Griliches (1957), Davies (1979) and Mansfield (1961). The papers aggregated in this community are often formal models of technology diffusion, such as Rose and Joskow (1988), looking at adoption rates in different types of energy utilities. Yet, Buzzacchi et al. (1995) is, for instance, a conceptual paper, studying the introduction of ICT in the banking sector and how it transformed the established "technological regime" - a notion that today is usually associated with *transition literature*.

Technological Systems and Transition Literature, `com.2`

This cluster is, with 1673 publications, the second largest in the sample [7] and the youngest. 821 of the records were published between 2012 and 2014, making this literature the fastest growing field among the different identified areas. Central outlets are Energy Policy, Technological Forecasting and Social Change, Technology Analysis & Strategic Management, the Journal of Cleaner Production and Research Policy. This distribution indicates already a tendency towards (renewable) energy and sustainability topics. This is supported by the central abstract-keywords: *transition, policy, energy, system, technology*. An even clearer picture can be seen, looking at the central references. Among those can be found the seminal conceptual papers of the technological transition (Geels, 2002; Geels and Schot, 2007) and the technological innovation systems (Bergek et al., 2008b; Hekkert et al., 2007) discussions. Both traditions emerged around the two relatively recent competing

[7] This can be a bias due to the snowballing approach to data collection.

frameworks that synthesize insights from evolutionary economics, innovation studies and, sociology of technology. Kemp et al. (1998) can be seen as a central foundation for the transition literature, emphasizing the role and management of technological niches for the development of desired technologies. This strand of literature emphasizes the path dependency of the established socio-technical regime and the difficulty to achieve a *transition* into a new (more sustainable) setting based on one, or a set of, radically different technologies. Smith et al. (2005) introduces a governance perspective on transitions. Unruh (2000) is a reference that takes a broader evolutionary and institutional economics perspective to argue for the existence of a persistent *carbon lock-in*. In both traditions (Transitions and TIS literature) this reference is used to argue for the existence of a systemic barrier to the development of sustainable technology. Closely related and preceding what is today seen as the *core* TIS literature is the work by Jacobsson and Bergek (2004) and Jacobsson and Johnson (2000), which discusses the transformation and diffusion issues in renewable energy technologies. Especially Jacobsson and Bergek (2004) seems to already include most of the elements of the later (highly cited and utilized) framework-papers.

Relevant discussions: The two traditions, outlined above, are clearly reflected in the sub-clustering of the level 1 community `2`.

Level 2 cluster `2.9` gathers nearly all papers linking to the TIS tradition and referring to the key contributions (Bergek et al., 2008b; Carlsson and Stankiewicz, 1991; Hekkert et al., 2007; Jacobsson and Bergek, 2004; Jacobsson and Johnson, 2000), while more transition-literature related research is distributed across a number of different sub-clusters. This suggests that the TIS related research is conceptually more consolidated, which might be due to the research scheme proposed by (Bergek et al., 2008b) and several similar papers that offer a clear and straightforward operationalisable scheme for analysis and, subsequently, has been adopted in many empirical studies. The transition literature contains, in contrast, a high number of conceptual discussions and the Multi Level Perspective (Geels, 2002) – while being a comprehensive framework for the understanding of technological change – does not seem to offer a comparable level of consensus generation for the adjoining research community.

The empirical focus in the community 2.9 lies within energy sustainability and the covered technologies are carbon capture and storage, biomass gasification, development of biofuels, energy grid development, and wind power – with a dominance of Danish cases in the latter technology area. Conceptually, the functions of the technological innovation systems are a central aspect of many papers.

Sub-cluster 2.3 does not show a particular technology focus, but a conceptual emphasis on *niches* (Kemp et al., 1998; Smith et al., 2005) and the spatial context of the city and urban environments as driver of sustainable transitions (e.g. Hodson and Marvin, 2010).

Energy transition and sustainability are the central topics of sub-cluster 2.5. Yet, many of the papers approach it from a different angle, studying future scenarios. Normative *backcasting* analysis, which aims at identifying pathways towards an desired future, is essential in this group of papers (Dreborg, 1996; Quist and Vergragt, 2006). This type of research is matched with *transition pathways* concepts, coming from the MLP-related literature (Geels, 2002, 2005). It contains at least 2 level 3 communities with papers related to the transformation of energy systems, specifically looking at cases from the UK (e.g. Hannon et al., 2013; Taylor et al., 2013). Using related theoretical foundations, sub-cluster 2.0 primarily explores transportation and particularly hydrogen and electric vehicle technologies.

Sub-cluster 2.2 is dominated by publications from the the Journal of Cleaner Production and Research Policy, which do not belong to one of the two larger traditions, but rather, look at the business and innovation management side of sustainable technology development. It contains, among other, the work by (Rennings, 2000) on the conceptualization of eco-innovation, the Porter Hypothesis (Porter and Linde, 1995), but also the core literature on strategic niche management (Kemp et al., 1998). Considering merely the central references, this literature does not reveal an explicit system perspective, however it provides valuable insights into the area of sustainable or eco-innovation from the micro or business-perspective. This connection to different systemic concepts is made in some of the papers that were assigned to the cluster. Oltra and Saint Jean (2009) links the eco-innovation argumentation to the sectoral innovation system approach (Malerba, 2002) and Berkhout (2002) discusses the implications of shifting the analysis from a discrete artefact-centred to a system-centred level under path dependence and in an environmental context. One interesting argument made by the article is a underestimation of the importance of multiple, cumulative and often incremental changes that can lead to a smooth reorientation of the system. To some degree this statement stands in opposition to the "lock-in argument", which often builds the starting point and basic assumption of articles in the broader group.

Industrial Dynamics & Innovation Management, `com.4`

The literature assigned to this cluster by the algorithm covers wide parts of the fields of industrial dynamics (ID) and innovation management. With nearly 2000 publications it is the largest cluster and the one that has been evenly growing since the early 1990s. The main discussions are rooted in the evolutionary tradition (Nelson and Winter, 1982) and aim at analysing economic development and structural change. The explored problems and phenomena lie mainly within organizations or are tightly linked to their behaviour, however there are also more focused sub-discussions on industry and sectoral levels (Klepper, 1996; Malerba, 2002; Utterback and Suárez, 1993).

Research Policy is the journal with the highest number of publications also in this cluster, once more confirming the general character of the journal for the broader field of innovation studies. Other central and more cluster-specific outlets are the Strategic Management Journal, Industrial and Corporate Change, Technovation and the International Journal Journal of Technology Management.

The process of obtaining and utilizing knowledge is a major theme and appears in all identified sub-clusters. The main reference apart from Nelson and Winter (1982), is – not surprisingly – the seminal paper on Absorptive Capacity by Cohen and Levinthal (1990). Other central references are the resource based view by Barney (1991), the two central articles by David Teece - (1986) on profiting from technological innovation and Teece et al. (1997) on dynamic capabilities, and the role of *recombination* for innovation and learning (Henderson and Clark, 1990; Kogut and Zander, 1992). In a nutshell, the community asks two symmetric questions: First: What are the effects of technological evolution on organizations? Second: What are the necessary characteristics and capabilities for organizations to achieve desired technological outcomes?

Relevant discussions: The majority of the sub-clusters are focused on non-technical dimensions of industrial organization and change, such as knowledge management, learning, and capability development. Two of the larger 10 sub-clusters are more directly related to the technological dimension. `4.2` explores the interplay between the technological capabilities of enterprises and the evolution of the technologies. Dominant designs and technological discontinuities (Anderson and Tushman, 1990), the architecture of technology (Henderson and Clark, 1990), and companies' response strategies play an important role in the publications within this sub-community. Technological standards and network externalities in level 3 community `4.2.0`, closely related but not equal to the dominant design concept, form another important theme. These discussions are later synthesized within the industry life cycle and other dynamic organization ecology models (Klepper, 1996; Utterback and Suárez, 1993). The single discussions are not as much interested in the evolution of the technology itself, as in the technological capabilities of the firms and the impact on their activity and performance. The concepts and arguments developed in this literature are useful for the understanding of actor behaviour involved in the transformation of technological systems. Sub-cluster `4.4` and particularly `4.4.6` integrate core elements form evolutionary economics (com. `0`), concepts from `4.2` with constructs explaining knowledge and capability acquisition (e.g. Cohen and Levinthal, 1990), introducing the notion and perspective of complexity. The core contributions to this strand are papers by Lee Fleming and Olav Sorenson (2001; 2001; 2004), which use patent citation data to explore the patterns resulting from the recombination of technological components. This research relates to the general idea of innovation as a process of recombination (Nelson and Winter, 1982, p.130) but also to Henderson and Clark (1990) who argue that a mere rearrangement of previously used components can result in major overall change.

`4.0` is the industry level sub-community within `4`, which is perhaps closest to the more mainstream field of industrial organization, yet rooted in the Schumpeterian tradition. Interaction between organizations embedded in networks and the innovative outcomes are central for this part of literature and several core publications such as Malerba and Orsenigo (1996) emphasize that these processes are technology- and sector-specific. The sectoral innovation systems framework (Malerba, 2002) appears as a core reference and clustered article. Differently from the other innovation system perspectives, policy seems to play a subordinate role in this discussion. Empirically, most examples stem from the pharmaceutical and biotechnology industries and ground on the analysis of patent data.

`4.0.5` is a closely related level3 community, heavily building on the work of Franco Malerba and co-authors. Rather than referring to sectors or industries, the prevailing concept in this discussion is the "technological regime", introduced by Nelson and Winter (1982). Also, the concepts of technological paradigms and trajectories in the dynamic perspective (Dosi, 1982) are used as a reference to distinguish companies. The hypothesis that companies belonging to the same regimes are assumed to learn and organize innovation similarly (Breschi et al., 2000) is tested empirically in the majority of the papers within the group using innovation survey data (e.g. Leiponen and Drejer, 2007). The understanding of the technological regime here is different from the concept in the transition literature in community 2 and as such, not of particular relevance for the goal of this thesis. Yet, the sub-cluster provides evidence that learning, interaction- and innovation patterns are significantly different in regimes with strong ties to (large) technical systems.

Innovation Systems

The "Innovation System" cluster is, with 1662 articles, similarly large as the other 2 big communities. The first contributions – found in the corpus – appear in the early 1990s and strong growth commences in the second half of the 90s. The numbers of publications peak in 2011 and 12, and decline again slightly since 2013. Yet, it is difficult to say whether this decline is a continuing trend. The technological and sectoral perspective – observed in the other groups – is replaced by a spatial focus in this tradition. Research Policy is also in this group the main outlet, however, the territorial character of many publications is also supported by the other main journals – *European*

Planning Studies an *Regional Studies*. Many of the assigned publications in this group, as well as the core references, address objectives and issues within the wider scope of innovation and lie within national (Freeman, 1987; Lundvall, 1992; Nelson, 1993; Porter, 1990), regional (Cooke et al., 1997; Morgan, 1997; Moulaert and Sekia, 2003; Saxenian, 1994), local or cluster boundaries (Bathelt et al., 2004; Maskell and Malmberg, 1999).

Overall, technological evolution is treated as an outcome rather than the object of analysis. Instead, the analysis often emphasizes the actor and policy dimensions, where the latter is a means to make the former more innovative.

Relevant discussions: Level 2 cluster `3.4`, for instance, contains 120 articles discussing different types of policy to promote innovation. Often the assumption is made that policies have to target the consequences of system failures instead of market failures (Klein Woolthuis et al., 2005). The supply side is addressed, focusing on the effect of internationally varying institutional configurations on companies' innovation capabilities (Casper and Whitley, 2004), the development of new forms of organizations and business models (Casper, 2000; Whitley, 2006), and the innovation strategies of firms (Whitley, 2000). In many of the studies, entrepreneurial companies play a central role. On the demand side, public procurement policies (Edler and Georghiou, 2007) can stimulate the development of innovative products and services.

Sub-cluster `3.6, 3.0, 3.5, and 3.7` have their focus at the different spatial levels – national, regional, cluster – that are mentioned above.

Publications sorted into the sub-cluster `3.2` have "University-Industry" linkages as their central point. A framework that became very relevant in this area is the Triple Helix by Etzkowitz and Leydesdorff (2000). These type of networks are seen as particularly beneficial to spur innovation and the development of technology through publicly-funded research. Apart from the more general empirical studies of the effects of different types of interaction patterns on innovative performance, there are articles looking at the entrepreneurial character of academic research Etzkowitz (2003) and university spinn-off activity O'Shea et al. (2005).

The thematic focus in this cluster is not directly related to the development of technological systems. However, many of the contained discussions are important points to consider when exploring the evolution of certain technological fields. It is therefore not surprising that most of the above mentioned concepts (e.g. public procurement, entrepreneurial experimentation, university-linkages) have later been integrated into the technology-oriented frameworks (e.g. Bergek et al., 2008b) that are dominating cluster 2.

Science and Technology Studies

The last (sufficiently large) group, identified by the algorithm, is cluster 5 containing 634 articles that belong to the "sociology of science and technology" tradition. This strand of literature emphasizes the influence of social factors that shape the evolution of technology. The central references within this cluster are seminal – and/although very diverse in many respects – contributions within science philosophy (Feyerabend, 1975; Kuhn, 1962; Lakatos, 1978; Popper, 2005). Among these central references there are also contributions addressing more specifically technology (Bijker, 1997; Dosi, 1982; Hughes, 1987).

Relevant discussions: With the exception of two, most of the sub-groups do not refer to technology but focus on science in general. At first sight, it is surprising to find the level 2 cluster 5.5. The group is very similar to 3.2 and congregates further 40 articles that utilize or relate to the Triple Helix framework. This classification suggests that the Triple Helix is the innovation system framework which is mostly related to sociology and philosophy of science tradition.

The other relevant group of articles is 5.1 with 153 contributions. At the core of this literature is the concept of *social construction of technology* with chapters from Bijker et al. (1987) and other work by Thomas Hughes and Wiebe Bijker as key references. The insights from this literature are important, as norms and habits are highly influential on the technological outcomes. Legitimacy and acceptance of technological solutions with the users and general public are required conditions for its success. The work by Bijker (1997) suggests that points where technology comes in contact with users and may somehow influence routines or norms are of particular importance. In the case of a systemic technology, it is therefore pivotal to identify the involved artifacts. Overall, these concepts and ideas are well reflected in the technologically-oriented analytic concepts in cluster 2 and should be considered when exploring the evolution of technological systems.

4 Summary

4.1 Insights for the overall thesis framework

Overall, the results of the above mapping exercise may lead to the conclusion that the more recent technology-specific conceptual frameworks in cluster 2 – TIS and MLP – are most appropriate for the analysis of the Danish smart grid emergence. The origins of the two conceptual buildings are different and so are the objectives that led to their emergence. Thus, the decision for one or the other will determine the perspective of the analysis.

There are at least three (interrelated) reasons for why TIS and/or MLP fit well to serve as an overarching framework for the present empirical case: (1) Both relatively recent traditions synthesize their respective frameworks drawing on the central insights from contributions in the other clusters that have a longer history. Doing so, they also interpret the causal mechanisms of earlier models of technological change towards a socio-technical perspective. Nevertheless, it is important to emphasise that several discussions or important elements found within the other 4 larger communities are not particularly highlighted in either TIS or in MLP. (2) The "output variable" in both frameworks is the achievement of a *desired* socio-technical outcome – not general innovation performance of companies or regions, economic growth, or general development. (3) The studied technologies are usually suffering form under-development due to market and system failures.

For all that, there are noteworthy differences between the two traditions that are revealed by the analysis.

Already the graphic layout in Figure A.3 points to the several tangential points with the clusters 5 (for MLP-related literature) and 3 (for TIS-related contributions).

The MLP tradition has a stronger focus on the various elements of the context in which *transitions* come about – giving much attention to the routines and institutions that are embedded in the established technological regime. In doing so, the tradition takes into account many elements from evolutionary thought. The ideas of technological path-dependency and lock-in play a central role and build the starting point of the framework construction. Innovative technologies are conceptualized in juxtaposition to the established *regime* and are expected – if successful – to break the momentum of the latter. This tension between *the old* and *the new* is very pronounced and propagates into all elements and rationales within the framework. This is not surprising, when considering the origins of the framework, which lies in the analysis of episodes of radical technological replacement in history such as the transition form sail to stem ships. Only later, with the work of, for instance Raven (2007), less radical forms of technological change – where new elements are "hybridising" with the old structures – were incorporated into the perspective.

TIS related literature takes a comparably functionalist-normative approach. The *new* and its emergence is much more emphasised than the established surroundings. The analysis is guided towards actors, institutions, their interactions, and clearly defined systemic functions that are expected to spur the favoured development. In the MLP framework, much of this functionality is situated at the so called niche-level – a protected space where novelty can exist detached from the selection environment. However, the TIS framework is not completely context-indifferent. An important step in the proposed analysis is the identification of "inducement and blocking" mechanisms (Bergek et al., 2008a).

When looking at the smart grid development, the often stated goal is, not to replace existing energy grid infrastructure, but to upgrade the existing system, thus increasing compatibility with the growing number of renewable energy sources in the system and exploit complementaries. At its core, smart grid development is most likely not a "transition" in the sense of a typewriter vs. computer set-up but perhaps closer to the current development of the driverless car—a "transformation". The concept of the car, the road and the traffic rules remain overall unchanged, while a layer of *artificial intelligence technology* allows the vehicle to drive autonomously, thus generating a variety of new options with the potential to change the paradigm of individual transportation.

The MLP is certainly more nuanced and thorough in its understanding of the context, but challenging to use, especially in the case of scenarios that are still unfolding with uncertain prospect. While the well operationalised analytical TIS framework seems to be suited for the smart grid case, it is important to inspect several of its elements and how well they fit the present technological set-up. Particularly, three areas should be discussed against the backdrop of the above literature review. (1) The delineation and understanding of technology in the centre of the analysis, (2) The perception of the context and the selection environment, (3) The conceptualization of innovation as a process of recombination. Basically, this points towards a strategy for the thesis characterised by "flavouring" the TIS-framework with some MLP-aspects.

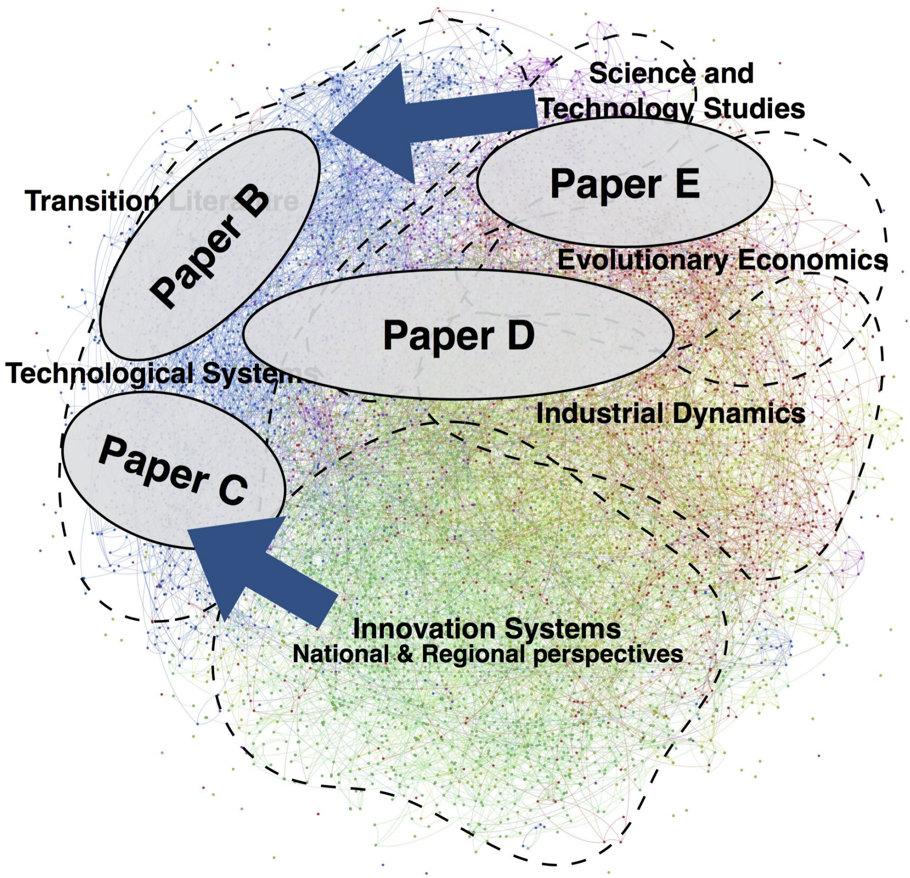
4.2 Conceptual integration of the thesis chapters

The thesis as a whole, and particularly chapter C, adopts the TIS as an overall framework making some adjustments. Many of the above mentioned – more focused – discussions are reflected in several other chapters of this thesis.

Technological regimes and trajectories as proposed by (Dosi, 1982) constitute a central theory block within chapter E. Particularly, the chapter presents a methodology to identify technological trajectories from natural text data generated by the open discourse found on the internet. This method stands in contrast with the more traditional approach that relies on the usage of patent data. Chapter B uses an preceding version of this methodology to accomplish a similar task in a static setting and using more *curated* data i.e. smart grid research project descriptions.

The latter chapter is less explicit about the association with the evolutionary concepts of regimes and trajectories, but rather links to the **social construction of technology** theme within the STS tradition (Bijker, 1997; Bijker et al., 1987). As technology exists to fulfil or support some societal functions through direct application or indirectly through derived products, it is always embedded in and framed by a societal, political, and organizational context, which co-evolves with it (Kaplan and Tripsas, 2008). Thus, the trajectories and applications that evolve – especially in the case of systemic technologies – are highly context-dependent, which should be the point of departure for the delineation of the focal technology. Having established that, the proposed approach does not dismiss the usage and validity of patent data, but merely

Fig. A.5: Mapping of the thesis chapters



Note: The blue arrows indicate the direction of conceptual influence. While the thesis does not contain chapters that directly use the national or regional type of innovation system framework, the TIS literature – even though forming a clearly distinguishable cluster – stands obviously in this tradition.

argues for more coherency between the spatial and technological delineation in empirical work that aims at understanding change of technical systems. One important finding from chapter B is that many of the technologies that the analysis identifies as key in the development of the smart grid (e.g. district heating systems and heat pumps) are "old components" and thus much of the innovation can be classified as architectural i.e. a process of rearrangement of existing components (Henderson and Clark, 1990).

Chapter E is more explicit about the idea of **innovation as recombination** (e.g. Fleming and Sorenson, 2001, and literature from 4.4.6), as it is aiming to uncover persistent combination of knowledge fragments. A further construct that becomes important in this chapter is the idea of modularity as a means to decrease technological uncertainty and moderate interdependency (Frenken, 2006). We identify the smartphone as a (at least today) platform technology in the field of "singularity" that allows for a variety of applications through the combination with other components through standardised interfaces (e.g. bluetooth and wifi technology). This finding is not particularly surprising when exploring the field of "singularity", as the interaction with the smartphone can be seen as the most intense – in terms of time spent and variety of tasks accomplished – and diffused form of human-machine interaction.

Chapter D aims at integrating ideas found in the TIS and MLP traditions on **protection of emerging technologies** with arguments found in the strand literature in 4.2. The analysis concludes that, facing the emergence of a potentially **disruptive technology** (Tushman and Anderson, 1986), incumbent players exploit established favourable structures (e.g. their stand in the energy system, resources and capabilities) to position themselves increasingly dominant in the research networks that develop the upcoming technology. While from this analysis we cannot say whether this shows their support for the new technology or an attempt to control or prevent change, we can speculate that they have a strong interest in the latter (Smink et al., 2013; Walker, 2000). The survey results presented in chapter C suggest that the Danish TSO implements proprietary standards limit competition.

5 Conclusions

This chapter used a combined approach to identify literature discussions and concepts related to the study of technological change. It combined a bibliometric analysis based on an extensive WOS dataset and a novel hierarchical clustering approach with a traditional review of the literature. The results identify the different traditions of research and allow for analysts to place them on a map and in relation to each other. Apart from the delineation of relevant literature, the clustering also indicates the scope and time dimension of the particular discussions. The proposed bibliometric analysis pipeline provides therefore a valuable tool to studying the structure and development of research fields.

The TIS framework which is often used in similar empirical contexts as the one of the present thesis is confirmed as an appropriate approach to study the development of the Danish smart grid system. Several conceptual elements from different strands of literature have been identified that can complement the framework in the present empirical setting: (1) The delineation and understanding of technology in the centre of the analysis, (2) The perception of the context and the selection environment, (3) The conceptualization of innovation as a process of recombination. Chapter C that adapts the TIS framework and scheme of analysis (Bergek et al., 2008b) aims at incorporating these aspects.

Finally, the chapter links several of the identified discussions to the papers contained in the present thesis, as summarised in the preceding subsection 4.2.

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Appendix

Fig. A.6: Comparison map form alternative corpus

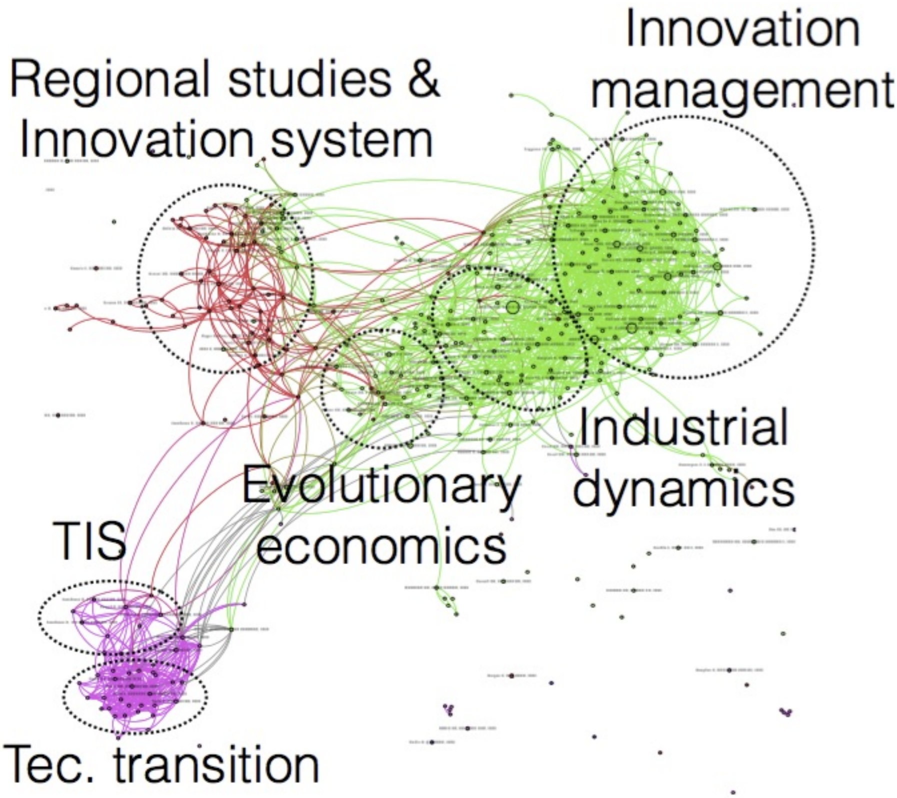

Table A.3: Top papers `Community 0`: Evolutionary Economics

Author	Year	Title	Publication Source	Cited
PAVITT, K	1984	SECTORAL PATTERNS OF TECHNICAL CHANGE - TOWARDS A TAXONOMY AND A THEORY	RESEARCH POLICY	1289
DOSI, G	1988	SOURCES, PROCEDURES, AND MICROECONOMIC EFFECTS OF INNOVATION	JOURNAL OF ECONOMIC LITERATURE	1104
MANSFIELD, E	1961	TECHNICAL CHANGE AND THE RATE OF IMITATION	ECONOMETRICA	651
ABERNATHY, WJ; CLARK, KB	1985	INNOVATION - MAPPING THE WINDS OF CREATIVE DESTRUCTION	RESEARCH POLICY	621
NORTH, DC	1994	ECONOMIC-PERFORMANCE THROUGH TIME	AMERICAN ECONOMIC REVIEW	544

Table A.4: Top papers `Community 2`: Technological Systems & Transitions

Author	Year	Title	Publication Source	Cited
Geels, FW	2002	Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study	RESEARCH POLICY	524
Unruh, GC	2000	Understanding carbon lock-in	ENERGY POLICY	438
Kemp, R; Schot, J; Hoogma, R	1998	Regime shifts to sustainability through processes of niche formation: The approach of strategic niche management	TECHNOLOGY ANALYSIS & STRATEGIC MANAGEMENT	429
Geels, FW; Schot, J	2007	Typology of sociotechnical transition pathways	RESEARCH POLICY	364
Geels, FW	2004	From sectoral systems of innovation to socio-technical systems - Insights about dynamics and change from sociology and institutional theory	RESEARCH POLICY	346

Table A.5: Top papers `Community 4`: Industrial Dynamics & Innovation Management

Author	Year	Title	Publication Source	Cited
BARNEY, J	1991	FIRM RESOURCES AND SUSTAINED COMPETITIVE ADVANTAGE	JOURNAL OF MANAGEMENT	8470
Teece, DJ; Pisano, G; Shuen, A	1997	Dynamic capabilities and strategic management	STRATEGIC MANAGEMENT JOURNAL	4850
KOGUT, B; ZANDER, U	1992	KNOWLEDGE OF THE FIRM, COMBINATIVE CAPABILITIES, AND THE REPLICATION OF TECHNOLOGY	ORGANIZATION SCIENCE	3088
DIERICKX, I; COOL, K	1989	ASSET STOCK ACCUMULATION AND SUSTAINABILITY OF COMPETITIVE ADVANTAGE	MANAGEMENT SCIENCE	2119
Grant, RM	1996	Prospering in dynamically-competitive environments: Organizational capability as knowledge integration	ORGANIZATION SCIENCE	1343

Table A.6: Top papers `Community 3`: Innovation Systems

Author	Year	Title	Publication Source	Cited
Bathelt, H; Malmberg, A; Maskell, P	2004	Clusters and knowledge: local buzz, global pipelines and the process of knowledge creation	PROGRESS IN HUMAN GEOGRAPHY	904
Boschma, RA	2005	Proximity and innovation: A critical assessment	REGIONAL STUDIES	738
Maskell, P; Malmberg, A	1999	Localised learning and industrial competitiveness	CAMBRIDGE JOURNAL OF ECONOMICS	637
Cooke, P; Uranga, MG; Etxebarria, G	1997	Regional innovation systems: Institutional and organisational dimensions	RESEARCH POLICY	420
Gordon, IR; McCann, P	2000	Industrial clusters: Complexes, agglomeration and/or social networks?	URBAN STUDIES	415

Table A.7: Top papers `Community 5`: Science and Technology Studies

Author	Year	Title	Publication Source	Cited
Etzkowitz, H; Leydesdorff, L	2000	The dynamics of innovation: from National Systems and "Mode 2" to a Triple Helix of university-industry-government relations	RESEARCH POLICY	846
Burawoy, M	1998	The extended case method	SOCIOLOGICAL THEORY	330
SABEL, C; ZEITLIN, J	1985	HISTORICAL ALTERNATIVES TO MASS-PRODUCTION - POLITICS, MARKETS, AND TECHNOLOGY IN 19TH-CENTURY INDUSTRIALIZATION	PAST & PRESENT	206
Atran, S	1998	Folk biology and the anthropology of science: Cognitive universals and cultural particulars	BEHAVIORAL AND BRAIN SCIENCES	186
PFAFFENBERGER, B	1992	SOCIAL-ANTHROPOLOGY OF TECHNOLOGY	ANNUAL REVIEW OF ANTHROPOLOGY	174

Paper B

Unpacking Big Systems - Natural Language Processing Meets Network Analysis: A Study of Smart Grid Development in Denmark

Roman Jurowetzki

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Abstract

Studies within the detection of technological trajectories and technology forecasting tend traditionally to rely on patent or bibliometric data. The main drawback of these invention-focused approaches is their inability to account for many mainly non-technical factors related to the social and institutional framing of technology. Value driven policies, technological and institutional path dependencies, or user expectations and routines have major impact on the technological outcomes in a particular context. This paper suggests a new method for the mapping and analysis of large (technical) systems and contained technological trajectories on a national level by using a combination of methods from statistical natural language processing, vector space modelling, and network analysis. The proposed approach does not aim at replacing the researcher or expert, but rather offers the possibility to algorithmically structure and, to some extent, quantify unstructured text data. The utilized filtered corpora consist of two types of Danish text-documents: 99 R&DD project descriptions and 574 (initially before filtering 813) non-academic/industrial journal publications dealing with the development of the smart energy grid in Denmark. Results show that in the explored case it is not mainly new technologies and applications that are driving change, but innovative re-combinations of old and new technologies.

Keywords: Technological Systems, Smart Grid, Path Dependence, Natural Language Processing, Topic Modelling, Network Analysis

JEL classification: O33; C88; L94

1 Introduction

The past couple of years have seen the emergence and growth of industries related to the generation of renewable energy (e.g. IEA, 2011). In many cases, these developments changed the paradigm in energy generation from energy-production to energy-harvesting, thus imposing new challenges on the energy transmission and consumption side (Foxon et al., 2010). While in the "old" system production would be adjusted to typical consumption levels, now production levels are literally dependent on the weather (Mattern et al., 2010). In addition electric mobility, solar cells on rooftops, and other new applications on the consumer side are altering consumption patterns (Elzinga, 2011).

The upcoming technological paradigm – in a Dosian (1982) understanding – that is evolving as a *normal solution* to cope with the new dynamics of energy generation can be found in the development of the *smart grid*.

Smartening the electricity grid means here the installation of a number of technologies along the generation-transition-distribution-consumption chain that will enable the grid to control and balance itself automatically given the new patterns of energy generation and consumption (Farhangi, 2010).

Even though the *smart grid* is increasingly gaining momentum as *the coping technology*, it still leaves much free space for technological variety to emerge in the different contexts in which *smart grid* systems are evolving. This is in line with an understanding of the technological paradigm as a problem-targeting environment which might contain a number of different technologies that potentially contribute to solving the defined problem. These technologies can be both competing and compatible and it is reasonable to assume that their composition will vary across different contexts given, for instance, the presence or absence of policies, the targeting of their development, or the existence of technological path dependencies (David, 2007).

The analysis of this systemic development is important in order to understand the state of the overall sustainable transition—and it comes up with a number of challenges. The first and possibly most intriguing is the delineation of the *smart grid* with affiliated technologies and applications. Particularly – in the case of this infrastructure system, where regulations on national, regional, or even local level have a strong influence on technological outcomes – the identification of technological trajectories within the borders of a particular country or region can provide valuable insights for understanding systemic change (Sawin, 2006).

This paper presents a new combined approach to assist scholars delineating complex systemic fields. It will be applied to map out *smart grid development* looking at both, the research and the industrial landscape in Denmark – a country which pioneered in the large scale integration of wind-power (Garud and Karnøe, 2003) and, as in 2011 was the country with the highest share of *smart grid* R&DD projects in Europe(Giordano et al., 2011). This share has increased in the recent years (Copenhagen Cleantech Cluster, 2014).

Methodologically, this research relies on the combination of methods from statistical natural language processing, vector space modelling, and network analysis. The proposed methodology is not aiming at replacing expert-insight, rather it should be seen as a tool that can help identifying patterns within complex set-ups and understanding the scale of components and, to some extent, their relations. The filtered data consists of two types of Danish text-documents: 99 R&DD project descriptions and 574 (initially 813) non-academic/industrial journal publications.

The paper is structured as follows. The following section provides a brief overview of the Smart Grid development in Denmark, some theoretical considerations related to the study of change in technical systems, and discusses various methodological approaches to exploring these. Following this Section 3 presents the text data and the preparation process. Section 3 provides a detailed description of the proposed "method-pipeline". Immediate (uninterpreted) results are presented in Section 5. Section 6 and Section 7 are short examples of how the results can be used to guide the preparation of cases. Finally, Section 8 discusses the benefits and drawbacks of the proposed method and possible further developments. Section 8 also summarizes the findings from the presented case.

2 Industrial Background, Theoretical, and Methodological Considerations

2.1 Smart Grid technology in Denmark

The traditional architecture of the electricity grid assumes a unidirectional energy flow from centralized energy plants via the transmission and distribution grids to consumers where energy production levels are constantly adjusted to match the over time fluctuating energy demand (Farhangi, 2010). Embracing the renewable energy paradigm, centralized energy production is gradually replaced by decentralized energy farming. The harmonization between production and consumption has thus to move from the traditional generation side into the transmission and consumption areas. ICT technologies will play a central role in supporting this process (Erlinghagen and Markard, 2012; Mattern et al., 2010).

In the Northeuropean set up two conceivably compatible approaches to integrating intermittent renewable energy sources are currently discussed. Firstly, the construction of a European transmission *super grid* to allow for instance energy exports from Denmark to Germany in wind-peak times (European Commission, 2010). Secondly, the development of a national *smart grid* that is able to transmit energy and information in both ways, thus allowing for harmonization by the means of flexible consumption.[1] This requires upgrading of the existing grid by adding a *layer of intelligence* – advanced measurement, communication and control technology – thus making the grid able to handle a higher share of decentralized renewable energy generation and the recently evolving consumption patterns (Elzinga, 2011). A potential socio-economic bonus of the technology: If flexible consumption can be activated by the introduction of smart functionality, costly investments in the reinforcement of the distribution system can be moved into the future or avoided (Forskningsnetværket, Smart Grid, 2013).

When defining the technology areas that are supposed to become part of the *smart grid*, the International Energy agency (Elzinga, 2011) and others refer to a framework by the National Institute of Standards and Technology (NIST, 2010). This framework identifies eight types of technology across six domains spanning from generation to consumption. These are:

- Wide-area monitoring and control
- Information and communications technology integration
- Renewable and distributed generation integration
- Transmission enhancement applications
- Distribution grid management

[1] It is often argued that both approaches can easily be combined and develop alongside e.i. *super grid* on the transmission and *smart grid* on the distribution levels, yet Blarke and Jenkins (2013) argue that the technologies might be mutually exclusive by identifying both technological and socio-economic conflicts of interest between the systems. Even though that is an important discussion, the present article will not examine this possible technological incompatibility further.

- Advanced metering infrastructure (AMI)
- Electric vehicle (EV) charging infrastructure
- Customer-side systems (CS)

While these "new" technologies are without a doubt essential for the development of the *smart grid* infrastructure, it is not given that *smart grid* systems in different countries and regions will homogeneously include all of these technologies and exclude others.

Denmark is already today counting the largest amount of R&DD projects within the smart energy area in Europe (Giordano et al., 2011, 2013). The extremely ambitious national energy agreement, passed by the government in 2012, targets a wind-power share of 50 percent by 2020; the more recently announced "Smart Grid Strategy" sees the country as a European laboratory for innovative energy solutions (KEMIN, 2013).

A recent report by the Copenhagen Cleantech Cluster (2014) suggests that in the Danish context it is more appropriate to talk about a "smart energy" system rather than a *smart grid* system. This argument has been made earlier by, for instance, Lund et al. (2012), who outlined the importance of thinking about electricity grids as embedded into a wider energy system—including energy conversion and storage. Technologies related to the transformation of renewable energy to other forms of carriers then electricity should therefore play a major role in the *smart grid* architecture. Denmark has a historically high share of buildings connected to the district heating system (Lund et al., 2010) and has made significant experiences with heat pump technologies in the past. Thus, it seems natural that these "old" heating and energy conversion technologies will have some influence on the development of the *smart grid* in the Danish context, particularly in the areas of energy conversion and energy storage. An explorative analysis of the national *smart grid* should therefore go beyond the identification of "new" technologies, taking their presence as a kind of benchmark. However, they should also account for the upgrading and integration of "old" adjacent technologies that might acquire a new role in the evolving system. Rather than checking for technologies from a predefined list, it seems more appropriate to search for involved technology components without preconceptions and then try to position and describe them and their relations to the surrounding systems.

2.2 Delineating the technology scope of an evolving technical system

The energy grid is a complex system with extremely interwoven technical, economic, institutional, and administrative structures and therewith it is a great example for a large technical system as defined by Hughes (1987). The system includes physical artefacts such as hardware components for the transmission and distribution of electricity. In addition, it contains organizations such as manufacturing firms or utility companies. All these components interact with each other following formal, normative, and cognitive rules. Since energy grids are physically connected to energy producers on the one side and users on the other, the aforementioned components also interact with artefacts and agents external to the system. Work by sociologists of technology (e.g. Bijker, 1997) give highly important insights into agency and the social construction of the technology, doing so by increasing the scope and thereby the complexity. The same is true for much of the STS literature, which focuses on socio-technical transitions (e.g. Geels, 2002). While the theoretical frameworks proposed by this literature are relatively easy to grasp multidimensionality, the high number of diverse actors and feedback loops make them hard to operationalise.

This is also the case for innovation system approaches. An analysis based on the functionalist Technological Innovation System (TIS) framework, which is often seen in energy industry studies, (Bergek et al., 2008; Hekkert et al., 2007) for instance builds on a clear *a pripri* identification of the technology in question. For the analysis of broader technological fields within the TIS framework, Hekkert and Negro (2009) rely on interpretative assessment of TIS-related events manually extracted from industrial publications.

An often taken approach is focusing on technology niches. The STS-Transition Literature depicts niches as protected spaces on the micro level for the development of innovation within rigid socio-technical systems. This strategy allows for a close exploration of the development in a narrow technological area and its interaction with the meso and macro levels. Yet, this approach requires *a priori* identification and to some extent delineation of the relevant niches.

In the present case, deciding on a particular technology focus is challenging for at leas two reasons: the large number of interacting technologies and components on the one hand and the system history aspect on the other. The latter reason relates to path dependency and institutional factors in a national setting (Kaplan and Tripsas, 2008). History matters, and therefore a *smart grid* system in country **A** will not build on the same technologies and components as in country **B**. Consequently, departing from a list of "novel" technologies such as the one on page 102 can be misleading.

The approach suggested in this paper takes one step back and helps the researcher to detect relevant techno-thematic fields in a given context that belong to a higher-level system. It makes use of text data to algorithmically identify re-occurring themes in a text-document-corpus. Rather than identifying pre-defined patterns in an existing *system*, the intention is to detect patterns in unstructured data. The number of documents in particular clusters, the date of publication, and other statistics can indicate the scope and scale of a technology component. Furthermore, the representation of the corpus as a network of documents allows the researcher to make educated guesses about the relations between single technologies. These can be studied, exploring the documents manually further in detail.

The analysis is similar to methods suggested within the stream of literature on technology- or patent mapping and will be briefly presented in the following section. The tuning of the method towards the exploration of project descriptions and journalistic texts – rather than for instance patent abstracts – adds a social, political, and organisational dimension to the otherwise purely technical analysis.

2.3 Methods for mapping of technological change

Patent analysis, particularly the exploration of citation networks, has been widely used to understand technological change and support decisions in strategic technology management (Ernst, 1997, 2003). Such networks can capture cognitive proximity between inventors inferred from joint awareness of literature that the inventors' patents have in common. The advantages and disadvantages of the usage of patent data is discussed in Griliches (1990).

Based on the seminal work of Dosi (1982) on technological paradigms and trajectories and adapting a methodology suggested by Hummon and Dereian (1989), Verspagen (2007) modelled and analysed the "flow of knowledge" using a patent collection in the field of fuel cells. Patent citation networks were used to study knowledge diffusion (Ho et al., 2014) and small world phenomena (Guan and Shi, 2012). Erdi et al. (2013) construct dynamic patent citation networks to predict emerging technology clusters. Chen et al. (2012a,b) propose an alternative method, using bibliographic coupling and clustering of patents within sliding time-frames to detect technology trajectories applied to the very case of *smart grid*. The study compares the patents filed by US inventors to the rest of the world's identifying technology areas, similar to those mentioned in Elzinga (2011).

In the last decade, various combinations of NLP and network analysis techniques have been increasingly used by a yet relatively small number of STI scholars. This research can majorly be associated with patent mapping or the detection of technology roadmaps.

Patent maps in their static-accumulative or dynamic versions are tools for the visualization of overall relationships among patents in a particular technology (Yoon et al., 2012). An established approach that incorporated NLP methods for the creation of such maps relies on pre-defined keywords and phrases in a given patent set. More recent publications criticize the use of author pre-defined keywords as a machine readable representation of the patent and suggest, rather, to deploy NLP techniques to algorithmically extract phrases that are required for the calculation of similarity from patent text fragments. Subject-Action-Object (SAO) triples as basic extracted elements are currently seen in a growing number of studies (Choi et al., 2013, 2012, 2011; Park et al., 2011). The claim, supporting SAO, is that, being syntactically ordered structures, they include the key-concepts and technological objectives of the patent (Cascini et al., 2004). While these structures are qualitatively richer, they come at the price of sparsity. The whole process of identification of semantic similarity relies on repeated term-co-occurrence over several documents in a given corpus. The combination of terms into term-chains such as SAO structures, increases the number of unique terms in the corpus and thereby reduce the probability of encountering re-occurrence. This is, however, a speculation that is yet to be tested empirically.

The basic process – similar to what this paper is presenting – can be summarized in three steps: (a) Existing or extracted keywords from text data are standardized in their spelling across a corpus using statistical NLP methods such as stemming or lemmatization, (b) a (vector space) model for dimensionality reduction is used to generate a document dissimilarity matrix given keyword co-occurrence patterns, (c) the documents (patents) are clustered given the calculated similarity measures[2].

Results of such clustering exercises help to understand technology development but can also be used to develop patent based company portfolios and technology roadmaps (Choi et al., 2013) or inventor profiles (Moehrle et al. 2005). Furthermore, this analysis can indicate areas of competition trends, emerging, even disruptive trajectories (Kostoff et al., 2004) and death-ends. Given proper expert analysis, they can support strategic R&D and acquisition decisions (Choi et al., 2011; Park et al., 2013; Yoon and Kim, 2011). Yoon et al. (2012) suggested a method to dynamically map technological competition trends, identifying areas of "patent vacuum" and what they call "technological hot spots" with strong recent patenting activity. In fact, semantic patent analysis proved to outperform other more traditional types of novelty identification (Gerken and Moehrle, 2012). Semantic patent mapping has been used to detect and evaluate risk of potential infringement in the cases of DNA chips (Bergmann et al., 2008) and prostate cancer treatment technology (Park et al., 2011). Moehrle and Gerken (2012) applied patent text similarity techniques to monitor convergence between technology areas in relation to design decisions.

While patents are a well structured and reliable source of information about theoretically available technology and its development, they do not reflect the application of the technology in a systemic set-up. The main drawback of such invention-focused approaches is their inability to account for many mainly non-technical factors related to the social and institutional framing of technology. Value driven policies, technological and institutional path dependencies, or user expectations and routines have major impact on the technological outcomes in a particular context. Thus, the conclusion made by, for instance, Chen et al. (2012b) that the observation of emerging US

[2] This basic structure is also applied in the present work. A detailed method description and introduction of the technical terminology is given in the following section.

patents in a certain field can be interpreted as the presence of a particular technological trajectory in the US, would rely on strong assumptions about a straight relation between patents and technology outcomes.

This study is an attempt to use a similar NLP driven approach for the mapping of large systemic fields. Here the method is used for identifying present technological trajectories within the *smart grid* in Denmark, accounting for some of the cognitive and institutional factors which shape the development of a technology in a national context (Kaplan and Tripsas, 2008).

3 Data overview & preparation

The analysis is based on two types of text-documents: approximately 100 descriptions of smart grid R&DD projects and initially 813 non-academic journal articles from Danish industrial publications. The former source is expected to represent the institutionally shaped technology development while the latter should provide rich information on the application, policy, and business side.[3].

Initially 102 project descriptions are obtained through `www.energiforskning.dk`, the joint database of publicly (co-) funded energy research in Denmark. The database contains detailed information on nearly 2100 projects, classified into 7 broad technology areas. This classification is interesting as such, since it indirectly grounds on the (partly political) decision to fund a particular activity or not. Thus, it can be assumed that this *pre-classified* data implicitly carries information about the technology perception by the public sector. The descriptions are usually 500 words long and briefly outline the background and purpose of the project, technologies used and, expected outcomes. Project start dates range from 1996 until 2013; however, the distribution is highly skewed towards the latest 5 years (see Figure B.5). In some few cases result descriptions are included for terminated projects—providing additional or more specific information on the technological outcomes of the

[3]The text-data used for this research was exclusively in Danish. Even though English descriptions are available for most of the projects, it is assumed that Danish descriptions are more accurate and rich. Text examples presented in this paper are translations by the author. Trajectory specific TFIDF-Keywords were however automatically translated relying on the Google Translate API.

particular activity. Since this research is not interested in the evolution of particular projects, but rather aims at identifying general technology trends where available, result descriptions are appended to the initial project descriptions. The projects span from basic research to deployment activities which is explicitly indicated in meta-data available for each activity but also can be inferred from the finance mechanism applied. That opens up for the analysis of potential technology development cycles for particular technological trajectories. Yet, this question was not central for the presented study. Project duration, budget, number and type of participants were not analysed explicitly. However, since named entities in the texts were not systematically identified and excluded, actor name appearance did certainly have an influence on document similarity calculation (see 4.2). Finally, selection filters were applied to exclude too short descriptions that indicated that a proper description is yet to be posted. A language detection module sorted out description in other languages than Danish, leaving 99 documents for the analysis.

In order to map out the scope of *smart grid* applications in a national context, non-academic industrial publications have been explored. These were retrieved from the Danish national publications database *infomedia*. A search-string was systematically built up by exploring term frequencies, n-grams, and collocations within the press releases by the Danish Smart Grid Alliance which, since it's initiation in April 2012, informs about the national *smart grid* industry[4]. An initial search returned 813 articles for the timespan 2004-2013[5].

The coverage of *smart grid* related themes remains marginal until 2009. The majority of articles before 2009 are published by the engineering journal *Ingenøren*. Only starting in 2009, more practically oriented periodicals take up the topic, indicating the upcoming interest for the *smart grid* outside the engineering community. Overall, articles come from 61 different periodicals largely affiliated with engineering and construction themes (see Table B.4 for more details). However, 81 percent of the publications relate to 12 journals

[4] `http://www.ienergi.dk/English.aspx`

[5] `(smartgrid OR (smart OR intelligent* OR klog*) DNEAR5 (grid OR energisystem* OR elnet*))`The english translation corresponds to: `(smartgrid OR (smart OR intelligent* OR clever*) DNEAR5 (grid OR energisystem* OR electricitygrid*))`, the `DNEAR5` command specifies that the distance between the array of adjective classifiers in the first parenthesis and the *grid*-synonyms in the second parenthesis is ≤ 5.

focusing on the national energy system, appliance installation, computer – and information science, the business part of the engineering, and energy industry.

Just like for the descriptions, language detection was applied to exclude non-Danish articles. Also here, too short texts (shortest percentile) were sorted out. A quick search within the retrieved documents confirmed that industrial publications often report on ongoing research projects or *smart grid* research in general. These reports are, however, not conducive for a detached exploration of technological trajectories in the domains of research and application. Documents that mentioned the term *project* or *research* in their titles or introductory abstracts were dropped. While most of the articles are clearly associated with national developments, it is possible that an article only covers technology or market developments abroad. An additional filter selected out documents that wouldn't mention "Denmark" or "Danish"in any part of the document. As expected, the number of excluded texts in this last step remained very low.

4 Methods

For both types of documents a three step analysis and several visualization techniques were applied. A detailed overview of the "analysis pipeline" is presented in Figure E.2 and Table B.1 contains explanations of language processing terminology used below. Project descriptions and the text-bodies of articles underwent (1) term extraction and filtering using basic Statistical NLP techniques. Arrays of nouns and nominal expressions were analysed for semantic similarity with the help of (2) vector space modelling. Thereby obtained document similarity estimates were used to construct a document network. (3) Network analysis algorithms were used to cluster the documents thematically. Finally, NLP was used one more time to (4) retrieve representative keywords for particular clusters and *sub-clusters*[6].

The following describes the above lined up steps in detail:

[6]NLP using the NLTK package (Bird et al., 2009), vector space modelling with the GENSIM package (Řehůřek and Sojka, 2010) within IPython, *community detection* and visualization within GEPHI

4.1 NLP based term extraction

The goal of the term extraction is to reduce the text-documents into bag of words (BOW) representations - an array of terms of high information content. These are usually nouns and noun phrases. Firstly, important noun phrases are selected by identifying high-document frequency (DF) bi-grams[7]. For project descriptions, which tend to use many standardized formulations, a domain specific stopword filter was trained and applied.

Part of speech (POS) tagging is performed using a Brill tagger, trained on the Danish Morphosyntactically Tagged PAROLE Corpus (Keson and Norling-Christensen, 1998) combined with two affix taggers. The POS identification accuracy ranges at 97 percent[8].

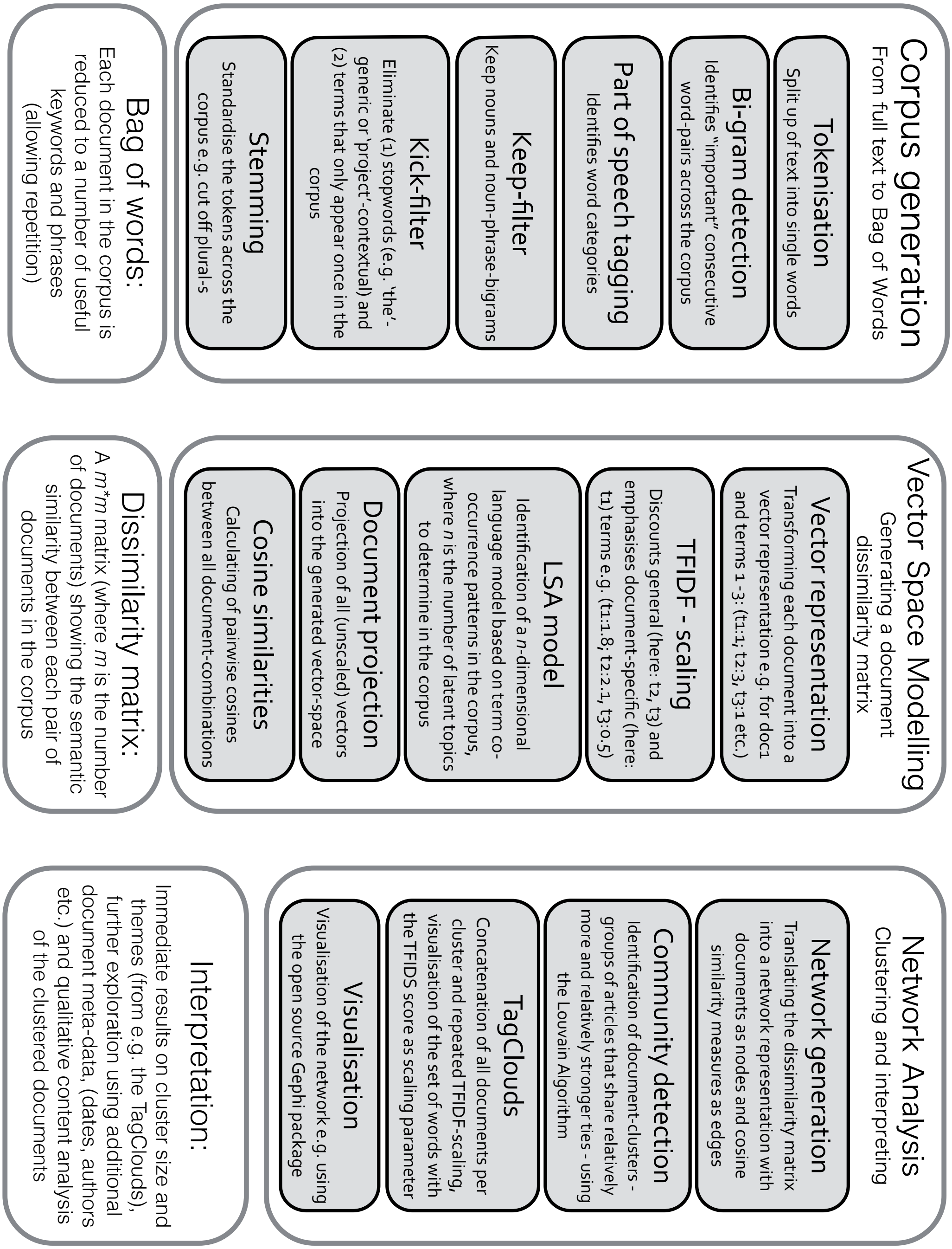
Not-nouns or noun expressions, domain specific- and general Danish stopwords, and low-DF words are dropped. For the presented analysis the low-DF threshold was set at 1, thus only excluding *singletons-* spelling-errors and very rare terms that would not contribute to the classification of documents. Finally, terms are reprocessed by stemming, which once again reduces the vocabulary by approximately 23 percent[9] .

[7]*n-grams* are consecutive term compounds of length *n*. Only compounds of nouns (e.g. "grid stabiliszation") and adjective noun phrases (e.g. "flexible consumption") were detected.

[8]The evaluation is performed by training the tagger on 90 percent (39190 sentences) of the PAROLE corpus and testing it on the remaining 10 percent (1022 sentences), which represent a previously unseen text (Bird et al., 2009).

[9]Stemming algorithms determine the root of any term and return it instead of the original term: *Innovation, innovative, innovations, innovating* $\rightarrow$ *innov*.

Fig. B.1: Detailed overview: Combination of utilized methods and techniques



4.2 Vector space modelling & Latent Semantic Analysis

The BOW extract of the documents is transformed into sparse vectors where each term is represented as (w, c_w^d) with w being the *word-ID* in the initially created dictionary and c_w^d the integer word count of w for the particular document. The resulting representation is then *tf-idf* (term frequency – inverse document frequency) weighted in order to discount generic terms across documents and equivalently promote document-specific terms.

$$TFIDF[t_i^d] = TF[t_i^d] \cdot IDF[t_i] \tag{B.1}$$

Where TF is the term t_i frequency in a document d divided by the document length and IDF the logarithm of the number of all documents divided by the number of documents, containing the term.

The returned vectors in normalized unit length of same dimensionality are then once again transformed into a vector space of lower dimensionality using the latent semantic indexing (LSI or LSA) algorithm (Deerwester et al., 1990; Dumais et al., 1988). See Figure B.2 for a schematic representation of the process.

Following Bradford (2008), a target dimensionality of 400 is chosen where each dimension can be interpreted as a topic inferred from the whole input BOW corpus. Each document is now represented as a 400-dimensional vector.[10]

$$\text{similarity} = \cos(\theta) = \frac{A \cdot B}{\|A\|\|B\|} = \frac{\sum_{i=1}^{n} A_i \times B_i}{\sqrt{\sum_{i=1}^{n} (A_i)^2} \times \sqrt{\sum_{i=1}^{n} (B_i)^2}} \tag{B.2}$$

Finally, cosines between the document vectors are calculated as a similarity measure.

[10]This choice is always a trade-off between language particularity, fragmentation and computational cost. Bradford (2008) evaluated different dimensionality and corpus size combinations, concluding that for this type of topic modelling a diminsionality of 400 is a “safe” choice.

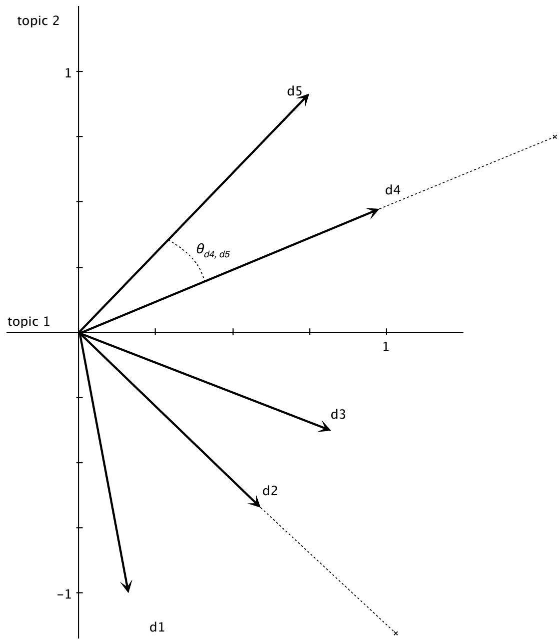


Fig. B.2: Schematic representation: Dimensionality reduction and similarity calculation within the LSA framework

4.3 Network analysis and community keyword extraction

The document similarity matrix is used as an input for a weighted undirected network where documents form nodes while edges are defined by the $\cos(\theta)$ values between the documents. The distribution of similarity values is highly skewed towards the lower bound. Therefore, a cut-off is set at $\cos(\theta) \approx 0.1$.

For project descriptions a threshold value for edge creation is set at the 80 percentile that corresponds to a maximum cosine of 0.14, meaning that cosines below that value (80 lower percent) will not form edges. For industrial publication, the percentile value was even higher (around 90 percentile). Modularity class calculation within *Gephi* is used to detect communities (Blondel et al., 2008). The basic intuition of the method is that ties within a community are more common than ties across communities. Yet, results suggest to re-run the algorithm on very large communities separately to split them up in *sub-communities*.

One observation is that industrial publications contain review-type documents that provide an overview on different technologies on the market and alike. These documents seem to be contra-productive for the clustering procedure, which implicitly assumes that each document is only associated with one particular technology or technology-area.

Therefore, for industrial publications, nodes with very high degree are manually allocated in a class container [99] before modularity classification is performed.

Keywords describing the communities are extracted by calculating TF-IDF values for community-aggregated texts using the same kind of TF-IDF transformation as before on a document-level. Scoring by TF-IDF values returns the most important keywords for a community (Salton and McGill, 1983). The TF-IDF weight can also be used for tag-cloud style visualization.

5 Results

This section exhibits the results of the above described analysis. It starts with an overview over the main detected techno-thematic communities, looking at results from the research project analysis and the article database separately. A subset of interesting fields are thereafter discussed more in detail.

5.1 Main technological trajectories in energy research

The filtering procedure, described above, generates 99 project description extracts.[11] Applying LSA and the modularity classification algorithm[12], returns a modularity value of 0.338, suggesting that the clustering is not optimal and overlapping communities might exist. As the clustering is based on the document-similarity measure and single projects can bridge over or are explicitly designed to connect different technological domains, the existence of overlaps is actually not surprising. 12 communities are detected, with an average size of 8 nodes – the largest communities having 16 and the single smallest 1 node (see Table B.2 for more descriptives). Figure B.3 shows the generated graph and indicates the thematic features of the communities in tag-cloud visualizations, where term size is determined by the respective TFIDF values.

Already the graph visualization indicates that the extent to which techno-thematic communities are clustered, varies across the the whole sample. Table B.2 in the Appendix provides a summary over the identified clusters and their features, Figure B.5 gives an overview over community sizes and start years for the constituent projects. Among the mostly identifiable technology centred communities we find projects related to the heat pump technology [4][13] and the large district heating cluster [11]. The later is however much less concentrated and seems to consist of two sub-communities, where one is more focused on the development of the technology itself and its systemic integration, while the other aims at connecting the technology to other technologies and applications. This community not only stands out in size but also is the oldest – meaning that its projects have the relatively earliest start-year on average.

Two further dense—yet rather application-focused—clusters can be found in [8], which gathers projects that explore the flexibilisation of energy consumption and [5], which aggregates activities related to systemic integration. The extent to which these thematic communities are diverse in their

[11] An automatically translated BOW extract example `[u'concept', u'air air', u'heat pump', u'focus', u'climate', u'electricity consumption', u'demonstra', u'play solution', u'heat pump'...]`

[12] using a resolution of 0.6, considering edge weight and enabling randomization

[13] Modularity class number interpreted as community or cluster e.g. [4]

technology-composition will be discussed below. Smaller unambiguously identifiable technology-areas are electric vehicles [2] and [6], decentralized communication technology and data security [0], and battery development [1]. An example for less identifiable communities can be found in [9]. Projects in this group are sparsely connected with each other. Also, (significant) ties outside the cluster are few and weak.

5.2 Central technologies, themes and applications within the industrial discourse

The initial sample of 813 articles is stepwise reduced to a number of 574. Even though the filters applied might seem very conservative, the analysis shows that 32 articles remain in the sample that seem to be very research-project-related and have been automatically grouped into one class conditioned on the presence of "project-terminology". 5 documents with the highest degree-scores in the sample have been manually allocated to the class container [99] before clustering. The idea here was to avoid "review articles" that inherently relate to all possible energy technologies and applications. A detailed analysis of the texts showed that, indeed, these 5 were very general in their contexts – providing an overview over the different *smart grid* technologies and applications that the future might bring. Apart from that, the modularity-class calculation with the same specifications as for the project descriptions, identifies 12 communities. A detailed overview over communities and their features can be found in table A2. As shown in Figure B.4, the technological clusters (heat pumps [9], electric cars [8] and district heating [4]) that can be found in the project-analysis re-appear. They form very dense clusters, not only seen in the visualization but also in the TIFIDF-value distribution. These communities do however merely account for 22.5 percent of the sample. Another 18 percent are made up by the wind-power [10], energy optimization and installation (primarily by *Schneider Electric*) [0] and residential solar [2]. As in the project-analysis, consumption flexibilization [5] is very central. New are the areas of energy business with a particular focus on export and collaboration with Asian countries [6], and the thematic policy-cluster [7]. Figure A2 summarizes the over-time development of the community sizes.

The remainder of the analysis will make further use of the thematic clustering to explore the overlapping technological area related to heat pumps more in detail. Furthermore, the business and export cluster, resulting from the publication analysis will be examined in order to evaluate the presented methods performance when applied in a less technical, and thus supposedly more abstract domain.

6 Trajectory Study: Heat Pumps

Heat pump units operate using electricity to drive compressors that concentrate and transport thermal energy. The thermal energy extracted from air or the ground can then be used for space and water heating. The reverse process is also possible to use the heat pump for cooling. In fact, using the technology for both heating and cooling simultaneously is most efficient, yet not a very common practice (Mathiesen et al., 2011a). Thermal energy can be stored for later use and pumps can also be combined with consumer side renewable energy generation units such as residential PV (Sanner et al., 2003). This option has led to growing interest in this rather mature technology in the recent years, since it can potentially become an important component for efficiency increase and because of the storage option for the flexibilization of energy consumption. The latter is particularly important for the build up of a smart energy system that is able to integrate large amounts of fluctuating electricity generation, e.g. wind power (Lund et al., 2012; Mathiesen et al., 2011b).

While the first theoretical description of a heat pump as a device for heating and cooling, by the French officer Nicolas Leonhard Sadi Carnot, dates way back to 1824, it was first in 1948 that the technology was applied in the Equitable Building, New York. Commercial heat pump unit distribution commenced in the 1950s but did not become popular until the 1970s and the Oil Crisis, when rising energy costs made electric furnaces less competitive (Hepbasli and Kalinci, 2009). Other reasons for the heat pump “boom” were the growing heat and warm-water demand and the transition from single-room to central heating. However, this was only a boom in relative terms and the technology was merely making up an average 1 percent in the European residential market share with significant difference in individual countries

(Laue, 2002). Environmental awareness and efficiency considerations can be counted as reasons for the European renaissance of heat pumps in the mid 1990s. Today heat pumps are seen as one of the key technologies to decrease CO_2 and other greenhouse gas emissions.

Denmark adopted the heat pump technology right after the oil crisis in the 1970s. Many producers entered the market, offering products that ranged from high quality pumps, some of which are still in use today, to products of very poor quality that cast a bad light on the industry (Poulsen, 2007). Today, the Danish Energy Agency estimates a total of 100.000 small residential pumps and 5.000 large industrial scale units installed. Even though this total number of installations is relatively low, the Danish market is catching up with 20.000 small mostly air-air units and 5.000 geothermal pumps sold every year (Frost-Knudsen, 2013). A new general tax on all heating systems to be passed by January 2014 is expected to make efficient heat pumps even more attractive.

6.1 Heat Pump development within Danish research

The project analysis selected 12 activities into the "heat pump" class. The TFIDF-Keyword-Cloud does not really provide much information about the important themes that constitute the cluster. Given a larger number of projects, a further clustering and topic modelling could be applied to identify *sub-clusters*. In this case, the direct "manual" analysis of the descriptions seems most appropriate. As shown in Figure B.6 the first project in the field was commenced in 2009. Until 2011 the number of newly started activities went up – peaking at 4 new projects. A brief qualitative analysis of the descriptions reveals two broad fields of activities among the projects that focus on the usage of the heat-pump technology within the new *smart grid* paradigm.

On the one hand there are projects that explore options for the integration of large-scale heat pump and district heating systems by connecting central heat and power plants (CHP) with large heat pumps, in some cases also solar systems. Such combined systems can become a more centralized way to allow for more intermittent wind power in the overall energy system, while combining the efficiency and storage options of heat pumps with the existing CHP infrastructure. On the other hand, there are a significant number of projects that focus on residential small-scale applications. These activities aim at developing and testing standards for *smart grid* ready plug-and-play solutions, remote control of pumps, test protocols, and other technology standards. While the units by themselves seem efficient and mature, knowledge about automatizes interaction with the grid has to be developed. Virtual power plant projects for small and large scale areas combine different ethnologies within a complex system with many components.

6.2 Heat Pump technology in national industrial publications

The distribution of industrial publications over time displays some similarities to the projects with overall 45 reports selected into the thematic heat-pump cluster. First reports that mention heat pumps in a *smart grid* context can be found in 2010.

Re-running of the clustering algorithm generates 4 *sub-clusters* that can guide the exploration. Two of those are obviously related to efficient residential housing and, for the most part, inform on different projects within new and old constructions. Much emphasized is the interaction between different domestic appliances; the heat pumps as heating device of choice and the management by intelligent (partly remote) control systems.

One of the *sub-clusters* takes a more industrial installation-perspective on the technology. An article (nr. 314), for instance, outlines the market potential and job creation opportunities once more heat pumps will be installed. It estimates up to 1 million new units until 2020. Other central topics of the *sub-cluster* are remote control standardization and the energy renovation of old buildings.

The largest *sub-cluster* is more (heat pump) technology focused. It outlines more generally the opportunities that the available technologies offer for the development of the energy grid, particularly concentrating on the energy storage options that are expected to facilitate the integration of more wind power and other fluctuating renewable energy sources. Another technological focus is the already in the research-analysis shown combination of heat pumps with solar. Furthermore, it groups market analysis and policy reports covering the area.

Overall, the brief analysis shows that there is a significant overlap between applications developed in research projects and the expectations towards the technology that is expressed in industrial publications. The deployment of heat pumps as a grid stabilization technology seems clearly to be one of the dominant technological trajectories within the Danish *smart grid* development.

Fig. B.3: Overview: Research project graph and cluster level TFIDF-Keywords

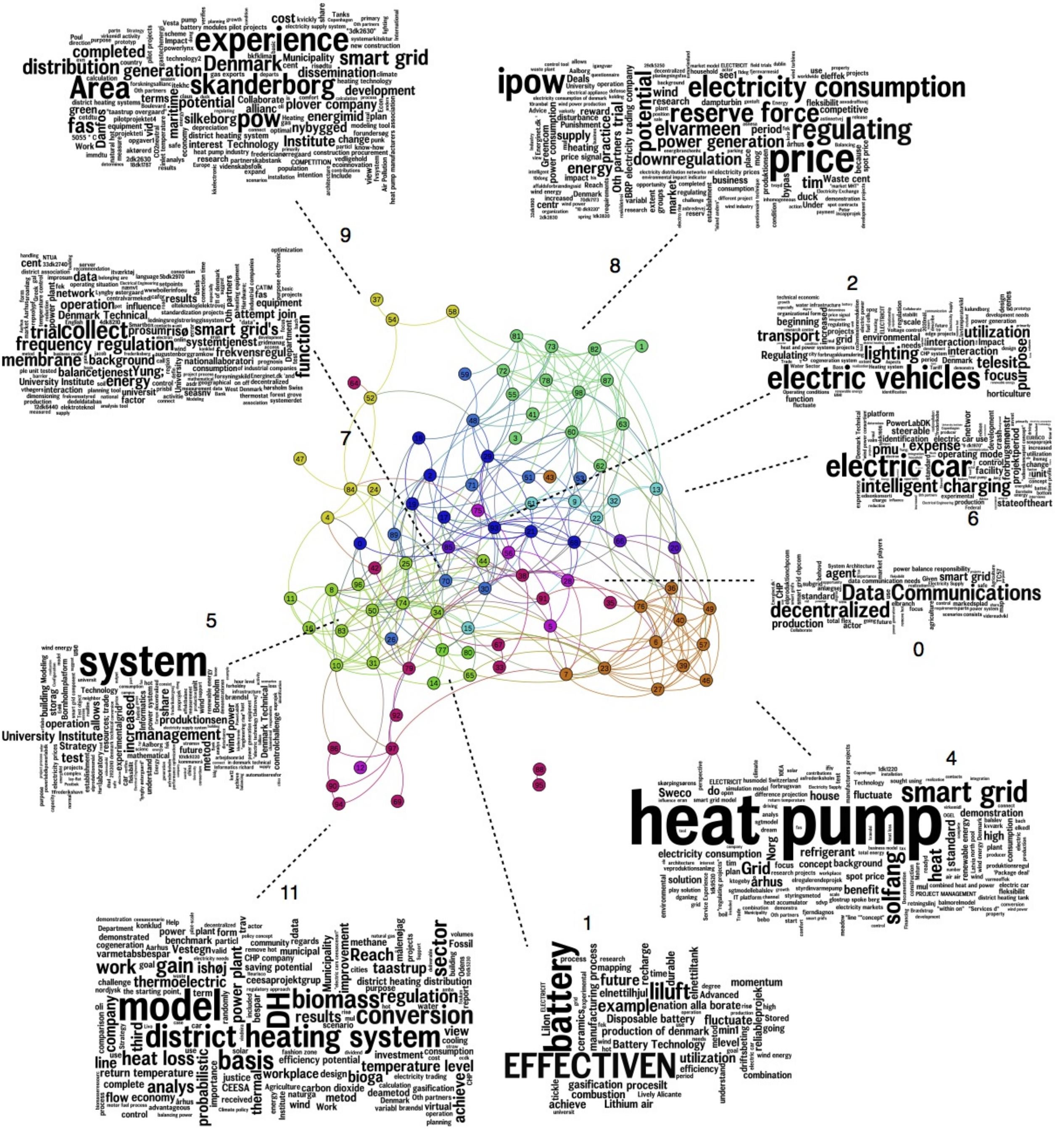
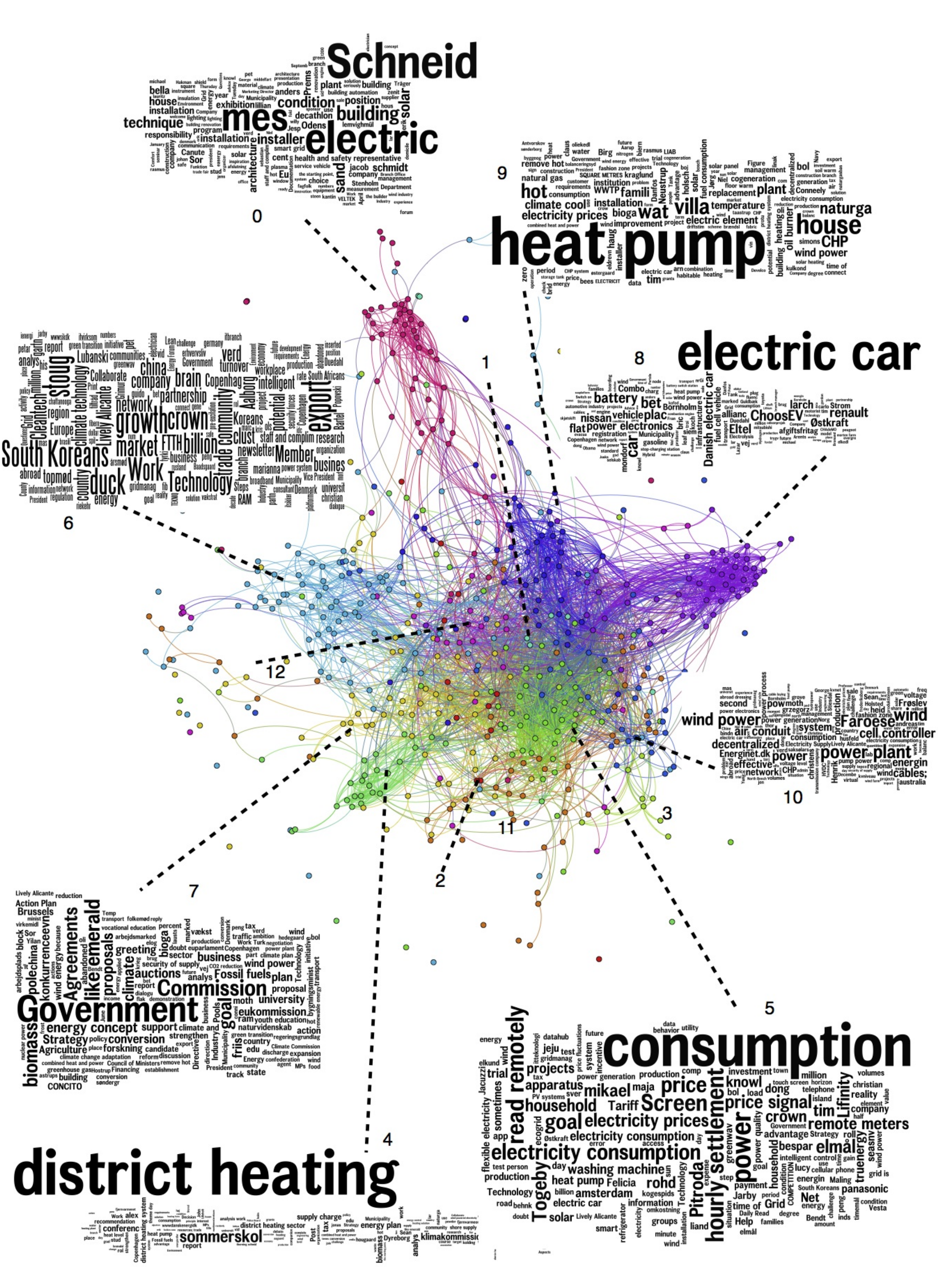


Fig. B.4: Overview: Industrial publications graph and TFIDF-Keywords



7 Thematic Field Study: Smart Energy Technology Business and Export

Gathering almost 20 percent of the publications, the Technology Export and Business cluster – as it can be called given the TFIDF-Keywords - is the largest thematic community. It has no technological focus but some of the specific targeted markets can already be identified in the extracted keywords. The clustering algorithm is used once again to generate 6 *sub-clusters*. 5 of which make up at least 97 percent of the initial group. One of the *sub-clusters* takes up 40 percent, the other 4 around 14 percent each.

The first, rather loose, *sub-cluster* does not refer much to business or trade but to job creation in the Danish installation and to some extent IT-industry. Opportunities arise, according to the grouped articles, from the connection of new hardware to the grid and the development of communication solutions.

The other nearby 16 percent *sub-cluster* is more dense and, to a higher extent, focused on the installation industry. Many of the publications present studies and estimations about the market opportunities related to the grid development and, more broadly, the energy system transformation. In the desired case, the industry is expected to earn 5 billion DKK (approx. 900 million USD) yearly up to 2020. Other market estimations also mention the most central national technology competences within the *smart grid* area: Grid-automation, smart-home appliances, and measurement technology have the potential to generate 2.500 jobs in Denmark and further 2.000 in the EU.

One smaller 12 percent *sub-cluster* summarizes more generally articles about required investments and changes in order to develop the *smart grid* in Denmark. While the creation of IT and hardware solutions is important, coordination is emphasized to be key in this technological system. One important step was the initiation of the Intelligent Energy alliance in 2012 that brings together around 130 players with interest in *smart grid*. A central publication outlines the importance of incentive creation for the utility companies that are the central actors in the current grid infrastructure.

The last small *sub-cluster* focuses on growth. It brings together further market development studies, reports on policies and initiatives that (could) perpetuate growth from the energy system transformation – where *smart grid* development is always central.

The large *sub-cluster* is primarily looking on the energy technology market and export development. *Smart grid* technologies are expected to repeat the success of wind power and district heating technologies that still drive Danish energy technology export. Outside the EU, the US, with the in late 2012 announced *smart grid* strategy, represent an important market. Much more pronounced, however, is the Asian marketplace and here particularly Korea as both market and strategic partner in the development of technology. The Asian country embraced the green paradigm rather late but is moving fast and expects *smart grid* investments of 7.2 billion through 2030. The Global Green Growth Forum, initiated in 2011 between Denmark, South Korea, and Mexico provides another platform to facilitate interaction and trade. In 2012 also Qatar, Kenya, and China joined the organization. Collaboration between different actors, especially the utility companies, is outlined as a key condition for success on the international markets.

8 Discussion

The depicted brief analysis demonstrates how the presented method can be used to map technology development and can help to structure and describe the socio-economic environment which contains applications, expectations, markets, policies and organizations. A detailed exploration or the elaboration of a case study or narrative was not intended.

Research project descriptions in summarized form as obtained through `energiforskning.dk` seem to be a concise and, in the same time, sufficiently rich and reliable source of data to map the various technology focus-points in the national research landscape. The brief summaries usually name the involved technologies, applications, and the technical context in which these are embedded. Yet, they vary in length and detail. The extracted industry publications contribute with many diverse and interesting insights into the variety of applications and environmental factors. They open up for the understanding of the cognitive level, or as proposed by Kaplan and Tripsas (2008), the collective technology framing. This seems to be useful for exploratory and descriptive studies of a complex systemic field. The applied topic modelling and clustering generates a structure and indicates the most pronounced aspect of the environment. However, in comparison with the project-analysis, the trade-off between rich and structured data becomes obvious. While project summaries follow an implicit structure, as for instance, research paper abstracts would do, industrial publications are inherently "messy". Smaller issues as for instance repeated reporting about one single event or policy can be avoided by limiting the analysis to only one journal; perhaps even only on one particular format within the journal. In the presented case, the Danish Energy Periodical (Nyhedsbladed Dansk Energi), which was the source of 44 percent of all articles, could have been chosen (see Table B.4). Even though the applied filtering of extracted text-files can be called rather conservative and the clustering did generate coherent thematic communities, the multidimensionality of the technology and, particularly of its surrounding environment, complicates the interpretation of the grouped publications. Often it is unclear whether a cluster can be interpreted as a dimension, such as policy or market, or rather represents a technical component such as the heat pump as part of the technology-dimension.

While not yet implemented here, automatized entity recognition could make the mapping more powerful. The exclusion of actor-names from the topic modelling would decrease the impact of actual actor interaction on the thematic structuring, while actor-context linking could indicate the activity of actors in particular technological or thematic fields. This in turn could enrich the analysis of "real" networks, e.g. research collaboration networks by generating actor-covariates. Another way to optimize the method could be through implementation of automatized hierarchy/taxonomy building as suggested by Henschel et al. (2011) .

Turning to the *smart grid* case, the exploration shows that *smart grid* technology is more than merely a combination of artefacts and services that are often mentioned under the collective notion of the *layer of intelligence*. These new ICT-heavy technologies are essential for precise controlling of the "new grid". Yet, in the Danish context, mature consumption side technologies, such as heat pumps and district heating systems, will become evenly important since flexible energy consumption and storage is necessary in order to integrate the growing amount of sustainable energy generation. *Smart energy* technologies are expected to contribute to economic growth and spur energy technology export. In the international context, a particularly interesting country – also for future comparative research – is South Korea. The Asian country does not only move quickly in the development of smart grid technology – obviously creating different technological paradigms – but also seems to have a great interest in collaborating with Denmark.

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Figures and Tables

Fig. B.5: Projects modularity classes over time (smallest excluded)

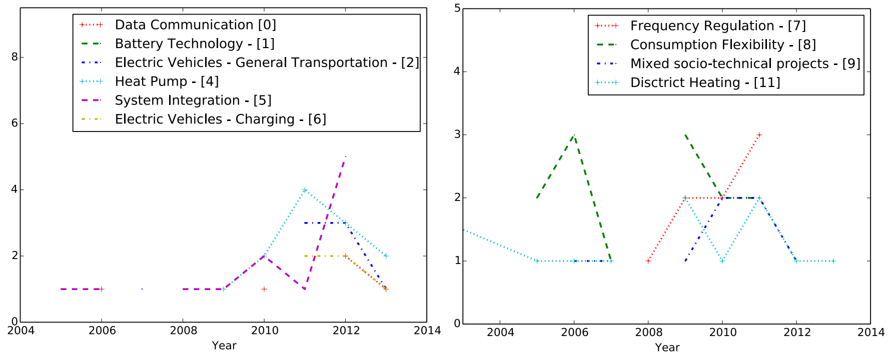
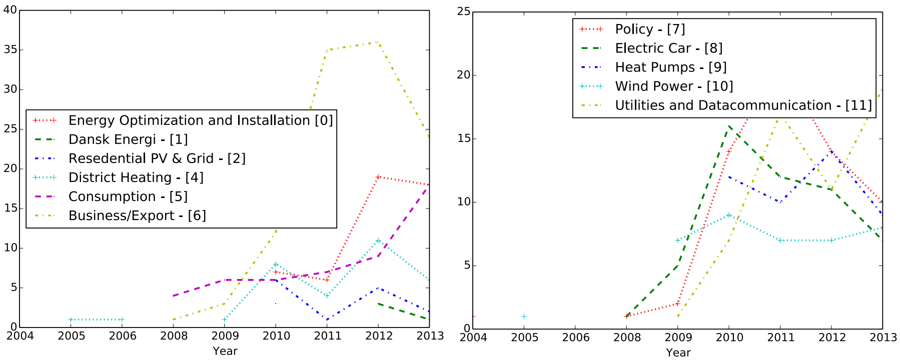


Fig. B.6: Publications modularity classes over time (smallest excluded)



Notes: Year indications are taken from project start years and article publication years respectively.

Table B.1: Overview table: Natural language processing terminology used in the article

Term	**Abbreviation**	**Definition**
Bag of words	BOW	Unsorted collection of not unique words that are meant to represent a document, usually nouns and noun phrases
Noun phrases		Expressions consisting of a noun and one or more other non-nouns that carry a specific meaning in this particular combination and sequence
(Bi-) n-grams		Combinations of n words following each other in a document
stopwords		Common generic terms in any language that as such are not carrying contextual information, for instance, prepositions and pronouns
Part of speech tagging	POS	Algorithmic identification and annotation of word types in a text
Brill tagger		Inductive and resource efficient algorithm to perform POS based on identified rules about any language learned from a training-corpus
PAROLE Corpus		Large collection of manually annotated text in Danish, which can be used to "train" a tagger
Document frequency	high/low-DF	Words that appear disproportionately often or seldom (1 time – singletons) in a text collection. While the former are often stopwords, latter cannot be used to induce similarity between several documents as they only appear once
Stemming		Algorithmic process for reducing inflected (or sometimes derived) words to their word stem in order to increase identical terms across documents in a text collection
term frequency–inverse document frequency	TF-IDF	Numerical statistic that is intended to reflect how important a word is to a document in a collection. The tf-idf value increases proportionally to the number of times a word appears in the document, but is offset by the frequency of the word in the corpus which helps to adjust for the fact that some words appear more frequently in general. (adapted from Wikipedia)
Latent Semantic Analysis	LSA (or LSI)	A technique in NLP, in particular vectorial semantics, of analyzing relationships between a set of documents and the terms they contain by producing a set of concepts (topics) related to the documents and terms. LSA assumes that words that are close in meaning will occur in similar pieces of text and allows to calculate semantic similarity values between documents in a collection. (adapted from Wikipedia)
Target dimensionality		LSA uses singular value decomposition to reduce the number of unique terms in the collection to a pre-defined number of topics which are in the same time the dimensions in the vector space model.
Document similarity matrix		Square matrix of all documents in a collection obtained by multiplying the rectangular matrix between by LSA identified topics its transponse.

Table B.2: Descriptive statistics, Project description clustering

MC	Technology/Topic	Start Year	AVD	Size	Rel. Size
0	Data Communication	2010.6	1.96	5	5.10
1	Battery Technology	2008.3	1.38	3	3.06
2	Electric Vehicles – General Transportation	2009.9	2.26	9	9.18
3	Water/Mambrane Energy storage	2012.0	0.00	1	1.02
4	Heat Pumps	2011.3	2.95	12	12.24
5	System Integration	2008.8	2.98	13	13.27
6	Electric Vehicles – Charging	2011.3	2.04	6	6.12
7	Frequency Regulation	2008.9	1.91	9	9.18
8	Consumption Flexibility	2008.4	2.48	14	14.29
9	Mixed socio-technical projects	2009.5	1.21	8	8.16
10	Consumption & Frequency control	2008.3	1.89	3	3.06
11	District Heating	2005.4	1.28	16	16.33

Notes: Modularity Class (MC), Technology/Topic interpretation from TFIDF-Keywords, average project start year for each modularity class, average (edge)weighted degree (AVD), Relative Size in percent.

Table B.3: Descriptive statistics, Industrial Publications clustering

MC	Technology/Topic	Publication Year	AVD	Size	Rel. Size
0	Energy optimization and installation	2012.0	15.64	50	8.71
1	Dansk Energi (company)	2011.3	32.26	7	1.22
2	Residential PV & Grid	2011.2	23.60	14	2.44
3	Dong Energy (company)	2011.4	15.08	18	3.14
4	District Heating	2011.1	18.75	32	5.57
5	Consumption	2011.3	32.71	50	8.71
6	Technology Export & Business	2011.5	15.44	112	19.51
7	Policy	2011.1	21.60	63	10.98
8	Electric vehicles	2010.9	27.59	52	9.06
9	Heat Pumps	2011.4	27.90	45	7.84
10	Wind	2010.8	23.66	39	6.79
11	Utilities and Data-communication	2011.7	20.81	55	9.58
12	R&DD Projects	2011.2	21.92	32	5.57
99	Excluded-Too high Degree	2012.0	78.88	5	0.87

Notes: Modularity Class (MC), Technology/Topic interpretation from TFIDF-Keywords, average publication year for each modularity class, average (edge)weighted degree (AVD), Relative Size in percent.

Table B.4: Overview: Sources industrial publications

Source/MC	0	1	2	3	4	5	6	7	8	9	10	11	12	99	Total	%
Alt om Data				1		1	2					1			5	0.9
Bedre Hjem		2				1				1				2	6	1.0
Bo Bedre										2					2	0.3
BygTek										2					2	0.3
Byggeri	1														1	0.2
Byggeteknik					1	1		2							4	0.7
CSR	2	1					2		1						6	1.0
Computerworld				3		1	10	1	2	1	1	1			20	3.5
DI Business				1		1	8	3	1			1	6		21	3.7
DI Indsigt							1								1	0.2
DSbladet					1								1		2	0.3
Dagens Medicin						1									1	0.2
Dansk VVS	2		2				1	1		2	1				9	1.6
EksportFokus							3						1		4	0.7
El og Energi								1	1						2	0.3
Electra	3		1			4	2	4	1	1	3	1	2		22	3.8
Elektrikeren	2		1			1	4		1	1	1	1			12	2.1
Elektronik & Data													1		1	0.2
Energiwatch							1					1			2	0.3
Erhvervsbladet							1								1	0.2
Erhvervsmagasinet Installatør	2														2	0.3
Fjernvarmen					15					6		2			23	4.0
Fritidsmarkedet						2				1					3	0.5
Hvidvare-Nyt	1					1		1						1	4	0.7
Ingeniøren	1	1	4		5	12	4	7	3	8	9	5	1		60	10.5
Installatør Horisont	8	1				1	3	1		3		1	1		19	3.3
Jern Og Maskinindustrien	6				1		5	1					1		14	2.4
Jern og Maskinindustrien	2								2	1	1				6	1.0
Karrierevejviser											1		1		2	0.3
Kommunen							1						1		2	0.3
LandbrugsAvisen								1							1	0.2
Magasinet Finans												1			1	0.2
Magasinet Statsindkøb	1							2							3	0.5
Magisterbladet							1	1							2	0.3
Mandag Morgen				1			2	3			1	1	1		9	1.6
Mandag Morgen Navigation						1									1	0.2
Mandag Morgen News							3								3	0.5
Maskinmesteren		2			2		3		1		1	1	1		11	1.9
Mester & Svend										1					1	0.2
Mester Tidende	3						1		1						5	0.9
Motor-Magasinet									3						3	0.5
Natur & Miljø									2						2	0.3
Nyhedsbladet Dansk Energi	13		6	7	7	19	51	34	33	13	20	36	13	1	253	44.1
Optimering														1	1	0.2
Pack Markedet	1														1	0.2
Proces-Teknik				2											2	0.3
Prosabladet							1								1	0.2
Samdata										1					1	0.2
Teknovation				2											2	0.3
Telekommunikation				1			2								3	0.5
Tænk						3									3	0.5
byggeplads.dk	2											1			3	0.5
danskVAND										1			1		2	0.3
Økonomisk Ugebrev CFO												1			1	0.2
Totals															**574**	**100**

Paper C

The Danish Smart Grid System – Elements & Functional Dynamics

Roman Jurowetzki

The chapter is based on the data and structure of the report Mortensen, J., Jurowetzki, R., & Dyrelund, A. (2014). The Smart Energy System: Asset mapping of Danish competencies across the value chain, Copenhagen Cleantech Cluster, 2014.
It uses the survey data and insights from interviews gathered for the report but follows its own structure and investigates a different objective.

I would like to thank Jonas Mortensen from the Copenhagen Cleantech Cluster and all other project partners that contributed to the elaboration of the report "The Smart Energy System: Asset mapping of Danish competencies across the value chain". I am also grateful to colleagues from the IKE group for their comments during the preparation of the survey.

Abstract

This chapter draws on the technological innovation system framework and the findings from Chapters B and D to explore the drivers behind the development of the Danish smart grid and the transformation of the adjacent energy system(s). The analysis investigates system functions and evaluates the performance of the TIS. The chapter draws on the report "The Smart Energy System: Asset mapping of Danish competencies across the value chain", co-authored with the Copenhagen Cleantech Cluster and is empirically mainly based on survey data gathered during the report preparation. Overall, results suggest that – spurred by strong collaboration between companies, target setting by the public sector, and engagement of the knowledge institutions – the electricity grid is moving towards "becoming smart". While this development is essential in order to maximise the benefits from increased renewable shares in energy production, the smart grid should not be seen as the final goal but as part of an evolving smart energy system. This development is conditioned on a more coherent institutional alignment, to happen in future, for instance, through the adjustment of the tax system that currently prevents the application of several promising solutions. Furthermore, the analysis suggests that the development can be spurred by increased collaboration across different technological fields and a more cautious integration of incumbent companies as it is currently the case.

Keywords: Smart Grid, Technological Innovation System, Danish energy system

1 Introduction

The development of the Danish smart grid and the current transformation of the various energy systems has been explored in Chapters B and D, focusing on specific aspects of this process. Chapter B used a novel approach to looking at the conceptualisation of the technology within the national research sphere and in the public discussion, drawing conclusions about the scope of the technology in the Danish case. As suggested by Lund et al. (2012) in the Danish case the developing smart grid is technologically much closer to what can be called a "smart energy system" and therewith differs from, for instance, the more specific but "narrow" smart grid understanding of the International Energy Agency (IEA). Chapter D analyses the evolution of related research networks, highlighting the role of the incumbent energy companies and identifying their growing dominance.

The results of these two articles have been informative for this chapter and a report co-authored with the Copenhagen Cleantech Cluster (CCC report) (Mortensen et al., 2014). The main objective of the report was to identify technological competences of Danish companies within the broad and poorly delineated field of "Smart Energy" but also give an understanding and evaluation of the development-drivers of these technologies. The results of Chapter B have been guiding for the design of the survey underlying the report and the present Chapter. While both are drawing on the same data sources, this chapter is very different from the report. Using the technological innovation system (TIS) approach (Bergek et al., 2008b), it aims at mapping the structure and functional dimension of the Danish smart grid field in its broader understanding. The approach with its strong functional assessment is also used because it allows to evaluate the performance of the focal TIS. It should be highlighted already here that the TIS framework as used in this chapter does not explicitly perform a dynamic analysis. The exercise is mostly an in-depth mapping that allows to infer conclusions about the drivers behind the technological development in question.

Some of the insights emanate from the CCC report and this will be explicitly commented. Unless otherwise mentioned all calculations and charts have been prepared specifically for the chapter.

A particular emphasis has been put on the mapping of the system's structural components – especially the actors. Given the broad scope of the field and the diversity of technologies that are part of it, it is not possible to point to a certain sector in order to find the involved actors. The results from Chapter B and expert interviews helped to generate a list of technologies that can be considered as related to the broader smart grid. Organisations have been identified as they reported to have activities in the listed technological areas. Also, this chapter exploits relational data and network methods. The association between companies and the different technologies is used to construct a network of technological activities and a map of actors. This allows to explore the relation between the different technologies and map the actors into the *technological space*.

Given the short time period between its explicit conceptualisation and mentioning in research and by policy makers, and also considering that large technological systems such as the energy grid are usually resistant to change, the Danish smart grid has made considerable progress. The 2013 edition of the European Commission's report "Smart Grid projects in Europe" (Giordano et al., 2013) outlines Denmark's strong leading position within smart energy research, development and demonstration. Among all European countries, Denmark has the highest involvement in R&D projects as compared to demonstration and deployment and the highest research investment per capita and consumed KWh.

Significant challenges for the development are among others: technological and regulatory uncertainty, the power of established companies that seem to employ strategies to maintain dominance and protect incumbent technologies (against more radical solutions), and the current energy tax framework.

This chapter is composed as follows: the following section presents the theoretical background and the TIS framework with a proposed scheme of analysis. Section 3 explains the empirical sources used. Then section 4 discusses and delineates the technical scope of the analysis. The remainder of the chapter is segmented following the TIS analysis scheme as proposed by Bergek et al. (2008b) – Mapping of the structural components (5), description of functional dynamics (6), assessment of system performance (7), identification of inducement and blocking mechanisms (8), and finally a discussion including a performance summary and detected key policy issues (9).

2 The Technological Innovation System as a Scheme of Analysis

The bibliometric literature review in Chapter A explored different strands of scholarly publications related to technological change and confirmed the Technological Innovation System (TIS) framework as being well suited to study the transformation processes of large technological systems. Its systems approach to innovation, the dynamic perspective, and the focus on delineated technological fields fit well with the present case. The review also identified several conceptual elements less emphasised within the TIS framework that can be used to refine the framework, helping to adapt it to the focal empirical setting. This section will present the TIS framework, highlighting the elements that will be added or altered in order to reach a better alignment for the analysis of the Danish smart grid development.

2.1 The emergence of the concept

The technological innovation system with its perspective on networks of actors and institutions associated with the generation, diffusion, and utilization of a particular technology has been widely used to understand processes of sustainable technological change (Truffer et al., 2012). A TIS is less broad and less complex than the national innovation system or the sectoral system and thus allows to focus and carry out analyses on lower levels of aggregation. What the various versions of the innovation system approach have in common is that they take a systems view on innovation, meaning that economic change can not be explained by individual firms or single episodes of technological change, but instead they must be understood as elements of a larger system (Carlsson and Stankiewicz, 1991). Technological change happens within the context of such systems and is to a large extent the result of interaction between system elements. Its focus on emerging technologies with a certain level of novelty in contrast to established solutions and the explicit approach to identification of barriers and drivers of innovation have made the TIS approach popular in the research of energy technology and more broadly sustainable technologies (Carlsson and Jacobsson, 1997; Jacobsson and Bergek, 2004).

The framework has been utilised in the more general studies on renewable energy technology (e.g. Jacobsson and Johnson, 2000) but also for more focused analyses of, for instance, wind power (Jacobsson and Karltorp, 2012), photovoltaics (Dewald and Truffer, 2011), biofuels and biomass (Meijer et al., 2010; Negro and Hekkert, 2008; Surrs and Hekkert, 2009; Suurs and Hekkert, 2009), carbon capture (van Alphen et al., 2010), fuel cell and hydrogen technologies (Suurs et al., 2009) and several other fields.

The article by Carlsson and Stankiewicz (1991) that proposed the framework contains many references to the notion of *development blocks* (Dahmén, 1988; Enflo et al., 2007) which are defined as “a sequence of complementaries which by way of a series of structural tensions, i.e., disequilibria, may result in a balanced situation”. At the core of such a block are one or several related basic technologies that follow their technological trajectories within an overall technological paradigm as later described by (Dosi, 1982). These processes happen within a particular context defined by the economic environment, organizational/institutional factors, and historical circumstances. This understanding of the technological basis of a TIS as a co-evolving cluster has become less pronounced as the TIS framework diffused and most of the attention of many studies have been put on clearly pre-defined elements and activities within the TIS. The present analysis will aim at highlighting the present interdependencies and interactions between technological artefacts within the focal system and in its immediate surroundings. The setting of the system boundaries and interaction with the surrounding structures have been pointed out as an analytically challenge (Carlsson et al., 2002). A recent article by the core authors within the TIS tradition picked up the theme of the context and argued for a better conceptualization of context interaction within the TIS framework (Bergek et al., 2015):

> Structures and processes inside a focal TIS are generally well conceptualized in the literature. [...] what happens outside and across the system boundary has been less systematically worked out.

Mapping the *outside* and the analysed system’s external connections is very important especially in the case of sustainable energy technologies that are supposed to function in a complex structure consisting of old and new elements. This set-up also implies that path dependence and interdependency play a much stronger role on several levels as compared to system independent or at least less dependent innovations. Yet, the established physical and institutional structures are not necessarily inhibiting (as often portrayed in transition literature) but can also generate opportunities and niches for innovative solutions, which will vary with the set up of the former.

For the present case, the concepts of tension, disequilibria and sequential complementarity seem useful. The transformation of the electricity grid, its adaptation to the increasing share of fluctuating renewable energy sources, and its development into a smart grid are seen as a sustainable transition of a large technical system – hence a dynamic process.

The dynamic force that drives much of the smart grid development can be understood as resulting from a disequilibrium between the development of energy generation technology and inertia in the area of the energy grid technology. Resolving the structural tension generates opportunities for progress and may lead to new tensions. Apart from the obvious structural coupling between the grid and energy production technologies, several other fields of potential tension are present and will be discussed in the structural analysis in section 5.

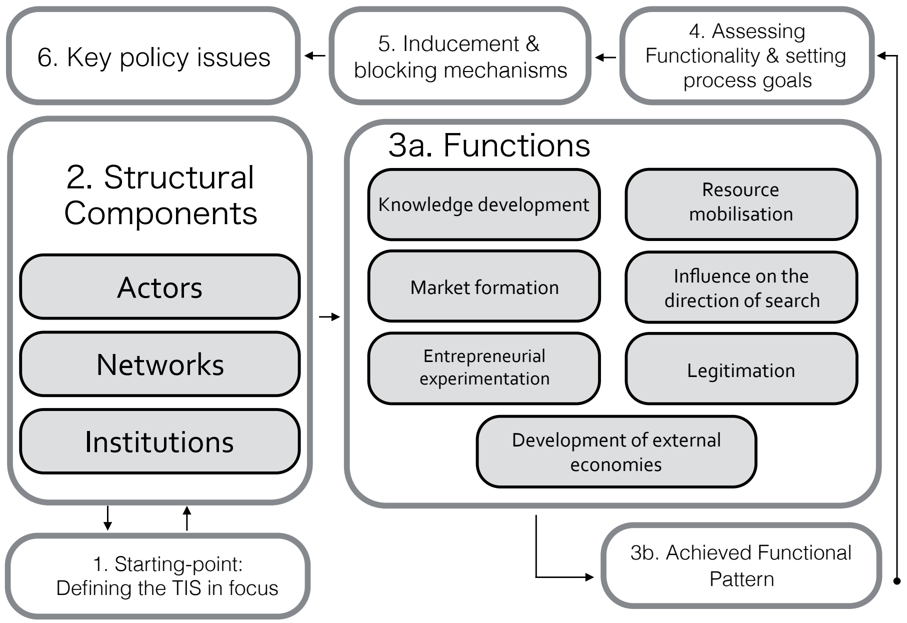


Fig. C.1: The scheme of analysis (adapted from (Bergek et al., 2008b))

In contrast, to other types of innovation system approaches, analyses that built on the TIS framework have put a stronger emphasis on the functioning of the system, rather than its structure. The "functional dynamics" approach goes back to the work by Johnson (2001) that was an attempt to overcome conceptual heterogeneity in the innovation systems concept, by understanding what is "happening" in the system rather than describing its structure. This type of analysis has become popular in academic publications and policy reports particularly since the publications of the article by (Bergek et al., 2008b) that outlines a scheme of analysis for the framework (cf. Figure C.1).

The scheme suggests the combination of six steps or sub-analyses – two of which, the structural and functional analyses, build the core and are more extensive as the others. The starting point is a working definition of the TIS in focus, step two represents a *structural analysis* of the system, a mapping of actors, networks, and institutions, which might lead to a redefinition of the initial TIS delineation. Step three is the central part of the analysis which is usually associated with the TIS analysis – the mapping of the functional patterns which are split into seven key processes. The theoretical reasoning behind the selection and evaluation of these functions can be found in Bergek et al. (2008a,b); Hekkert et al. (2007). In step four the scheme suggests assessing the overall functionality of the TIS against the backdrop of the earlier findings and with respect to the current development stage of the system. This requires to find and evaluate indicators that are appropriate for the current stage that can be formative for new and experimental fields. The TIS can also already have developed towards a growth phase in which case indicators relating to economic activity would be more informative than measures that reflect research and experimentation efforts. At this point it should also be considered to look at the interaction dynamics between the functions as argued by (Hekkert and Negro, 2009b), which can lead to reinforcing positive or inhibiting negative cycles. The fifth step aims at identifying inducement and blocking mechanisms that impact the described functions. This part of the analysis is supposed to reveal policy issues that can be specified in the final sixth step.

This chapter will adapt the above depicted scheme, putting a strong emphasis on the challenges associated with the delineation of the system. Particularly the findings from chapter B will be used to inform the system definition. Closely related to that is the issue of context awareness and coupling of the TIS on different levels with surrounding structures.

Besides, the chapter will intend to highlight the role of path dependence as a core property of LTSs and how it influences the key functions of the TIS.

The following section will provide a brief overview of the data sources that are used for the analysis.

3 Empirical Sources

The present chapter is empirically based on data obtained from several complementary sources. The central of those is the report "The Smart Energy System: Asset mapping of Danish competencies across the value chain", co-authored by the thesis author with the Copenhagen Cleantech Cluster. The report itself relies on an extensive survey and interviews with actors from the energy sector. The primary goal of the publication was to map competences of Danish companies. Yet, both, the survey and the interviews were informed by the theoretical considerations and findings of the earlier chapters of this thesis, and thus the obtained data is also suitable to assess the development of the Danish smart grid (as a part of the smart energy system) more broadly.

The survey was conducted in spring 2014. It has been sent out to members of the largest Danish energy related industry organisations, including the Confederation of Danish Industry (DI), the Danish Board of District Heating (DBDH), and the Lean Energy Cluster.[1] The 15 question of the survey covered roughly 5 areas: basic company characteristics that were complemented by company register data, further fields were technological specialization & competences, innovation & barriers, revenue & exports stemming from *smart energy technologies*, and collaboration patterns including a detailed collaboration partner mapping.

174 companies and organisations responded to the survey. The sample was reduced to 148 to fit the below technical discussed scope of this chapter. A detailed overview of the questions will be given below, along with the analysis of system functions. The questionnaire can be found in the appendix.

In addition, a number of interviews have been conducted.[2]

[1]A response rate can not be provided, as no pre-specified survey recipient list was used – partly in order to identify organisations that are related to the field without deciding on that *a priori*. Generally surveys carried out by CCC have a very high response rate, as participating companies appear in the report, which can be set equal with "free advertisement placing". As benchmarks for the assessment of the sample size can be considered (1) the number of individual organisations in the analysis in Chapter D – 132 and (2) the number of innovative Danish companies that very broadly associate with renewable energy – 290 (Christensen et al., 2016)

[2]Experts who have contributed to the report include Anders Dyrelund, Rambøll, Leif Sønderberg Petersen, DTU National Laboratory for Sustainable Energy and World Energy Council, Allan Schrøder Pedersen, DTU Energy Conversion, Lea L. Lohse, DTU PowerLabDK, Brian Elmegaard, DTU Mechanical Engineering, Lars Hummelmose, DBDH, Preben Birr-Pedersen,

Results from paper B were considered not only during the construction of the survey but also as inputs for the structural mapping of the system and the assessment of system functions, related to *knowledge production* and *guidance of search*.

The reports by EUJRC (Giordano et al., 2011, 2013) provided a valuable European perspective on smart grid research for comparison. Finally, the chapter also draws on a large amount of "grey literature" — policy documents, press releases by associations, industrial publications and other related documents.

4 Setting the Scope: The TIS behind the Danish Smart Grid development

The process of defining the focal TIS that will be the object of the analysis can be broken down into three elements, which translate into questions to be answered here. The first one, the choice of the spatial domain is straightforward – this study takes a national perspective looking at the Danish system. The technological focus and the choice of an appropriate level of aggregation are more challenging. At this point the framework suggests deciding between a product or a knowledge field to be used as a focusing device. In the present case, the focal system is connected to a number of related knowledge fields, which all contribute to the development of various technologies that have to function within one integrated system in the future. Chapter B aimed at delineating the field looking at the technological scope of the Danish Smart Grid research and the industrial discussion related to it by analysing text data. The results of this exercise show that smart grid is seen broader as the purely technological international definition would suggest it. The International Energy Agency (IEA) defined the smart grid as "an electricity network that uses digital and other advanced technologies to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands to end-users". The understanding of the smart grid in the political and industrial discussion comes much closer to what energy experts would refer to as the "Smart Energy System". Such a system goes beyond

Lean Energy Cluster, and Sune Thorvildsen, DI Energy.

the development of the power grid into a smart (but still electricity) grid. The smart energy system – as it is envisioned – integrates different, traditionally unconnected grids in order to optimise the overall efficiency. In this chapter, this broader understanding of the smart grid will be taken as a point of departure and it will be specified when the smart power grid is meant. Now, where to draw the line?

The mapping in chapter B indicates for instance that energy conversion and storage technologies such as heat pumps are seen as essential components, located at the intersection between the (smart) power grid and the heating system, which in the Danish case constitutes a well-developed grid on its own. Far less developed but technologically similar and potentially complementary is the cooling grid. The gas grid is another system that forms part of the evolving smart energy system. A large number of decentralised combined heat and power plants form already today functional links between the gas, heating, and electricity systems (Lund et al., 2012). Further (smart) components are also being added at these intersections to allow for efficiency increasing functionality, which mostly aims at conversion and storage of excess electricity from renewable sources utilising other energy carriers – e.g. synthetic gas, heat, and cold. Finally, with transportation, there is an area that traditionally has not been related to the energy system. Electric mobility is yet rather marginal, yet once it increases in scale, it will impose challenges for the electricity grid. But it can also offer opportunities in terms of decentralised storage and balancing capacity within the batteries in each vehicle. The technology elements on the grid side that are expected to manage the interaction between vehicles and the grid are certainly parts of the smart grid – even according to the more *conservative* definition as for instance by NIST (2010).

This broad view implies a high level of aggregation, which will make it difficult to identify issues in different areas of the transforming energy system. Also, such a delineation brings together technologies initially belonging to very different industries and maturity levels. However, at this point, it is important to remember that the term smart grid is (also) a political *buzzword* and that therefore same policies and regulations are likely to address (perhaps) technologically different areas. Besides, it should be highlighted that the overall transformation of the energy system (also the electricity sub-system) can be seen as a process of decentralisation and integration during which a growing number of heterogeneous technologies are joined within one system. This leads necessarily to increasing complexity but allows to exploit efficiency margins.

In the same time this approach seems fruitful from an evolutionary perspective. The set-up implies selection processes will depart from a high level of technological variety.

Summarising, the knowledge field underlying the smart grid TIS will be delineated here – taking the broad view – as the area related to established and evolving technologies that are permanently connected to one or more energy systems with the objective to adapt the systems' functionality to changing energy production and consumption patterns. This definition includes all technologies that are part of the traditional smart grid delineation but also energy conversion and storage technologies that are planned to automatically contribute to balance the power grid. Such a delineation is in line with the technological composition of the smart grid research in Denmark – as shown in the previous chapter B – and in alignment with the patterns seen in the structural analysis in the following section.

5 Identifying Structural Components

This section is aimed at identifying structural components of the Smart Grid TIS in Denmark. These are actors involved in the system's development, various networks between them, and key institutions e.g. norms, standards, and policies that are present in the field. The first part of the structural analysis – the identification and location of actors will utilise a graph representation of one part of the survey results that relates organisations in the sample to specific technical activities or technologies. The approach is chosen as it allows to identify actors in a technologically broad area that spans across a variety of NACE classifications. This relational data can be used to detect latent relationships between actors (technological similarity) and related technologies or activities.

The identification of networks and institutions follows a more traditional approach.

5.1 Actors

The identification of actors is based on the survey, which can be found in the appendix. Additionally, respondents have been asked to name up to five key collaboration partners. This snowballing-exercise revealed central players in the area that did not participate in the survey.

Sample and general energy value chain field

The initial sample of 174 survey respondents was reduced to 147 to better match the above-discussed delineation of the Danish Smart Grid TIS.[3] The organisations selected their areas of competence from *energy production*, *energy transmission and/or distribution*, *energy conversion*, *storage*, and *intelligent energy consumption*. A third of the respondents indicate that they associate with only one part of the energy value chain. The majority selected multiple of the above-listed areas. 16 in the sample state that they have activities in all 5 areas. Among those are large international companies, that are established in the energy sector (e.g. ABB) and several technical consultancies such as Rambøll, Cowi, or Brix & Kamp Energi.

Mapping of actors and activities

The majority, two-thirds of the respondents, indicated that their main activity type is development and/or production of basic technology components or specialized systems, which contribute to smart energy systems. One-third of the respondents indicated that they provide technical consultancy services. Slightly under a third, named other activities (that could be additional to the former two given the structure of the survey) such as energy transmission and distribution, trading, technical service, and research.

Taking a closer look at the different technological areas shows that more organisations work (among other activities) within the field of energy consumption optimisation and least with energy storage. The difference in relative terms is however very low and generally, one can conclude that (apart from the production area which has been to some extent excluded from the

[3]The excluded respondents indicated that their activity was exclusively related to energy production. It is assumed that if these organisations had activity related to the Smart Grid, as defined above, they would have indicated more fields of competence.

sample) respondents are equally distributed to the areas, if relying on this classification.

The survey went one step further and investigated the association with more specific technologies and activities within the 5 broader energy value chain fields. The resulting matrix of firms and their selected technological competencies on this more detailed level allows to perform two types of mapping exercises[4] First, the different technological activities can be visualised as a projected network in a "field mapping". This helps to identify how activities are related to each other (assuming that organisations tend to simultaneously engage in technologically related activities) and how "generic" or specialised they are in the Danish set-up. This type of mapping is also helpful for re-adjusting the technological delineation of the TIS (see. section 4). Second, analogously, a network of organisations can be projected and clustered. Such a map will show communities of "related" organisations. The size and position of these communities on the map indicates the significance of respective technological fields in the TIS and how the communities relate to each other.

Technological competence and activity areas

The "field mapping" shows that the various detailed technological areas fit well with the broader categories, as defined by the survey. Energy transmission and distribution forms to a large extent a prolonged cluster. Transmission and distribution of heating and cooling were located in a different community together with energy conversion technologies such as heat pumps, which makes sense as they are related technologies. Energy consumption is similarly coherent with the exception of the area of hydrogen vehicles and infrastructure which has been placed at the periphery of the network close to syn-gas technologies. This and the low degree of the node (depicted by the node size) indicates that the field is rather weak and not strongly integrated with other technologies. Energy storage technologies are similarly scattered at the edges of the map. This is not surprising, since these are technologically

[4]The matrix is constructed as a bipartite network and projected onto the first modes. A detailed description of the method can be found in Chapter A, where the method of graph representation and clustering is applied to bibligraphic data. Here, a simple weighted projection approach is used rather than Newman's collaboration algorithm.

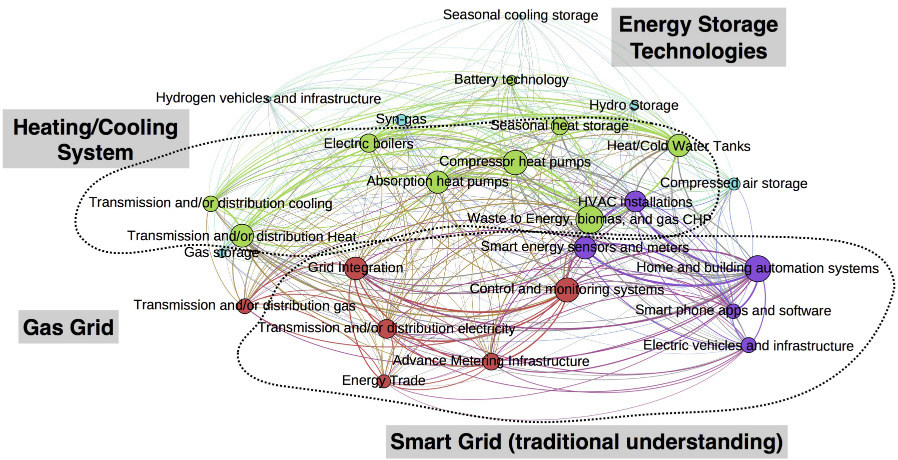


Fig. C.2: Technological competence field mapping according to co-selection by responding organisations

very different from each other. The peripheral position suggests as in the case of hydrogen vehicles that apart from seasonal heat storage, energy storage technologies are not among the strongly developed fields in Denmark. Particularly interesting is the "core" of the network that can be interpreted as showing a strong integration of the different broader fields by IT technologies (Grid Integration technologies, Smart energy sensors and meters, and Control and monitoring systems), as defined by the general Smart Grid technology delineation (NIST, 2010)[5]. Overall it can be concluded that the picture showing in the network visualisation, generally confirms the above-provided delineation of the Danish smart grid and the assumed close integration with other energy grid areas, most prominently the link between the power, energy consumption, and heating systems.

Mapping of the organisations in the sample

The next to explore are the characteristics of the survey respondents: How many organisations are active in the different areas, depicted above? What is the ratio of start-ups to established players? And as how innovative do they

[5]A detailed discussion of the technological aspects and boundaries can be found in the Introduction 2.2.

see themselves?

The network visualisation can be understood as complementary to the network described above. It relies on the exactly same data, however now the projection goes the opposite way. The organisations are placed according to their selected technological competence co-occurrence in the survey. The closer two organisations are, the more their activities are similar. Organisations at the core of the visualisation are "generalists" while organisations at the periphery have a more specific skill-set. Colouring indicates belonging to an identified community. The size of the nodes reflects the employee number in Denmark.

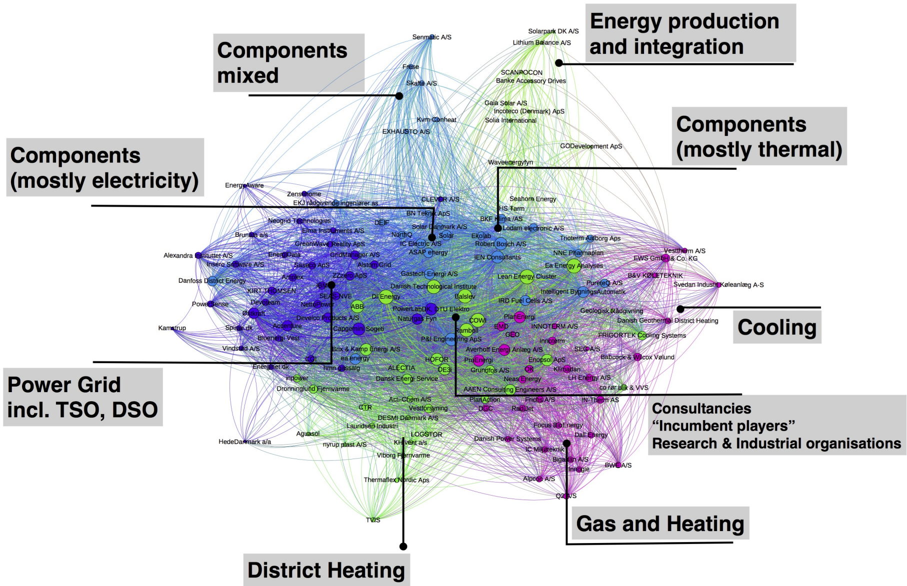


Fig. C.3: Organisation mapping: Survey respondents located according to their technological competencies

Overall the clustering algorithm identifies 5 coherent groups of organisations[6] which together make up nearly 94% of the sample. An isolated visualisation of each group is provided in the appendix. The clusters are similar to the above-described activity fields:

The largest cluster is the *Smart Grid community* (narrow definition), mostly

[6] Lovain community finding algorithm at a resolution of 0.9 (Blondel et al., 2008). Note that "cluster" and "community" are used synonymously

associated with electrical power technologies. In the open organisation description field of the survey respondents indicate working within the areas of energy management, smart metering, distribution automation but also home automation. Among the actors in this cluster are many established players such as the Danish TSOs and DSOs and large international companies as IBM, Accenture and Brunata. Particularly the presence of IBM but also many small companies with a strong share of IT firms, technology consultancies, and software developers shows that the Smart Grid field is perceived as developing and offering new business opportunities.

Table C.1: Identified communities

Community	Size	Organisations	Activities
Smart Grid (narrow definition)	35	IBM, National TSOs & DSOs, Accenture	Electrical power technologies, Energy management, Smart metering
Energy conversion	31	Neas Energy, high number of small companies	Various approaches to energy conversion
Heating and energy efficiency technologies	27	Danfoss District Energy, Bosch	manufacturing of district heating and metering components
District Heating	26	Grundfoss, ABB	Operators of DH systems and suppliers
Consultancy & Associations	19	Cowi, Rambøl	Technical expertise, project management, and interest representation

Note: Organisations and activities are exemplary and not necessary representing the whole scope of the community. 94% of the sample were attributed to one of the larger 5 groups. The remaining 9 organisations could not be related to a group nor were they similar to each other in terms of performed activities, and are therefore not listed in the table nor are they further discussed.

Similar in size (21%) is the *energy conversion cluster* with a strong core of heat pump producers but also companies working with various gas and cooling technologies. Waste-to-energy and biomass technologies are another focus point of the community. The aggregation of these technically at first sight rather heterogeneous organisations by the clustering algorithm can be explained by the shared usage of heat/cooling as an energy carrier. Many of the organisations in the group state in the survey that they develop technologies that are linked to the power and the heating systems, such as efficient small biomass CHPs, smart grid ready heat pumps, and district heating systems. The community is dominated by small (1-10 employees) and medium size companies (11-50 employees), suggesting a relatively higher intensity of entrepreneurial experimentation in this field.

A technologically related group of companies, but slightly smaller (18.5%) can be found populated by predominantly manufacturing companies working with *heating and energy efficiency technologies*. The technological diversity in this group seems to be lower – mainly limited to district heating components and metering devices. In the group, there are also several large supplier of district heating technologies such as Danfoss District Energy and Bosch. Many of the organisations in this community have been placed very centrally in the network layout and close to the smart grid community, again suggesting technological integration between the power and the heating systems. Particularly companies specialising in metering, monitoring, and controlling components seem to play an important bridging role.

The following again slightly smaller identified community consists of companies that can be largely related to the *district heating* sector, either in the role of a system operator or supplier of mostly mechanical components. Grundfos and ABB are the largest two companies in this group with otherwise many (around 70%) smaller firms.

Finally, the smallest cluster (13%) is a blend of large *consultancy firms* – Rambøll, Cowi, and Baslev – and *industrial associations*, located very central in the network, and companies that mainly belong to the energy production site but remained in the sample because of their additional activities such as grid integration.

Overall, the mapping shows that organisations with different technological backgrounds are engaged in the field. The density of the network is a sign of interrelatedness between the various technologies. The clustering and the layout of the map suggest existing integration between the electricity and heating sector in Denmark in the transformation of the energy system. Several energy conversion technologies are also well connected. This finding fits well with the observations made in Chapter B in relation to Danish smart grid research projects and the public discourse. Energy storage and hydrogen-based technologies so far not strongly represented.

Approximately 70% of the organisations are small and medium-sized companies, which indicates high rates of entrepreneurial activity and experimentation. It is also a sign of uncertainty with regard to standards and dominant designs. Thus, it is possible that some smart energy system technologies will experience strong growth, as for instance happened with wind power in Denmark or solar PV in Germany in the renewable energy production domain while others remain at the demonstration level. The presence of large incumbent firms in the sample – complementary to the findings from chapter D – can be seen as a sign of legitimacy of the technology, or at least the perceived need to engage in the transformation process.

5.2 Networks

The above-presented network visualisations and clustering exercises based on competence co-mentioning implicitly suggested some kind of interaction between the actors. Such interpretation would go far beyond what this data and analysis can express. Understanding existing interaction patterns between the actors is central for assessing the TIS. This section will present various networks that exist within the investigated field: Formal networks such as industrial associations and the informal collaboration network, constructed from the survey data.

Formal Networks

Following the legislative target setting, a "Smart Grid Research Network" with researchers from the technical universities and practitioners from the Danish TSO energinet.dk, the Danish Energy Association, and the energy group within the Confederation of the Danish Industry was established. In 2013, the network published a report commissioned by the Ministry of Energy, Utilities and Climate, which draws up a roadmap for the development of the Danish smart grid (Forskningsnetværket, Smart Grid, 2013). The time horizon is the year 2020 by which the Danish energy system should integrate 50% renewables [7]. The report identifies fields which will require considerable

[7] These goals are based on the energy agreement reached by the former government in 2012. The conservative government, elected in June 2015, seems not to prioritise environmental issues to the same extent and, therefore, targets might get altered. For instance, the current legislation changed tax regulations that have benefited the diffusion of electric vehicles, making Tesla's model S one of the most popular new vehicles. The cancellation of the tax exemption from January 2016 is likely to raise the prices for the car to a level at which demand will cease (pol, 2015).

research efforts but also areas with strong Danish competences and experience that can attract foreign investment or contribute to technology export. The schedule puts the development of the electricity smart grid first but emphasises that the smart grid should be seen as a part of the emerging smart energy system. The report points out that the recommendations it makes do not assume tax or regulatory adjustments – which can be determinant for the system development – but merely technological factors. This highlights once again the political dimension of the energy sector and related technologies. The strong involvement of universities and research institutions can be interpreted as a sign of prioritisation of the long- term objectives set by the government.

Another important organisation that was set up in march 2012 is The Danish Intelligent Energy Alliance (DIEA), a sub-network under the Danish Energy Association. The organisation engages strongly in knowledge dissemination and supports interaction between its members from different areas related to the transforming energy system. The intention is to stimulate the interaction between DSOs, knowledge institutions, and suppliers of energy technology. For instance, one focus point is the coordination of international and Danish standards in a period of uncertainty. The association is organised in 5 sections: Energy efficiency, home automation, IT security, market design, and grid development. The segmentation in these areas reflects the industrial perspective on an integrated energy system in the future. To implement demand response and flexible energy use, the system not only requires the appropriate hard and software in the grid and on the consumer side but also the right market mechanisms in place. Thus, the broad scope, covering the institutional and technological fields seems useful. The network highlights also its role as a bridging organisation, connecting research at technical universities and practical implementation.

A similar network with a stronger industrial production focus but lower number of organised activities is The Confederation of Danish Industries' Smart Grid Network, which counts around 90 members – mostly industrial supplier companies with an interest in the smart grid development. Also, in this network, the international standardisation processes play an important role.

This issue seems so pivotal that also The Danish Standards Foundation set up a Forum for Smart Grid and Renewable Energy.

Several other, more specialised associations such as the Danish Board of District Heating (DBDH), the Danish Wind Industry Association (DWIA) and several other organisations complement the networks listed above.

The presence of these organisations, especially the very active DIEA, suggests incremental coordinated interaction between the actors, involved in the transformation of the national energy system. The overall national schedule, underpinning policymaking in the field, is proposed by a broad consortium of technical universities, institutes, the Danish TSO Energinet.dk, the national energy agency, and the Confederation of Danish Industry. Overall the formal networks seem to stimulate coordination and collaboration between research, industry and policy.

Collaboration Patterns

The survey aimed at exploring interaction patterns and requested respondents to name up to five important collaboration partners. The responses were used to construct a directed graph. Central nodes in this graph represent interaction partners that have been named particularly often by organisations in the sample. While this list could have been just summed up from the answers without venturing into network analysis, the graph format also allows to see if there are particularly dense fields of collaboration, community structures, and other patterns. Organisations that have been named at least two times as collaboration partner have received a label in the graph visualisation.

The network does not show a strongly pronounced community structure. Three clusters can nevertheless be identified: A district heating community top-right, a group of metering and controlling components suppliers, diagonally spanning from top left to bottom right, and what appears the group of organisations working on the grid infrastructure mid left. The list of central collaboration partners is lead by DTU – the largest technical university, the Danish energy company Dong, Energinet.dk, and Aalborg University. The list continues as follows: Danfoss, Teknologisk Institut, Siemens, IBM Denmark, Rambøll, Niras [8]. Under the top 10 collaboration partners are large

[8] In fact, this graph shows strong resemblance with the network generated from research

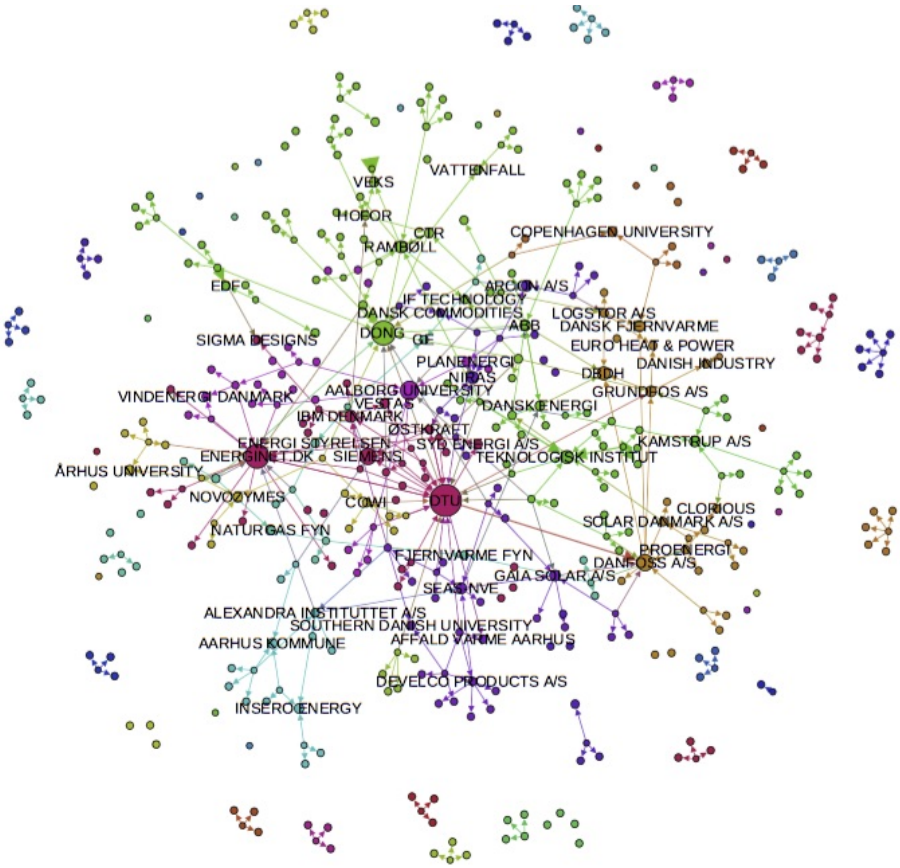


Fig. C.4: Collaboration mapping based on survey response

Note: The network structurally resembles the graph in the CCC Report. Yet, in the report, the collaboration structure has not been analysed in detail.

established players from the energy sector, technological consultancies, and large companies that are entering the energy field. The results – taken at face value – indicate intensive collaboration between industry and the technical universities in Denmark. This collaboration patterns are not surprising, given the novelty of the perused technology combinations, but may be also in part the result of the public research funding schemes. In any case this type of interaction suggests that companies are using the knowledge produced in national research organisations. The ranking above should, however, be interpreted, taking into consideration that the universities are few and large, and thus naturally bundle many collaborations. Overall the collaboration patterns show that organisations in the survey are most likely to collaborate with other Danish firms (30% of the reported collaborations), international firms (18%), business associations (15%), universities (14%), public organisations (13%).

5.3 Institutions

This subsection will be kept brief as all of the listed institutional elements will be discussed in detail further below. According to the TIS analysis scheme at this point, they should be named without further evaluation. Yet, it is barely possible to establish their relation to the focal theme without mentioning in which way they influence the explored technological field. Four influential sets of institutions can be listed below that have been selected as they tend to appear in smart grid related academic publications (e.g. Xenias et al., 2015), reports (e.g. Forskningsnetværket, Smart Grid, 2013), and policy documents (e.g. KEMIN, 2013a). The areas fit with the specification by the TIS framework, yet the list does not claim to be comprehensive, as other institutions key to the focal TIS may exist.

The electricity market architecture and pricing schemes have been designed many decades ago and were adjusted to a system with central energy generation, one-way transmission and consumption at the end of this chain. Since the liberalization of energy markets short-term productive efficiency

collaboration data in Chapter D. This points to the important interaction shaping role of publicly co-financed energy research.

has been highlighted and not so much dynamic efficiency and innovation (Müller, 2011). Many of the established routines – including the one tariff system and the energy sales agreements with neighbour countries – within this framework may be revised as the system is transforming (Lo Schiavo et al., 2013).

The tax system is not favourable for the integration energy conversion technologies, which might become a Danish core competence. Under the current framework, conversion of electricity to energy stored in form of heating is not profitable. For instance, could excess wind-generated electricity be used to heat up water for the district heating system. This would increase the percentage of consumed renewable energy in Denmark. The taxes and tariffs on electricity – as energy carrier – are, however, prohibitively high for the CHPs. Instead, the surplus electricity is sold to market prices abroad (Energy Supply, 2015).

Data standards and protection regulations Flexible consumption relies on sharing of up to date consumption data that may contain sensitive and private information. The regulative framework within which data is collected, transmitted, and analysed as well as its acceptance by end-users will have a strong impact on the overall functionality of the model (Xenias et al., 2015).

The energy agreement and smart grid roadmap are policies created to support the transformation, including altering the above-listed institutions. As all institutions, these policies are sustained as long as they assume legitimacy. The currently announced deviations by the new Danish government might undermine the agreement and regulations building upon it.

6 Functional Dynamics

The mapping of the functional patterns of a TIS represents together with the later assessment of the overall performance the core of the analysis. The conceptual literature behind the TIS scheme of analysis has come up with several variations of relatively similar function lists (e.g. Hekkert et al., 2007). The system functions have been compiled from various innovation approaches and refined based on insights from a large number of studies of predominantly north European technological systems (Truffer et al., 2012). In that sense, these processes are not new to the domain of innovation studies but in earlier approaches they have often been treated implicitly. One contribution of the TIS framework is, therefore, the analytical decoupling of components and processes in the system. The evaluation of the overall system performance is placed after the mapping of structural and functional components, as it should represent an assessment of all elements in interaction. The Dutch TIS tradition has been particularly highlighting the cyclical interaction between the key processes as an important feature that has to be focused on in the analysis (Hekkert and Negro, 2009b). They argue that the presence of some functions can trigger others to take up and vice versa. For instance, growing perceived legitimacy of a technology will lead to resource mobilisation, knowledge creation, etc. triggering so-called virtuous circles. This dynamic goes obviously also the other way. The aim of this section is first and foremost to map the functional patterns in a similar manner as has been done above with the structural components. The analysis scheme emphasises that no normative evaluation should be made at this point. Each subsection will introduce the respective function, its theoretical rooting, and the mechanisms through which it influences the TIS. Where additional data is used that is not related to the CCC report survey, it will be presented. Many indicators used in the section to evaluate the functions are proposed by the TIS framework article (Bergek et al., 2008b). The use of alternative indicators is made explicit in the particular parts.

6.1 Knowledge development and diffusion

These processes have always been central to the entire field of innovation studies. It is, therefore, no surprise that the TIS framework puts them as the first function on the list, outlining the different types of knowledge that are essential for innovation: Jensen et al. (2007) distinguishes for instance broadly between STI (Science, Technology, and Innovation) and DUI (Doing, Using, Interacting) types of knowledge production and learning. Other, more fine-grained taxonomies have been proposed to better address the production of manufacturing knowledge (Lundvall, 1992), imitation knowledge (Nelson,

1992) or market knowledge[9].

While the first type of learning and knowledge diffusion (STI) can be assessed in a relatively straightforward manner, e.g. evaluating patents, publications and other documented research activities, the second type is more challenging to explore. The survey that is used here as the main data source did not include a detailed part on knowledge production, yet the question investigating R&D intensity of the organisations and the collaboration patterns with knowledge institutions may be indicative. Furthermore, detailed data on publicly co-funded R&DD projects in Denmark and statistics on the research environment (researchers, centres, and publications) will be used to get a better picture of this function. To map DUI related activities, the section will consider deployment projects with a particularly complex and interactive set-up such as for instance the EcoGrid project on the island of Bornholm.

Research Landscape

Throughout the past decade Denmark has followed the ambitious target of becoming a European centre for Smart Energy research and demonstration. This goal was once again highlighted in the Government's 2013 Smart Grid Strategy and with the launch of 27 new publicly co-funded research projects in 2012, further 15 in 2013, 21 in 2014, and already 15 registered projects as of August 2015. Figure C.5 provides an overview of the research project number development broken down by the different programmes that together cover all stages within the R&DD process - from basic R&D to commercialization[10].

The 2013 edition of the European Commission's report "Smart Grid projects in Europe" (Giordano et al., 2013) outlines Denmark's strong leading position within smart energy research, development and demonstration. Among all European countries Denmark has the highest involvement in R&D projects as compared to demonstration and deployment and the highest research invest-

[9] A further distinction to consider here is *codified* vs. *tacit* knowledge as introduced by Polanyi. The first means knowledge that can be written down and passed on to be utilised by the recipient while the latter is the type of knowledge that has to be developed through intensive interaction. STI type knowledge production generates a large share of codified knowledge while DUI can be mainly associated with tacit elements. The STI/DUI distinction is selected here since it directly links to the activities that are associated with knowledge production and thus better fits the functionalist overall framework.

[10] Note that some of the programmes are not any more active or have been merged.

ment per capita and consumed KWh. A third of all national smart energy projects in Europe are conducted in Denmark. Furthermore, Denmark participates in 30 percent of all multinational smart grid projects in Europe. Together with Germany, Denmark is the leading country with projects focusing on consumer engagement.

A quick and rather restrictive evaluation of scientific publications listed in the Web of Science database [11] shows Denmark only on the 18th rank, with the United States and China sharing almost 50% of all publications. Set in relation to the size of the country, the scientific output in the field is however only surpassed by Singapore. Within the Danish publications approximately 50% come from Aalborg University, another 30% from DTU and the remaining 20% are distributed across several institutes and research departments of companies. Numbers of graduates in related study programmes have also been suggested as a measure of knowledge creation b(Bergek et al., 2008b). While both DTU and AAU offer master degree specialisations that are very related with here analysed field, statistics are only available on the overall programmes of "Energy Engineering". Here the numbers of graduates went up form virtually zero in 2008 to 126 graduates in 2012 and stabilise in the two (available) years after. This rise goes parallel with the growth of publications seen in the bibliometric data.

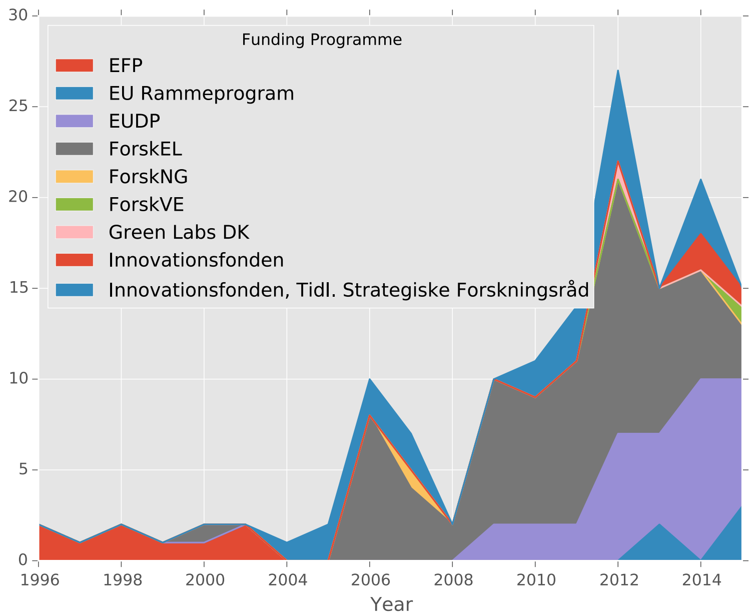
Company R&D intensity

A common method to assess the R&D intensity of companies is based on the exploration of patent data. In the present case, this approach is not promising for a number of reasons. First, as showed above, the technological domain is very broad and heterogeneous, making a delineation related patents challenging. Second, much of the innovation in smart energy is based on recombination of established technologies from different fields to serve a "new" purpose, rather than new technology.

Chapter D showed that a large number of Danish companies are involved in research projects, supported by public schemes. The number of projects and participants has since been growing. The CCC report survey aimed to

[11] Searchstring:`TS=(smart AND grid) OR TS=(intelligent AND grid) OR TS=(intelligent AND energy AND system) OR TS=(smart AND energy AND system)`

Fig. C.5: Publicly co-funded smart grid and systems research projects by funding scheme (calculated from energiforskning.dk)



Note: EFP: (Energiforskningsprogramm) The Ministry's energy research programme, initiated 1976 and currently discontinued as more specialised schemes have evolved. EU Rammeprogram: EU Framework Programme; EUDP (Energiteknologisk Udviklings- og Demonstrationsprogram): Energy Technology Development and Demonstration Program; ForskEL, Forsk NG, ForskVE: Programmes coordinated by Energinet.dk; Green Labs DK: Programme by the Danish Energy Agency supporting establishment of large scale demonstration facilities; Innovationsfonden: Innovation Fund Denmark, former Danish Council for Strategic Research.

address R&D intensity directly by asking organisations to point out how important R&D activities are for them on a scale from 0 to 10. Overall, an average of 7.5 suggests high importance. The value is by far not the same for the different sub-groups of organisations. The highest value of 8.6 (and the lowest standard deviation) can be attributed to the smart grid community, while the lowest of 6.3 is stated by the district heating sector. The other groups show values around 7.5.

Deployment projects

DUI generated knowledge is extremely important in the present case, as the various technologies not only will have to interact embedded in a highly complex large system but also will be used by various actors. Apart from technical and business knowledge, the transforming sector needs to collect experience about the behaviour of energy users facing new opportunities and requirements. Real application experience is obviously most valuable but for new technologies – particularly in the case of sustainable technology with weak need articulation on the demand side – these experiences are limited. An additional challenge is the systemic nature of the technology, making it difficult to collect valuable experiences with single components. What is needed is the kind of experience accumulation in the complex set ups in which the technologies will be embedded. Large deployment projects provide an opportunity to explore the performance of single technologies when integrated into a complex system. Among the above listed R&D activities, there are several of these projects that aim at generating realistic conditions for the testing of new grid infrastructure technologies in a controllable environment.

One of the most prominent projects in Denmark and Europe is taking place on the island of Bornholm. With only one submarine power cable from Sweden connecting the island to the rest of the (energy) world, it is possible to isolate the grid from outside interferences and track changes precisely. Additionally, Østkraft (Bornholm's utility company) is continuously building the share of sustainable energy sources in their energy mix. 75% of the electricity produced and 45% of the total energy consumed by the 40.000 residents come from sources like wind, solar and biomass. The island has been host-ing a number of national and international deployment projects related to the smart grid development, including testing of electric vehicles integration.

Another ambitions project was "Smart City Kalundborg". The aim was to build a next-generation energy system that combine information from electricity, heating, water provision along with transportation and building data. The broad scope of the project is clear when looking at the 12 project partners. EV's, solar, utilities, smart grid management systems, sensor technology companies and more are involved the process. A central part of the project is the "Energy Hub" – an open it-platform that offers citizens and companies user friendly services that increase flexibility within the grid. The project had to be stopped a year earlier than scheduled because the partners could not agree on the architecture and functionality of the central it-platform, which again demonstrates how complex it is to coordinate different technologies within the system.

The results in chapter B suggest that research projects in more specific areas – looking at a variety of different designs and solutions – are often followed up large deployment projects that build on the results of the former, selecting the more viable solutions.

6.2 Influence on the direction of search

This function is associated with the different activities that signal a certain level of legitimacy and intent to develop a specified technology (Hekkert and Negro, 2009a). An example of such an activity would be a policy announcement to aim for the production of a certain share of renewable energy by a specified date. This leads to decreasing uncertainty among technology developers and users, and may spur resource mobilisation.

In the present case three major elements should be considered as guiding for the direction of the trajectories in which the various technologies are developed. First, the technological change that has shaped the necessity to redesign the grid infrastructure – i.e. intermittent and decentralised renewable energy sources, growing and widening electricity consumption. Second, the existing complementary technological environment – e.g. the presence of a developed district heating system. Third, the target-setting of the Danish government made explicit in the national smart grid roadmap (KEMIN, 2013b).

The growing load on the electricity system due to new applications – such as electric transportation and space heating – is demanding, but not as pressing and immediate as the intermittency challenge that creates the imperative to balance energy generation in decentralised units with consumption. The ambitious goal setting of the Danish energy agreement: By 2020 half of the total electricity consumption is to be covered by wind power, in 2035 all heating and electricity supply is to be based on renewable sources. By 2050, the country's energy consumption including transport has to be covered by renewables. These target setting together with Denmark's pioneering role in the area of wind power led to fast-growing generation capacity. As depicted in the introductory chapter, today the imbalance between the well-developed energy production side and the grid often results in an inability to use the produced energy, not to mention the use of renewable sources as base load. Hence, the transformation of the smart grid will be a process of tension resolution (Dahmén, 1988) and the direction of associated technological trajectories will be conditioned by the features of the imbalance. The main focus lies on wind power integration, and only to a more limited extent on solar power and other intermittent renewable energy sources.

As shown in Chapter B and repeatedly found in different types of data on the broader field, many research activities relate to potentially complementary technologies that are present in Denmark. For historical reasons, there is a well developed district heating system and a gas system that among other intersections are both coupled with the power grid through a high number of CHPs. The experience with heat pump technology is another precondition that influenced the search. Electric vehicles and projects investigating this technology as a further way to harmonise the grid are present, yet not central. This might be partly explained by the absence of car manufacturing in Denmark but also by a strong focus on alternatives to personal transportation: innovative urban planning, public transport, and cycling.[12]

The roadmap that schedules development activities in the field has been developed by the Smart Grid Research Network (Forskningsnetværket, Smart Grid, 2013), an alliance of technical universities and institutes together with

[12]Let alone the general challenges associated with electric mobility such as high investments in infrastructure or battery standardisation.

the TSO energinet.dk and energy industry representatives. This is supposed to generate faster agreements on standards and required regulations between industry and policy makers. The strong involvement of research organisations – even though not uncommon for technologies in their early stages – signals to some extent that the development is supposed to follow a scientific rational rather than exclusively business interests.

6.3 Entrepreneurial experimentation

The exploratory mapping above shows that in all of the identified sub-groups small companies make up at least 30% of the population. Especially the energy conversion area with its great variety of energy forms and applications many different approaches are explored by small firms. Here the share of small firms is at 45%. Overall one might expect a larger share of small firms in an emerging sector and suspect the selected sample being biassed towards more established organisations. Then again, the energy sector is characterised by challenging standards and regulations that may impose entry barriers. The above numbers are in line with the ratio of small companies present in publicly funded research projects that lie around 35% (see Chapter D), which can be regarded as a comparison benchmark. Setting small firms equal to entrepreneurs is not entirely correct. For the sample in Chapter D only around 10% were classified into the category. The survey results suggest also that smaller companies in this field are not necessary more innovative than others following form innovation output and their stated importance of R&D activities.

As shown and to some extent discussed above, the field attracts also established firms from adjacent sectors that see the transformation of the energy grids and smart grid development as a chance to diversify into a new area. Uncertainty is a general feature of technological development and characterises the context of the TIS not only in its early stage (Rosenberg, 1996). Entrepreneurial experimentation is often seen as a way to decrease technological uncertainty (Foxon et al., 2008, p.85). In the present case, it is true for the development of single components. However, a source of greater uncertainty seems not so much the performance of single artefacts but the ability to integrate them into the overall system.

6.4 Market formation

Assessing the market formation for products in this field is challenging for several reasons. First, the diversity of technological components and applications goes parallel with a variety of customers and markets. While the market for electric vehicles and accessories is or will be a consumer market, smart metering infrastructure is to be acquired by utility companies. Second, as with many sustainable technologies customer needs are poorly articulated due to the lack of direct benefits for the consumer – under the established framework (Hargreaves et al., 2013). Several studies exploring consumer behaviour in a demand response scheme found that incentives to change consumption patterns are yet not high enough to be effective (e.g. He et al., 2013).

The results of the survey suggest however that markets are forming. When asked for the percentage of revenue that can be attributed to "smart energy technology" 28% of firms in the sample stated over 75% and further 14% between 51 and 75%. These numbers are significantly higher for smart grid and the energy conversion communities. 38% of the firms in the smart grid community indicated to receive more than 75% of their revenue from these new technologies. For energy conversion the number is 35%. An interesting observation is the extreme split in the group for this indicator among the smart grid related firms. Half of the companies have indicated that the percentage is between 0 and 25%. Among these companies are mainly large established players (e.g. energinet.dk, SEAS-NVE) or large diversifying firms such as IBM.

A step towards market formation – in fact, this can be seen as market nursing or niche market creation (Dewald and Truffer, 2011) – is established in the legislative energy agreement from march 2012 that constitutes the basis for the later agreement with the energy companies to roll out smart meters for all electricity consumers between 2016 and 2020. This is key, as these meters will enable hourly consumption data and allow to further develop flexible consumption. On the consumer side they will provide the necessary link for new types of appliances (e.g. smart grid enabled fridges, heat-pumps, etc.). Thus, the roll-out has the potential to reduce uncertainty in terms of standards and generate demand for complementary or compatible technology.

Export markets should also be considered in the evaluation, as 61% of the respondents indicated export activity for "smart energy-related products". Most of the exports are within the EU, particularly Germany and the UK. Outside the EU exports go to the US, China, South East Asian countries, and Russia.

6.5 Legitimation and Legitimacy

Legitimacy is a pre-requisite of resource mobilisation, market emergence and hence TIS formation (Bergek et al., 2008c). Legitimacy stands in the end of conscious processes of legitimation and characterises the alignment of a technology or practice with social norms (normative legitimation) and relevant institutions (regulative legitimation) (Aldrich and Fiol, 1994; Rao, 2004).

This dimension may be decomposed in the analysis of at least 3 different perspectives: the legislation, industry, and customers – i.e. private households. The strong involvement of the state in promoting these technologies suggests high legitimation from this side. Among the reasons behind this strong backing are: (1) the ability of these technologies to reduce or postpone necessary and costly investments in capacity enhancement in the distribution grid, (2) integration of national renewable energy sources and increased energetic independence, (3) creation of a new industrial field and hence employment, and exports. Yet, in the open text parts of the survey and the interviews a lack of appropriate regulation was repeatedly mentioned – here particularly the inappropriate taxation framework.

The legitimation on the business side is ambivalent. On the one hand, the presence of start-ups and entry by large players from adjacent industries (e.g. IBM) is a sign of growing legitimation (Carroll, 1997). On the other hand established companies in the energy sector are likely to be challenged and opposed to the change, as yet business opportunities for them do not justify the investments (Shomali and Pinkse, 2015) and given alternative solutions such as the super-grid that are technologically closer to the status quo (Blarke and Jenkins, 2013). The latter argumentation is obviously more an assumption than empirically observable. One indication confirming this assumption could be however that many of the responding companies in the survey mentioned the energinet.dk as a "barrier to innovation", accusing the

TSO of using its dominant position to prevent "uncomfortable" technological innovation by establishing proprietary standards that close out companies with innovative specialised solutions.

Legitimation from the customer perspective is also complex: Denmark has been pioneering the development of sustainable technologies for several decades and general acceptance of these technologies is high. While there is little prospect of customers actively changing their energy consumption behaviour at the expense of comfort and more sophisticated solutions will be needed to promote demand response, Danish customers might be less concerned about the data security aspect of smart metering. The capturing and transmission of detailed energy consumption data has been subject to concerned debate in the UK (Xenias et al., 2015). The critics fear privacy violations as this data is suitable to reconstruct and analyse behaviour patterns of citizens. In Denmark, this aspect is mentioned in all policy documents related to smart grid development. Data security forms also one of the sub-groups of the largest industrial network – DIEA. Generally, Danish consumers are open to innovative solutions and used to a high level of data transparency. A high level of general trust is often taken as an explanation for low data protection concerns over new services such as the joined electronic ticketing system "rejsekort", mobile payment, or the use of personal identification numbers. Apart from these anecdotal indication, the absence of strong data privacy concerns in the Danish population is confirmed by the yearly European Data Protection Survey (Eurobarometer, 2015). Danes are significantly less concerned about the use of their data by authorities and private companies for other purposes than initially collected for while expressing that more and more personal data has to be provided today than earlier. Also the general trust in organisations to protect collected personal data is much higher than the European average[13].

6.6 Resource Mobilisation

This section will be kept relatively brief, as much of the above is a result of successful mobilisation of resources. The rising number of R&D projects reflects growing investment through public schemes and companies. Yet, in

[13]Reaching 89% for health institutions and banks versus 74% and 56% at the EU average.

the CCC report survey financial constrains due to a lack of investors and customers unwillingness to pay have been named as second and third most significant barrier to innovation. Some companies explain the fair amount of investor's reserve with uncertainty due to inappropriate or lacking regulation.

The growing numbers of graduates in the field – reported under knowledge generation – can be interpreted as increasing availability of human resources.

Taking a broad perspective, the growing amount of installed renewable capacity and, on the consumer side, the roll-out of smart meters can be interpreted as rising complementary assets.

6.7 Development of positive externalities

This function is important but less "straightforward" compared to the other given the present explored system. On the one hand, the TIS scheme highlights the importance of external economies (Bergek et al., 2008b), referring to Marshal's and Porter's ideas. Given the systemic nature of innovation within the TIS and efficiency being the set target in the present case, complementarity and positive spillovers should be key. On the other hand, it may also be the case that the presence of other actors will lead to competition for the dominant design (Utterback, 1994) or for the dominant system (e.g. Wind vs. Solar in the context of renewable energy production). Then again, when considering the general sustainable transformation, one can argue that positive externalities already emerge from the mere presence and development of sustainability-oriented technologies, which jointly contribute to destabilisation of the "carbon-based regime" (Raven, 2005).

The "smartening" of the energy system has a clearly stated primary reason – the integration of fluctuating renewable electricity. Therefore, growing wind power capacity, for instance, can not be considered an externality. The prognosed external positive effects are yet to be observed and again the smart meter roll-out may trigger these effects. Once communication standards and new energy market mechanisms are set, electric mobility, intelligent domestic appliances and efficient heat pumps are likely to reach higher market penetration. This can be related to the emergence of new companies, high quality employment, and rising exports.

Another positive side effect expected by the policy is that these technologies might avoid, reduce or postpone necessary investments in the grid infrastructure – unavoidable if maintaining the current architecture and facing growing capacity demand. To which extent smart grid and systems can contribute to cost savings is, however, hard to say at this stage of development.

7 Reaching Goals: System Performance

Having compiled a descriptive mapping and a tentative assessment of the different functions, following the TIS framework this part will evaluate the overall "goodness" of the structure. The scheme emphasises that it is key to account for the current phase of development of the TIS in order to find appropriate indicators and interpret them considering what can be expected from the TIS in the given stage. Broadly, the framework distinguishes between the *formative*[14] and the *growth phase*, which are at first sight self-explanatory classifications. However, authors of the analysis scheme (Bergek et al., 2008b) emphasise that the distinction might be not as straightforward and list several potential criteria to make the classification more systematic.

The time dimension: TISs that have existed for shorter than a decade are rarely able to escape the formative stage. The Danish smart grid and systems TIS has not taken off until the 2010s. This can be concluded from the time dimension of academic publications, research projects, and the establishing of formal networks. The time frames stated in the policies (i.e. roadmap) point in the same direction. With regard to this point, the TIS is certainly in the formative stage.

The extent of uncertainty: Both technological and institutional uncertainty are present, which is a standard feature in this formation phase, as technological variety is created through experimentation with different approaches and

[14]The distinction between *formative* and *growth phase* relates to the TIS as described above and not to the technology that itself may be characterised as *emerging* and being the output of the TIS dynamics.

regulatory alignment still has to be found. Particularly in the energy conversion area, the analysis reveals a great variety of solutions and it is yet unclear whether only some of these technologies will be "selected" and diffuse or perhaps the system will develop open standards and become a platform to allow for this variety. In the survey some companies express concerns with regard to the defined communication standards. A company working with street light management, smart metering, and demand response remarked for instance: "Energinet.dk have designed the data hub in such a way that it blocks all innovations from third party vendors.". While the definition of standards is important, as it decreases uncertainty, the selection of proprietary standards to early in time can generate suboptimal results as seen in many examples in history (e.g. qwerty-keyboard, VHS etc.). Institutional uncertainty is particularly expressed in the tax regulations. Over 10% of the companies in the survey named energy taxes as "the greatest challenge to overcome in the next ten years", while inappropriate or lacking regulation was selected the most significant barrier to innovation.[15]

Price-performance ratio: Measuring performance from a consumer perspective in the case of energy supply (unless comparisons are made with less developed regions that experience energy shortage and blackouts) seems not appropriate. The question should be rather: Can the transforming system reduce prices while maintaining performance and increasing efficiency? The overall target is to make the whole system more efficient, including price efficiency from a higher usage of renewable sources that have been becoming cheaper throughout the past decade. Wind power production per kWh has dropped by more than 80% within the last 20 years making prices competitive with new CHPs (Danish Wind Industry Association, 2015). These savings are not necessarily given further to the consumer. A study looking at the roll out of smart meters in Germany concluded that under the current regulations and tariff systems customers might even be facing higher costs due to the roll-out and maintenance costs for the new system while saving opportunities are still small (Earnst & Young, 2013). The variety of technologies and stakeholders in the present case makes an evaluation of this dimension hard and not unambiguous. Single components might be very efficient and well

[15]This point is further elaborated in section 8

performing, however, it is the price performance of the larger system that is important here and a proper evaluation will be first possible once it is more established.

Overall, the above suggests that the Danish smart grid system, seen in a broader understanding, is in the later part of its formative stage and developing quickly. The structural analysis indicates the engagement of actors from different backgrounds that anticipate business opportunities. Apart from established firms in the energy field, the survey identified small young companies that specialise in various components of the upcoming system, and large players from adjacent sectors. The survey indicates that already today technology is not only sold domestically but also exported – mostly to other Nordic Countries, Germany, and the UK. Coordinated R&D between knowledge institutions (particularly DTU and AAU) and companies experiments with a variety of technological solutions. Also outside these collaborations, entrepreneurial experimentation seems vibrant. This is also favoured by the presence of developed energy systems (i.e. district heating and gas), that allow combinations of technologies and solutions that would not be possible in another context.

Several industrial networks, such as The Danish Intelligent Energy Alliance (DIEA) and The Confederation of Danish Industries' Smart Grid Network have been created to spur interaction between the actors, to agree on standards, formulate R&D targets, and to facilitate the dialogue with regulative authorities.[16] Interaction and definition of standards seem key in this process of technological transformation and integration. While the technologies in the analysed field experience overall strong legitimacy, particularly from the corporate and policy side, technological uncertainty still is widespread. This may be one of the reasons for financial constraints that companies report to experience. The upcoming full roll-out of smart meters might decrease uncertainty providing a platform to link to and on top of which new applications can develop.

The role of established energy companies is ambiguous. Their assets and knowledge are necessary for the transformation process and as Chapter D and the above mapping argues, they are present in the build up of the smart

[16]See subsubsection 5.2 for an overview of the different network organisations.

grid. Their engagement also fulfils an important signalling function, which is spurring legitimacy. There are however theoretical[17] and observed reasons that suggest that their engagement might not always be beneficial for the overall process. Most of these are listed in Chapter D. The survey indicates additionally that these incumbent players may use their influence to define standards and thus shape trajectories that favour their interests while leading to less efficient outcomes.

The ambitious national energy agreement has been a framework for the development of the overall energy system. However, to date the important institutional alignment concerning the tax system, electricity markets, and subvention frameworks did not happen. Inappropriate or lack of regulations is pointed out as the most concerning problem by the survey respondents highlighting this problem. With the new conservative government, elected during summer 2015, this challenge might persist. The new responsible minister has for instance recently raised doubts about the feasibility of a tax reform, that would make sustainable energy technologies more attractive, to happen in this legislative period.

To summarise: Knowledge development and entrepreneurial experimentation are well defined and there is an explicit roadmap that defines the research direction. While markets are present for some components, they are not (yet) for others. The same is true for the inflow of resources. Here it should be pointed out that the roadmap and related policy documents schedule the development of the electricity grid first (the narrow smart grid) followed but the larger integration of the energy infrastructure later. Resource constraints and lack of markets for some technologies can be explained by the yet high level of uncertainty – not associated with the legitimacy of the general idea but with the yet unknown standards to be established. With regard to the positive externalities: The whole purpose of the ongoing transformation process of energy systems is to set off a chain of positive externalities. While the technologies as such don't produce anything directly, they allow to increase the share of renewable energy sources, improve efficiency of the various grids, and decrease costs. These effects will however not appear until at least the narrow smart grid is working and the TIS has left the formation

[17] e.g. the reasoning present in most of the sustainable transition literature

phase.

8 Inducement & Blocking Mechanisms

This section relies on the above-presented findings and the analysis of the open-text part of the CCC report survey, to map the interaction between inducement and blocking mechanisms, and the TIS functions. These are mostly external factors that affect the functional dynamics of the TIS (Bergek et al., 2008b; Hekkert et al., 2007). This mapping provides an efficient approach to summarising the different influencing elements on the TIS functions development. An overview of the inferred influences is presented in Figure C.6.

Since many of the mechanisms and relations are already mentioned in the preceding functional evaluation, this presentation will be confined to a brief listing in form of bullet points.

Inducement Mechanisms

- The *R&D policy* of the Danish government supported almost 150 projects – a majority n the past five years – through various funding schemes. Numbers of graduates in related fields have been rising as well as publications in the field, particularly at the energy engineering departments at Aalborg University and DTU. Knowledge has also been accumulated within the field of energy planning. The funding schemes mobilised resources to support projects that brought together different actors and ideas, thus allowing for entrepreneurial experimentation with different solutions.

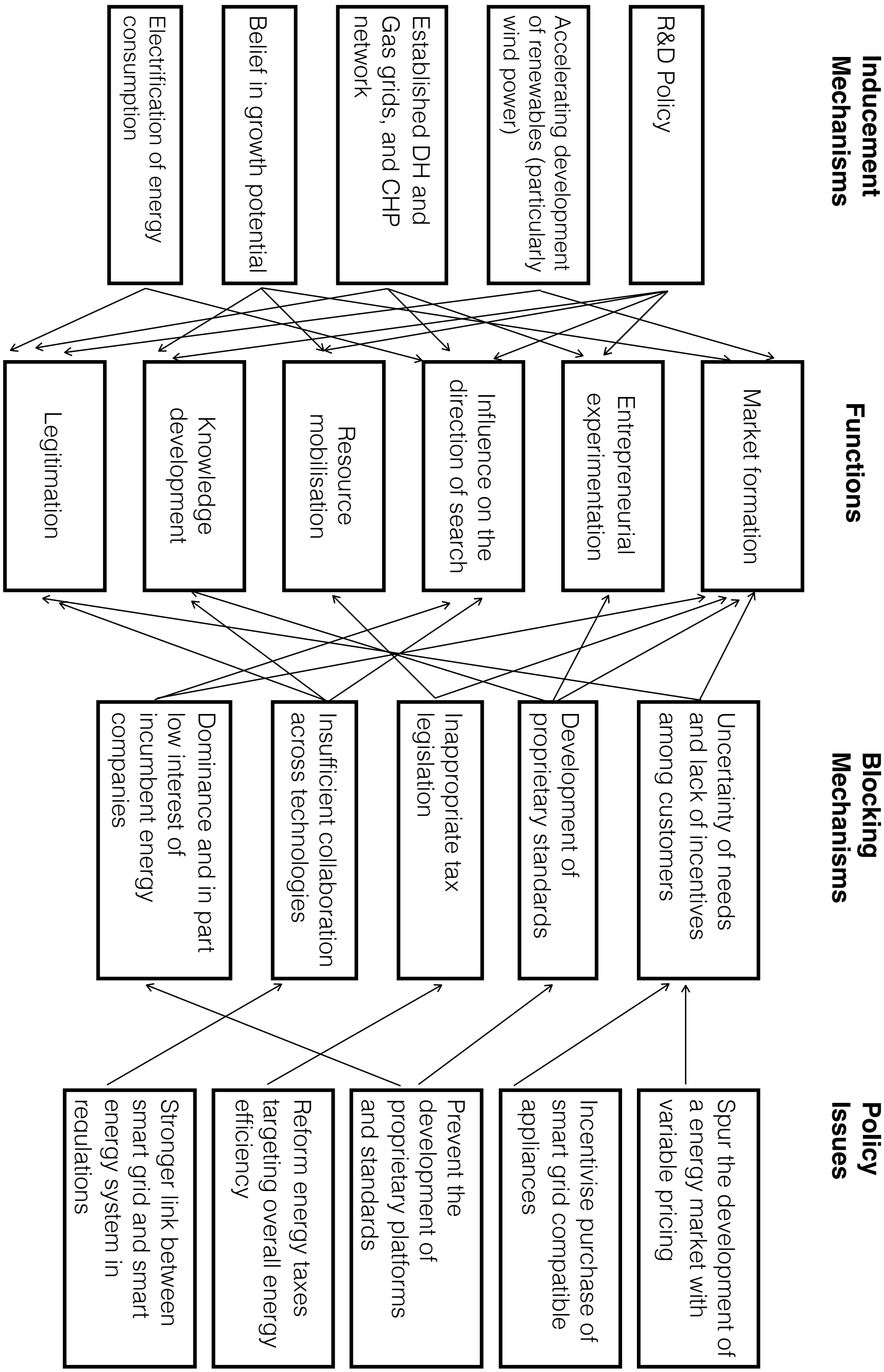
- The *Accelerating development of renewable energy sources and growing installed capacity* can be seen as a causing problem and driver of the energy grid transformation. The current inability to use harvested energy to a greater extent, supports the legitimacy of the transformation process. Also, growing installed capacity of wind and solar power in Denmark and worldwide promises increasing market potential.

- The *Electrification of energy consumption and growing energy demand* is a further reason to develop the energy system, thus adding legitimacy to the TIS. The changing patterns of energy consumption – e.g. electric space heating and transportation – lead to specific challenges and thus they alter the direction of search.

- Denmark has *established, well developed district heating and gas grids, and a dense network of combined heat and power plants*. This technological context opens up for the exploration of solutions and application that are not possible in other places and further legitimates the TIS through the presence of these complementary assets.

- The technologies explored within the TIS are not facing the same type of uncertainty as innovations introduced in a hypothetical *vacuum*. Rather, they are intended to fill a space which currently can be described as a bottleneck that to some extent blocks the diffusion of several technologies and applications. The *belief in growth potential and positive externalities* from the side of companies and the policy is, therefore, justified. This belief fuels the interest of many companies, making investments and engaging in research activities. Furthermore, it has a positive effect on the creation of markets.

Fig. C.6: Overview: Inducement & Blocking Mechanisms, their interaction with the system functions and policy implications



Blocking Mechanisms

- Especially the private consumers seem uncertain about the new technologies. As often with sustainable technologies, there is no obvious economic benefit for the user – altruistic and environmental motivation set aside. To put it differently: Electricity and heating do not become different in nature by being sustainable and a smart grid enabled washing machine does not wash clothes cleaner. Incentives for consumers to acquire and use these technologies must obviously come from the cost saving potential, altruistic environmental concerns taken aside. Many CCC report survey respondents indicated that creating these incentives is the greatest challenge in the medium run. This is in line with several studies that explored the consumer side of the smart grid introduction (Ghanem and Mander, 2014; Wolsink, 2012). The *customer uncertainty and lack of incentives* on the consumer side has a negative impact on market formation and legitimacy. While the smart meter roll out might contribute to familiarity with he technology, uncertainty and established routines will persist until usage can achieve host savings without compromising comfort. As highlighted by Ghanem and Mander (2014), in the public discourse, the image of an ideal consumer that is interested in the optimization of own energy consumption and understands (and even analyses) the generated data prevails. This is deemed more than unrealistic and may lead to unfeasible expectations and produce inappropriate product designs on the consumer site.

- *Development of proprietary standards* has been mentioned as a potential threat to innovation in the field. Energinet.dk has according to survey participants established a smart grid data hub using a proprietary standard that excludes third party solutions. The definition of standards is important in order to decrease technological uncertainty. However, when these are defined too early by incumbent players the outcome may be less innovation as incentives for entrepreneurial experimentation decrease. This also has a negative effect on knowledge development and market formation while the position of established companies is strengthened.

- *Inappropriate tax legislation* was the aspect that was mentioned mostly in the survey under the category "future obstacles". Many companies point out that the current regulations supports energy consumption as it is established today. The current tax construct disfavours – according to the responses – particularly energy conversion and storage technologies. Companies also seem to experience instability, meaning that changes of regulations are difficult to predict and can happen within short time. This has a negative impact on investments and market formation.

- *Insufficient collaboration across technologies* has been pointed out as another blocking challenge. Although different types of technologies are supported in research projects and considered by policy and research, solutions are often searched for within the particular fields rather than combining different technologies. This may alter the direction of search away from integrative solutions and diminish research insights.

- Finally, insight from the Chapter D that was confirmed by survey responses is the *dominance and in part low interest of incumbent energy companies*. Established energy firms seem not to have an obvious business opportunity with the upcoming technologies (Shomali and Pinkse, 2015). At the same time they seem to gain dominance by positioning themselves central in smart grid and systems research, and strategic decisions such as the already mentioned standards definition. As representatives of the established regime (Geels, 2002) they have strong incentives to canalise change into a direction which favours the established system. This may alter the direction of search towards less conducive solutions, while disturbing market formation.

9 Discussion

The present paper used the TIS framework to explore the development of the different technological trajectories related to the broader understanding of the emerging smart grid in Denmark. The survey, underlying this analysis, was set up broadly to cover not only the *narrow smart grid* but also technologies falling into its broad conceptualisation which follows the understanding of the technology conjunct in the public discussion. This delineation, guiding the survey design, results in part from the findings in Chapter B.

Tools from the field of network analysis have been used in the structure mapping part to identify relations and patterns built by the different technologies and activities, the organisations responding to the survey, and in the collaboration structure.

9.1 Performance Summary

The Danish smart grid and systems TIS is developing well. Given the short time period between its explicit conceptualisation and mentioning in research and by policy makers, and also considering that large technological systems such as the energy grid are usually resistant to change, the TIS has made great progress. The structure of the TIS is well defined, with many heterogeneous actors engaged, several active formal networks, and institutional back-up in form of legislation that strongly supports some of the technologies and the overall concept. Functionally, the TIS shows features of a field in a late formative stage. Knowledge development and entrepreneurial experimentation are well defined and there is an explicit roadmap that defines the research direction. While markets are present for some components, they are not (yet) for others. The same is true for the inflow of resources. Here it should be pointed out that the roadmap and related policy documents schedule the development of the electricity are first (the narrow smart grid) followed but the larger integration of energy infrastructure later. Resource constraints and lack of markets for some technologies can be explained by a yet high level of uncertainty – not about the legitimacy of the general idea but about the yet unknown standards to be established. Some of the institutions fitted to the properties of the current system, such as the energy tax framework and the electricity market, have to be aligned to support the functioning of the evolving system. With regard to the positive externalities: The whole purpose of the ongoing transformation process of energy systems is to set off a chain of positive externalities. While the technologies as such don't produce anything directly, they allow to increase the share of renewable energy sources, improve efficiency of the various grids, and decrease costs. These effects will however not appear until at least the narrow smart grid is working and the

TIS has left the formation phase.

9.2 Key Policy Issues

One key element of the change is the concept of demand response on the energy user side, i.e. the adjustment of consumption to the generation levels. This behavioural change – regardless if it is active, such as through using the washing machine by night, or passive by installing appliances that react automatically, such as, refrigerators and heat pumps – has a cost for the consumer and has to be incentivised by potential saving opportunities in form of for instance a lower energy bill. The development of an electricity market with flexible pricing and of incentives to acquire smart grid ready appliances is, therefore, key to strengthening legitimation on the consumer site and support market formation. The roll-out of smart meters is an important first step but until the data generated by these meters is transformed into changes in energy consumption, they are of not much value for the efficiency in the system[18]. Smart grid ready appliances in the residential sector could be for instance labelled similarly as done within the European Union energy labelling.

It is important to maintain appropriate levels of entrepreneurial experimentation and the evolving field attractive for start-up entry as well as for diversifying companies from other sectors. This includes the prevention of quasi monopolistic power in the new system through for instance the establishment of proprietary standards for central platforms. Such standards might appear attractive in the short run but may be not only harmful for innovative companies in Denmark but also contribute to isolation from international developments.

The obstacle most often and most explicitly addressed by the survey is the energy tax framework. Institutional alignment is needed to support the efficient new applications. Particularly solutions involving energy conversion are currently facing severe disadvantages and thus the conversion of intermittent electricity into other energy sources is not as attractive as it could be, given its efficiency benefits.

Finally – and this is related to the former point – the public debate and

[18] Apart for better data estimate future demand levels.

legislative action should be even more based on an understanding of a integrated smart energy system as a more immediate target of the transformation rather than a remote goal. Thinking about the smart energy system as a set of sub-systems that can develop in separation to be later – once they are mature and functioning – joined into one large system might create the kind of separation between the sub-systems that will prevent or, at least, make the connection difficult. While the R&D policy obviously supports exploration of various technological approaches (see Chapter B), activities that experiment with the combination of various solutions, favouring collaboration between technological domains are more seldom. The architecture of the Smart Energy Alliance with its broader perspective and the division in five sections (energy efficiency, home automation, IT security, market design, and grid development) is indicative, for that the broader perspective is more natural from an industrial and technological point of view. This view is in line with the picture that emerges from the activity clustering in section 5 and has been proposed by scholars from the field of energy planning (Lund et al., 2012).

The success of Danish wind turbine technology has often been attributed to an evolutionary bricolage approach and set in contrast to the less successful intent to develop this technology in the US that was led by large aerospace companies (Garud and Karnøe, 2003). The smart grid and systems field in Denmark is developed in a context that technologically favours a bricolage approach of broad collaboration, co-creation of trajectories and modest gains through combination of existing resources. Eventually, some paths will prevail over others but this selection should not be made *a priori* whether explicitly or in an indirect manner by allowing proprietary standards that lock out alternative solutions or taxes and regulations that discriminate against potential solutions.

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A Figures and Tables

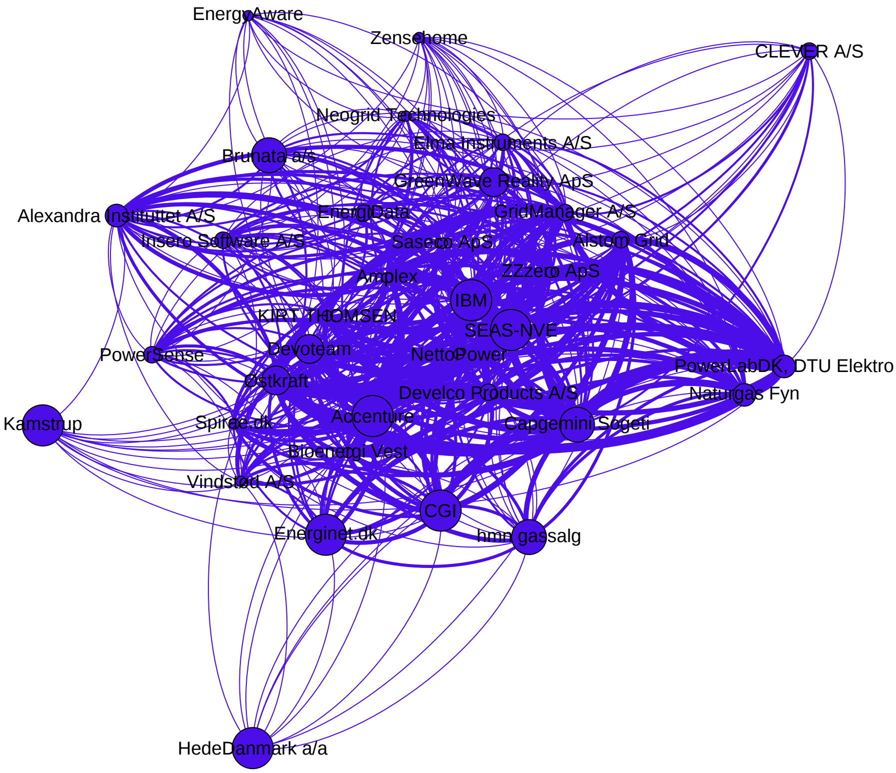

Fig. C.7: Organisation mapping: Smart Grid (narrow definition)

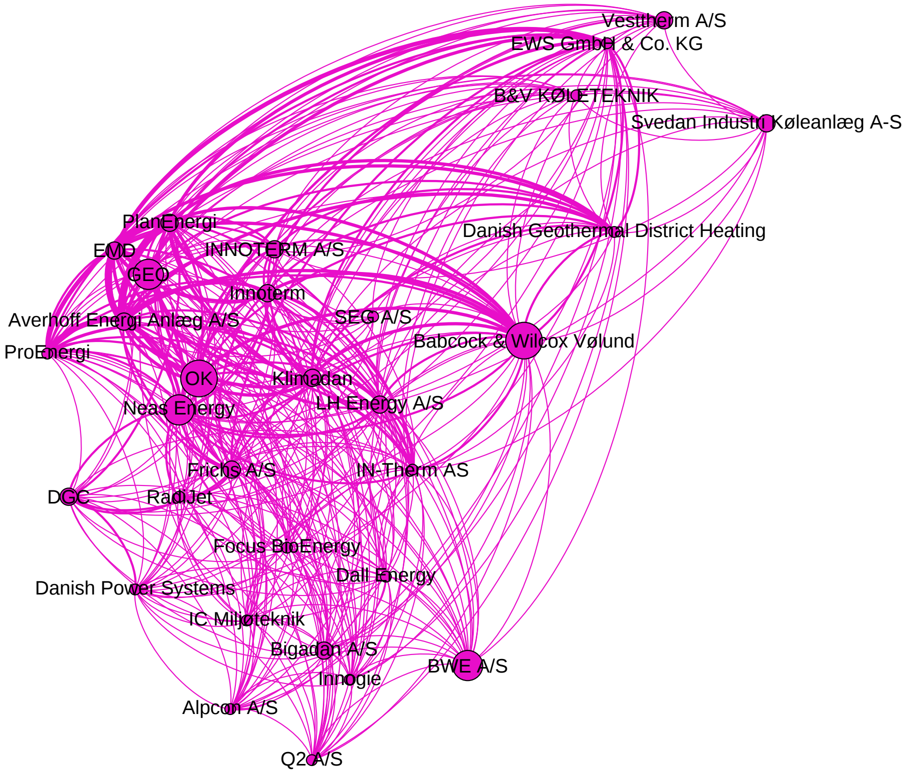

Fig. C.8: Organisation mapping: Energy Conversion

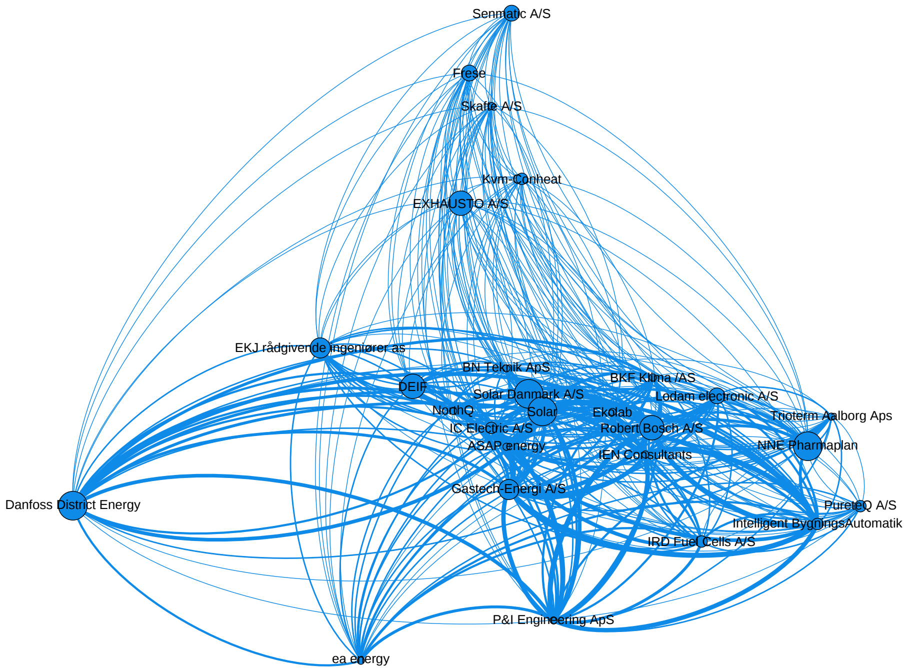

Fig. C.9: Organisation mapping: Component Suppliers

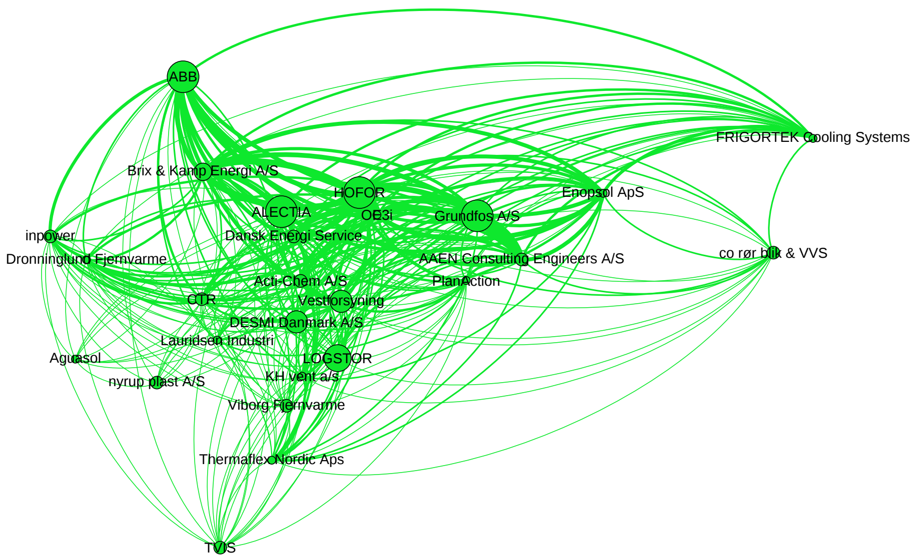

Fig. C.10: Organisation mapping: District Heating

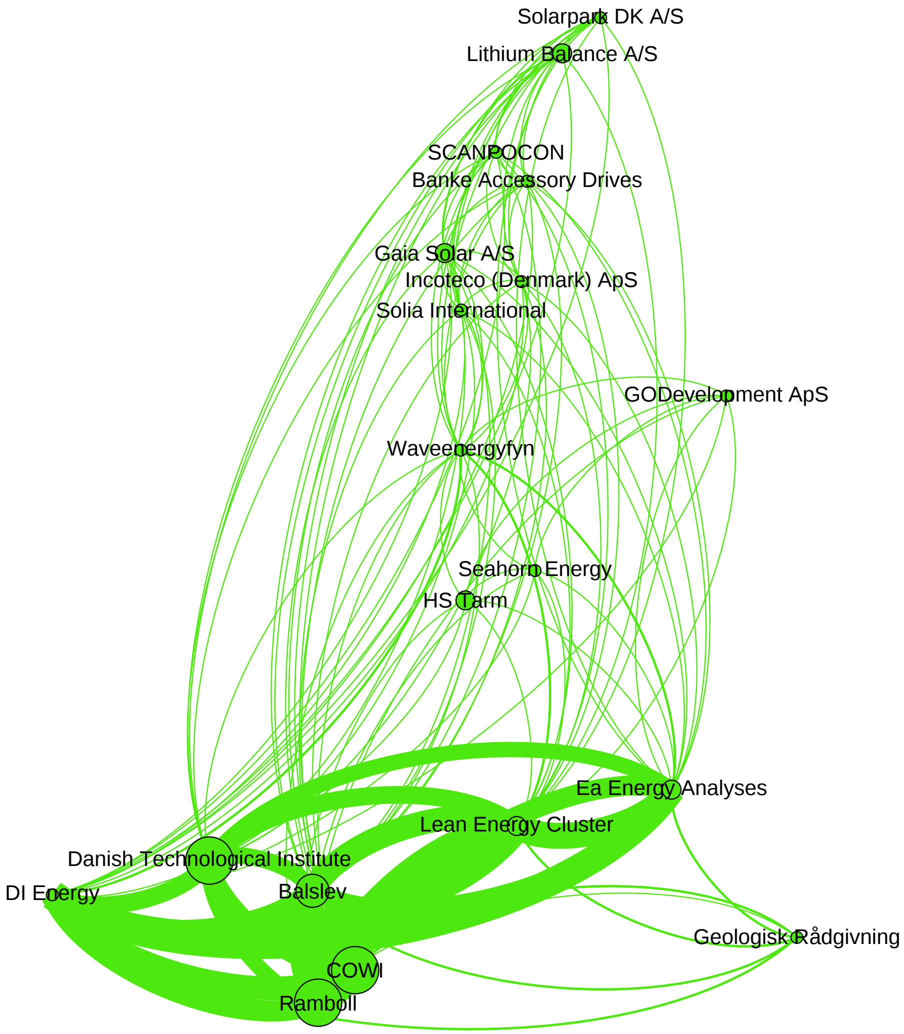

Fig. C.11: Organisation mapping: Consulting companies

B Questionnaire of the CCC report survey

The final draft of the questionnaire which was forwarded for distribution (formatted as an online survey).

Intro til spørgeskemaet – mail-tekst:

Copenhagen Cleantech Cluster udarbejder i øjeblikket i samarbejde med AAU og Rambøll en samlet oversigtsrapport over det ”smarte energisystem” i Danmark. Rapporten skal være med til at skabe opmærksomhed om det unikke danske energisystem, og hvordan det er under udvikling for at leve op til de energipolitiske målsætninger. Foruden at skabe et let tilgængeligt overblik over de danske kompetencer og produkter, vil rapporten indeholde et opslagsværk over danske teknologileverandører og rådgivningsvirksomheder på området (inkluderet produktion, distribution & transmission, konvertering, forbrug og lagring af el, gas, fjernvarme og fjernkøling).

For at indsamle data til rapporten og virksomhedstabellerne udføres en kort spørgeskema-undersøgelse. Undersøgelsen indeholder 15 spørgsmål, som det tager 5-7 minutter at besvare. Vi håber, at du eller en kollega vil sætte denne tid af til at besvare spørgeskemaet, så [virksomhedens navn] bliver en del af rapporten.

(link til spørgeskema)

Du kan i øvrigt se eksempler på lignende rapporter om ”Smart City” og ”Grønt og Smart Byggeri” udarbejdet af Copenhagen Cleantech Cluster her: Rapporterne bruges bl.a. til at give udenlandske aktører et let tilgængeligt overblik over bestemte dele af den danske cleantech sektor. Den seneste rapport om smart og grønt byggeri i Danmark blevet downloadet over 300 gange og er blevet distribueret i mere end 500 fysiske eksemplarer til en række danske og udenlandske aktører ved diverse arrangementer.

Er der yderligere spørgsmål til undersøgelsen, bedes I kontakte undertegnede på mail eller telefon.

Tusind tak for jeres tid,

Med venlig hilsen…

Welcome to the survey, which aims to provide an overview of the companies and stakeholders contributing to the Danish Smart Energy System!

We use the following definition of the Smart Energy System:

The Smart Energy System is ”the flexible and intelligent system of integrated electricity, gas, district heating and cooling grids, which ensures the most cost-effective and sustainable energy production, distribution, storage and consumption”

Q1_What is the name of your company?

Q2_The company works with…: (feel free to mark more than one X) (if 4-->Q22 alternative ending)

1. Development and/or production of basic technology components or specialized systems, which contribute to smart energy systems
2. Consultancy related to smart energy systems
3. Other smart energy related activities (please specify)
4. The company does not have activities related to smart energy systems

Q3_Which part(s) of the smart energy system does your company operate within? (feel free to mark more than one X) (if: 1 --> Q4, 2 --> Q5, 3 --> Q6, 4 --> Q7, 5--> Q8)

1. Energy production (i.e. wind, solar heat, solar PV, hydro/wave, biogas, geothermal, biomass)
2. Energy transmission and/or distribution (e.g power grids, gas grids, district heating and cooling grids, Advanced Control and monitoring systems and Metering Infrastructure, grid management, energy trade)

3. Energy conversion (i.e. waste/biomass to energy, Combined heat and power, Compressor heat pumps to heating and/or cooling, absorption heat pumps electricity to gas)
4. Energy storage (i.e. batteries, pump storage, gas storages, hot and cold water storage tanks, seasonal heat or cold water storages, ATES).
5. Intelligent energy consumption (i.e. efficient heating and cooling installations, Building automation, intelligent lighting, electric cars, hydrogen cars, smart phone apps)

Q4_Which of the following technology domains for basic energy production does your company operate in? (feel free to mark more than one X)

1. Wind energy
2. Water energy (incl. tidal and wave)
3. Photovoltaics/solar cells
4. Solar hot water panels
5. Biogas
6. Syngas
7. Geothermal energy
8. Biomass
9. Other (please specify)

Q5_Which of the following areas within energy transmission and distribution does the company operate in? (feel free to mark more than one X)

1. Transmission and/or distribution of electricity
2. … of gas
3. … of heat
4. … of cooling
5. HVAC installations in buildings
6. Control and monitoring systems
7. Advance Metering Infrastructure
8. Grid integration (incl. Vehicle-to-grid)
9. Home and Building automation
10. Other (please specify)

Q6_Which of the following technology areas within energy conversion does the company operate in? (feel free to mark more than one X)

1. CHP – Combined Heat and Power (from waste, biomass and/or gas to heating and power)
2. Compressor heat pumps
3. Electric boilers
4. Absorption heat pumps
5. Syn-gas
6. Other (please specify)

Q7_Which of the following types of energy storage does your company's technology and/or consultancy support? (feel free to mark more than one X)

1. Hydro storage
2. Gas storage
3. Heat and cold water storage tanks
4. Seasonal heat storage
5. Seasonal cooling storage
6. Storage of electricity in batteries
7. Compressed air storage
8. Other (please specify)

Q8_ Which of the following technology areas within intelligent energy consumption does the company operate in? (Feel free to mark more than one X)

1. HVAC installations
2. Home and building automation systems
3. Smart phone app for intelligent energy consumption
4. Smart energy sensors and meters
5. Electric vehicles (incl. charging infrastructure)
6. Hydrogen vehicles (incl. charging infrastructure)
7. Other (please specify)

Q9_Please describe the key product or service of your company in one or two sentences (open answer)

Q10_What is the number of employees in the Danish part of your company? (If: 7 --> Q12)

1. 1-10
2. 11-50
3. 51-100
4. 101-250
5. 251-500
6. >500
7. Cannot provide information

Q11_How large a percentage of your company's employees in Denmark work on a daily basis with tasks related to the smart energy system?

1. 0 – 25 %
2. 26 – 50 %
3. 51 – 75 %
4. 76 – 100 %
5. Cannot provide information

Q12_Approximately how big was the revenue in DKK in 2013 for the Danish part of the company?

(Note: Answers will not be published for each individual company, but will only be used to generate an overview of the total revenue of the Danish sector for smart energy technologies) (If: 8 --> Q14)

1. Under 2 million
2. 2-10 million
3. 10-25 million
4. 25-50 million
5. 50-100 million
6. 100-200 million
7. >200 million
8. Cannot provide information

Q13_How large a percentage of the company's revenue in 2013 stems from sales of smart energy related products / technologies / services?

(Note: Answers will not be published for each individual company, but will only be used to generate an overview of the total revenue of the Danish sector for smart energy technologies)

1. 0 – 25 %
2. 26 – 50 %
3. 51 – 75 %
4. 76 – 100 %
5. Cannot provide information

Q14_Which foreign markets does the company export smart energy related products / technologies / services to? (feel free to mark more than one X)

1. European Nordic countries (i.e. Sweden, Norway, Finland, Iceland)
2. Germany
3. United Kingdom
4. Other European countries
5. USA
6. Russia
7. China
8. India
9. South East Asia (e.g. Indonesia, Phillipines, Malaysia, Singapore)
10. South America
11. Africa
12. Others (please specify)
13. No exports

Q15_Which actors working within the following industry sectors has your company collaborated with in 2013? (feel free to mark more than one X)

	wind	hydro(incl. wave)	solar	gas	geothermal	Waste & biomass	District heating and/or cooling
Business Association							
Other organization							
Danish company							
Foreign company							
University or knowledge institution							
Public authority							

Q16_Please name at least 3 of your most important collaboration partners in 2013 (optional)

Name of collaboration partner:
Name of collaboration partner:
Name of collaboration partner:
Name of collaboration partner:
Name of collaboration partner:
Name of collaboration partner:

Q17_Did the company introduce new or significantly changed smart energy related products / technologies / services in 2013?

1. Yes
2. No
3. Cannot provide information

Note: An innovation is the implementation of a new or significantly improved product (good or service), or process, a new marketing method, or a new organizational method in business practices, workplace organization or external relations. The minimum requirement for an innovation is that the product, process, marketing method or organizational method must be new (or significantly improved) to the firm – and it is anticipated that there will be a market for it.

Q18_How important are R&D activities in your company? (please 'click' on the line) (der sættes X på linje med "not important" helt til venstre og "very important" helt til højre)

Q19_What kind of barriers does the company experience, which prevent or seriously restrain further smart energy related innovation? (Feel free to mark more than one X)

1. Financial constraints, mainly due to lack of investors
2. Financial constraints, mainly due to customers' unwillingness to pay
3. Lack of or inappropriate regulation
4. Lack of or inappropriate standards
5. Inappropriate organizational setup of the energy sector
6. Other (please specify)
7. NO!

Q20_Within the next ten years, what do you think will be the greatest challenge for the efforts to create an even smarter integrated energy system in Denmark? (last question, optional)

Q21_slut:

Thank you for participating in the survey!

The results of the survey will be part of a report on the Smart Energy System, which will be published at the International Cleantech Network's (ICN) annual conference in the beginning of May 2014. This year the conference is hosted by the Copenhagen Cleantech Cluster, which is one of the leading cleantech clusters in the world.

Please visit our website - www.cphcleantech.com - for more information.

Further questions? - contact Project Development Manager, Jonas Mortensen (jom@cphcleantech.com, tlf. 31 69 48 19)

Q22_alternativ slut:
Unfortunately, your company falls outside the scope of this survey. We are sorry to have taken your time.

For more information about the survey, please contact Project Development Manager Jonas Mortensen (jom@cphcleantech.com, tlf. 31 69 48 19)

Paper D

Incremental by Design? On the Role of Incumbents in Technology Niches

Daniel S. Hain and Roman Jurowetzki

Accepted for book proceedings of the ISS 2014

We would like to thank all participants of the Jena ISS conference 2014, the Nice KID workshop 2014, the Copenhagen DRUID society conference 2014, the Stanford Network Forum ST2014, the IKE research seminar series 2014, the Oxford AIE conference 2013 and the Halle ENIC workshop 2013 for invaluable inspiration and feedback. All opinions, and errors, remain our own.

The layout has been revised.

Abstract

In this paper, we study the evolution of governance structures in technological niches. At the case of public funded research projects and the resulting cooperation networks related to smart grid and systems in Denmark, we raise the questions which actors over time inherit a central position – associated with high influence on the development of research trajectories – in the network. We are particularly interested in what role incumbent actors, connected to the old regime of fossil based energy production, play in shaping future technological trajectories. The protected space theoretically created by such public research funding offers firms an environment to experiment in joint learning activities on emerging technologies, shielded from the selection pressure on open markets, thereby facilitating socio-technological transitions. Generally, the engagement of large incumbent actors in the development of emerging technologies, particularly in joint research projects with entrepreneurial ventures, is positively perceived, as their resource endowment enables them to stem large projects and bring them all the way to the market.

However, growing influence of incumbents might also alter niche dynamics, making technology outcomes more incremental and adapted to the current technological regime. Potential influence on rate and direction of the technological development can to a large extend be explained by actors' positioning in the network of the niche's research activities. We create such a directed network of project consortium leaders with their partners to analyze if network dynamics of joint research projects in technological niches favor incumbent actors in a way that they are able to occupy central and dominant positions over time. To do so, We deploy a stochastic actor-oriented model of network dynamics, where we indeed discover path-dependent and cumulative effects favoring incumbents. Our findings suggest a development of the network towards an incumbent-dominated structure.

Keywords: innovation networks, industry dynamics, network evolution, public funded R&D, incumbents, technological change

1 Introduction

In order to address the environmental sustainability challenge many of the established large infrastructure related systems have to be transformed. One central area is the energy system. The shift from fossil based to renewable energy production is increasingly embraced as the solution, but the intermittent characteristics of electricity generated by sun and wind lead to severe implications for the electricity grid in its current architecture that is designed to transport steady energy from large central power plants to consumers. The construction of a smart grid and working towards a smart energy system is seen as a possibility to address this challenge. One issue that emerges in relation to this upcoming transformation is the ambivalent role of established firms from the energy sector. Their resources, capabilities, and cooperation are needed for this new development, yet they are likely to be the players that have a strong interest in maintaining the established systems unchanged.

In this paper, we study the evolution of governance structures in technological niches. At the case of public funded research projects and the resulting cooperation networks related to smart grid and systems in Denmark, we raise the questions which actors over time inherit a central position – associated with high influence on the development of research trajectories – in the network. We are particularly what role incumbent actors connected to the old regime of fossil based energy production play in shaping future technological trajectories.

The multidisciplinary literature on system innovation, often empirically focused on sustainability transitions, outlines the significance of niches for the protection and development of path-breaking technologies in early stages (Geels, 2002, 2004; Hoogma et al., 2004; Kemp et al., 1998). Public funded research, development and demonstration (R&DD) protects represent such a protected space, offering firms an environment to experiment in joint learning activities on emerging technologies. In the same vein, literature originating from the Technological Innovation Systems (TIS) approach also highlights the importance of creating protected spaces to foster market formation and diffusion (Bergek et al., 2008; Hekkert et al., 2007).

The engagement of large incumbent actors in the development of emerging technologies, and especially joint research projects together with young SME's, is generally positively perceived as they have the capabilities to fulfill necessary systemic functions in a better way than new start-up firms (Suurs and Hekkert, 2005). Apart from the direct effect of the engagement, it is likely to have a positive signaling effect. Thus, it might contribute positively to the status of the niche, improving financial viability and triggering interest of other companies (Smith et al., 2005). Arguably, the involvement of incumbents might, however, alter niche dynamics, making technology outcomes more incremental and adapted to the current unsustainable socio-technical regime. This is particularly evident if the emerging technology is a potential substitution to the existing solutions (Bower and Christensen, 1995; Tushman and Anderson, 1986). Indeed, literature on sustainable transitions suggests that incumbent actors – who over time carried out fixed investments in infrastructure, developed technological competences and secured market shares – have a high incentive to protect and replicate the old regime's logic and reinforce existing technological trajectories rather than develop new ones (Geels, 2011). This reflects a more critical and nuanced consideration of network structures in research collaborations, which may not necessarily be fully cooperative and consensus oriented, as mostly envisioned in innovation system and networks oriented approaches.

The incumbents' ability to influence the trajectory of technological development can, to a large extent, be explained by their position in the niche network. Here, a large body of literature on networks of innovators has produced ample theoretical reasoning and empirical evidence on how a firm's strategic positioning in interorganizational networks affect it's innovative performance (e.g. Baum et al., 2000; Powell et al., 1996), and the structure of the overall network affects the innovation output on the aggregated (Fleming et al., 2007) and firm-level (Kudic, 2014; Schilling and Phelps, 2007) alike. Consequently, firm-level cooperation choices build the micro-foundation for the rate and direction of innovation and technological chance in innovation networks. It is further argued that networks of innovators by no means are static constructs in time and space, but rather constantly rearrange in an evolutionary process, which is to a large extend path dependent (Doreian and Stokman, 2005; Powell et al., 2005; Tsai, 2003). Existing ties often tend to become more persistent over time (Burt, 2000), and preferential attachment makes the likelihood of creating new ties influenced by the actors stock (Barabási, 2005) – leading to a process of structural reinforcement (Gulati, 1999). This effects are also well known determinants influencing the allocation of public research grants (Viner et al., 2004). In the terminology of innovation and transition literature, that relates to the development of a niche into a "proto-regime" (Geels and Raven, 2006) with increasingly established institutions and emerging stabilization mechanisms. While these stabilization mechanisms are well-known features of social networks (e.g. Barabási and Albert, 1999), the question how characteristics and rationales of central actors affect the outcome of such networks is discussed seldom from a network perspective.

Yet, when envisioning public funded research networks as technological niches, this question becomes particularly important for two reasons. First, the organization of public funded R&DD projects distinguishing between a project consortium leader and further project consortium partners by design imposes a governance structure, where project leaders are able to determine main parts of the project's content. Consequently, actors in central positions of such networks are likely to have a high influence on the rate and direction of future research through their higher social influence and their role as "knowledge hubs". Second, a main argument put forward to protect the space within technological niches is that they offer the actors the opportunity for broad experimentation which is not influenced by the selection pressure of the current regime (Smith and Raven, 2012).

Having that said, to allow path-breaking ideas to unfold in technological niches, it becomes crucial that they initially contain a broad set of actors with heterogeneous knowledge bases as well as "hidden preferences" regarding the future development of the niche's technological trajectory. While over time evolutionary processes will lead to a concentration and consolidation of the network, in early phases broad experimentation in different direction is needed. A requirement for this endogneous selection processes to unfold is the emergence of internal selection logics. However, the smart grid as a technological niche is heavily connected to the current energy system, in terms of infrastructure and other physical assets as well as applied knowledge. Furthermore, public authorities who allocate resources in this niche are likely to be in some way connected to the old regime.

To conclude, path-dependent and cumulative characteristics representing the old regime and favoring incumbent players are replicated in the technological niche of smart grid research, evolutionary processes will enable them to obtain central and dominant positions and thus shape the niche's further development by their will.

Following earlier argumentation, actor-strategy driven network dynamics in technological niches can be assumed to lead to more incremental outcomes which reinforce old technological paths if (i.) the network evolution is driven by endogenous and cumulative effects, such as the actors size, age, reputation or network position; (ii.) incumbent actors embodying such characteristics are involved; and (iii.) there exist possible new niche trajectories which lead to an underutilization of their accumulated resources.

The empirical context is the evolution within the Danish electricity grid-infrastructure network of joint participation in public funded R&DD projects in the period 2009 until 2012. Companies and projects were identified by exploring the Danish research project database. The Danish case is of particular interest because of the explicit political aspiration to become a European technology hub for the development and testing of advanced energy grid technologies (KEMIN, 2013). A national smart grid strategy from May 2013 emphasizes the importance of interaction between research institutes, utilities and technology producers, and the development of various technologies. A number of research programs were established to support R&DD projects from basic research to large-scale demonstration and commercialization.

The purpose of the present paper is to study structural dynamics and path dependencies of research networks in technological niches at the case of public funded research projects. In particular, deploying a stochastic-actor-based model (Snijders et al., 2010b), we analyze if network dynamics of public funded R&DD in technological niches favor incumbent actors in a way that they are able to occupy central and dominant positions. Against the empirical and theoretical background, we conceptualize the research network as consisting of directed ties between the actors, assuming the project-leader to project-partner link as a hierarchically ordered relationship. By doing so, we are able to analyze up to now unobserved cumulative and self-reinforcing effects of network dynamics.

As a result, we indeed find such path-dependent and cumulative effects in the development of the research network that favor incumbent actors, in the long run leading to a a reinforcing process of structural stabilization with central and influential positions.

The remainder of this paper is composed as follows: The following section 2 aims at linking different streams of literature that advocate for the creation and protection of technological niches with network theory. This connection is made to understand strategies of different niche actors and possible macro outcomes of their behavior. Section 3 provides an overview of the technological and policy context of the smart grid development in Denmark. In section 4 we introduce the stochastic actor-based model deployed to identify the evolution in the niche-network, and describe the research networks data used for the analysis as well as our empirical strategy. Section 5 presents the results, and the final section 6 concludes.

2 Theoretical Background

2.1 Inertia at micro and meso levels in large technical systems

The achievement of the environmental sustainability goals – such as the reduction of greenhouse gas emissions, exhaustion of natural resources, and destruction of ecosystems – in highly dependent on the determination and ability to transform a number of large technical systems (LTS's) worldwide. LTS's, such as the energy grid, the transportation or the agri-food sector build complex, extremely interwoven technical, economic, institutional and administrative structures (Hughes, 1987). Such sectors heavily build and rely on existing tangible and institutional infrastructures (e.g. development and trial systems, supplier and distribution networks, energy transmission grids, and other complementary assets). This dependence leads to high entry barriers in aforementioned industries and explains why key players are likely to be large companies (e.g. electric utilities, car manufacturers, railway operators).

Incumbent firms with substantial shares of their resources bound in an established technological regime are said to struggle in maintaining a certain level of innovation activity - particularly when facing radical, discontinuous technological change (e.g. Bower and Christensen, 1995; Wagner, 2010).[1] In

[1] One can broadly distinguish between *competence-enhancing* innovation building upon exist-

case of *competence-enhancing* technological innovation, established firms have incentives to actively engage in and support the development of the technology updating the existing (Gilbert and Newbery, 1982) regime.*Competence-destroying* innovation in turn appears as more likely to be pioneered by newcomers (Anderson and Tushman, 1990; Tushman and Anderson, 1986).

Over time, incumbents might also develop adoptive capabilities, enabling them to absorb knowledge on more radical novelties and combine it with their stock of knowledge to develop superior products and processes (Bergek et al., 2013). This can be done i.a. by engaging in joint R&D projects with entrant firms or the acquisition of their technology (e.g. Wagner, 2010). However, once internalized, the absorbed novelty is likely to be aligned with existing resources in a complementary way. Therefore, when engaging in joint R&D projects, we assume that established firms – given the power – will influence technological trajectories in a way that makes the outcomes more compatible with their established assets and therefore potentially less radical.

Once a LTS has gained momentum these strategies become part of the resistance mechanisms against change on the system level (e.g. Van der Vleuten and Raven, 2006; Walker, 2000). The resulting set-up creates a power and capability imbalance between usually small enterprises that are pioneering the development of sustainable solutions and incumbent actors (Hockerts and Wüstenhagen, 2010). As long as production and distribution processes within existing trajectories are economically favorable, incumbents will not see urgent reasons to make large investments and reorganize existing production structures. On the contrary, they are most likely to defend the system against change (Walker, 2000). In the most extreme case this leads to inertia and lock-in (Arthur, 1989), as one might observe in our current fossil fuel dependent energy system (Unruh, 2002, 2000).

2.2 System innovation thinking

Technological change embedded in large systemic context has been conceptualized and analyzed throughout the past three decades. The technologi-

ing technological and organizational structures, and *competence-destroying* innovation turning them obsolete (Tushman and Anderson, 1986). This distinction to a certain extent reflects the notions of *incremental* and *radical* innovation.

cal innovation system TIS sub-orientation (Bergek et al., 2008; Carlsson and Stankiewicz, 1991; Hekkert and Negro, 2009) within the innovation system (IS) literature is increasingly used for the analysis of emergent industries on the basis of radically innovative technologies and the institutional and organizational changes that accompany the technological development (Truffer et al., 2012). A number of system functions (Hekkert et al., 2007) focusing on the support and nurturing of emerging technologies are seen as intermediate variables between the structure of the system and its performance, emerging out of the interplay between actors and institutions (Jacobsson and Bergek, 2011). While it is acknowledged that incumbent players may employ strategies to prevent disruptive innovation (Hekkert et al., 2007), their participation in the TIS is generally seen as fruitful – highlighting their resources, knowledge integration capabilities (e.g. Bulathsinhala and Knudsen, 2013) and the positive signalling.

In the recent decade, a second stream of literature situated closer to the science, technology and society (STS) tradition gained considerable attention. The multi-level perspective (MLP) at the center of the transition literature explains socio-technical transitions by the interplay of three systemic concepts. The landscape on the macro-, the socio-technical regime on the meso-, and niches on the micro-level respectively (Geels, 2002, 2005). The character and intensity of the interplay between the three levels define the paths, which a socio-technical transition might take. The key concept of the MLP is the regime, which represents a coherent, stable structure at the meso-level, combining established products, technologies, and institutions (routines, norms, practices). The regime is characterized by a high level of "structuration" (Coenen and Díaz López, 2010), well articulated rules, and hence path-dependency and mechanisms for self-stabilization. It corresponds in many respects to the selection environment in terms of evolutionary economic theory and generates entry barriers for innovative technologies.

2.3 Niches & protected spaces

Niches are conceptualized as spaces that shield path-breaking innovations in early stages of development from selection pressure on mainstream markets (Hoogma et al., 2004; Kemp et al., 2001; Schot, 1992). These spaces help overcome the lock-ins existing in the current unsustainable system due to economic scale and scope effects (Arthur, 1989), and institutional regime stabilization mechanisms that are constantly reinforced by established actors (Unruh, 2000). Given alternative selection criteria, population and interaction dynamics, niches can develop own technological trajectories substantially differing from the established regime.

The direct funding of R&DD in selected technologies of interest represents an integral component of modern innovation policy. Shielded from the selection pressure of open markets, these research projects present an ideal platform for a broad, experimental and long term oriented search for new technologies. Nurtured with public investments, new entrants and incumbents alike are able to stem projects which would, due to their high technological uncertainty and long payoff periods, not be carried out otherwise. Given the proper institutional set-up, public R&DD financing offers a powerful tool to directly influence rate and direction of research activities (Pavitt, 1998) and to create technology niches.

A challenge for policy-makers is the selecting of the appropriate protection level as well as its continuous assessment. Failure to find the right balance between protection and exposure to the selection environment can result in overprotection of "poor innovations" (Hommels et al., 2007), incompatibility with the surrounding technological context, or a too low level of protection of promising emerging technologies(Smith and Raven, 2012). The latter can happen when actors belonging to the established unsustainable technological regime achieve dominance in spaces that are actually meant for the development of solutions that are potentially meant to replace parts of the current regime. As Smink et al. (2013) conclude "innovations with significant sustainability gains tend to be non-incremental and are therefore likely to have adverse effects on the business interests of regime actors". Therefore, we assume that their presence as dominant actors – and especially positioning as project leaders – in such niches might undermine the efficiency of the sustainable innovations under development.

2.4 A network perspective on technological niches

Cooperation and interaction between various actors involved in processes of technology development such as universities, firms, intermediate, and end users, are said to be of high importance for the smooth functioning of innovation systems (e.g. Hekkert et al., 2007; Lundvall, 1992; Malerba, 2002). A major task for science and innovation policy is therefore to facilitate the development of favourable R&D network structures (Carlsson and Jacobsson, 1997), triggering interaction between heterogeneous actors and the generation of technological variety. Organizations form collaborative alliances in order to get access to their partners' technological assets and capabilities. Yet, potentially fruitful interaction with other corporations also comes at the risk of opportunistic technology appropriation by the counterpart, making careful selection of partners crucial (Li et al., 2008).

One can broadly distinguish between two categories of information that actors can use in cooperation and partner selection decisions. First, reputation, mostly stemming from past performance in similar settings (Shapiro, 1983), and their demonstrated capabilities. Second, information about an actor's position in relevant networks (Benjamin and Podolny, 1999; Burt, 1992; Granovetter, 1973), where usually better connected actors appear also as more attractive partners for further cooperation. Both appear to be highly interdependent, since an actor's reputation can be influenced by the reputations of past and current exchange partners (Benjamin and Podolny, 1999; Podolny, 1993) and collective reputations can be transferred to the a groups individual actors (Schweizer and Wijnberg, 1999).

From a network perspective, a certain level of progressive centralisation and increasing dominance of incumbent players is therefore expected. Against the backdrop of the argumentation found in the transition literature, a strong centralization would however mean that niche protection is only limited. Particularly if incumbent actors, increasingly assume project-leader roles, the development of sustainable innovation is virtually handed by the regime.

2.5 Summary

Overall, the above presented streams of literature draw a similar picture from their respective point of view: Innovation is particularly complex and costly in systemic set-ups. Path dependencies are especially pronounced in sectors with a high share of infrastructure. Frameworks that inform policy measures to spur change in these areas agree on the need to actively create technological and market niches in order to foster alternative technologies and in general solutions. Yet, the role of incumbent player within these niches needs more inquiry.

Innovation paths that are compatible with regime technologies are attractive for established firms. Resulting innovations can address some of the existing problems on the regime level – to use the MLP terminology – without compromising existing socio-technical structures. Established firms are therefore likely to initiate or engage in niche activities, such as R&DD projects, which investigate such applications.
Facing radical or architectural technological change, they will not directly support the early development of path-breaking innovations, but rather aim at gaining control, acquiring, and integrating novel and existing technologies (Bergek et al., 2013; Pavitt, 1986). Strong ties to the existent structures and technologies on the one hand and technological uncertainty, on the other lead to a relatively late but determined entry of incumbents into the development of these technologies. We assume that this may alter the particular innovative technology towards a less radical solution. In the case of sustainable technologies that would mean that generally more desirable superior solutions are possibly devaluated as they become compatible with the existing unsustainable system. From a policy perspective, and in the particular context of public research funding, that also raises the question related to *outcome additionality*.

3 Sociotechnical context of the smart grid development in Denmark

In order to understand and assess the structural dynamics of Danish smart grid and systems R&DD projects, it is important to consider the technological and policy context of the smart grid development. This section will introduce the fundamental technological concepts, components, and challenges related to the ongoing paradigm shift in the Danish and many other energy systems.

Furthermore, the second part of this section will provide a brief overview of the policy ambitions that inform and guide the setup of publicly funded research programs. We fully acknowledge that funding programs and specified calls are intended to direct the technological trajectories of research projects. To some extent selection procedures by public authorities also predetermine their composition in terms of which types of actors and consortia constellations are awarded with grants and which not. Yet, the duality of selection in content as well as actor characteristics might lead to politically unintended developments regarding the evolution in the resulting research network – such as the rapidly growing dominance of certain actors.

3.1 Paradigm shift in energy production and the response in the grids

The traditional architecture of the electricity grid assumes a unidirectional energy flow from centralized energy plants via the transmission and distribution grids to consumers, where energy production levels are constantly adjusted to match the over time fluctuating energy demand (Farhangi, 2010; Fox-Penner, 2010). Embracing the renewable energy paradigm, centralized energy production is gradually replaced by decentralized energy farming. The harmonization between production and consumption has to move from the traditional generation side into the transmission and consumption areas. ICT technologies will play a central role in supporting this process (Mattern et al., 2010).

In the Northeuropean set-up, two options are possible and currently discussed. Firstly, the construction of a European transmission super-grid to allow, for instance, energy exports from Denmark to Germany in wind-peak times. Secondly, the development of a national *smart grid*, that is able to transmit energy and information in both ways, thus allowing for harmonization by the means of flexible consumption. This requires the upgrade of the existing grid by adding a *layer of intelligence* - advanced measurement, communication and control technology - thus making the grid able to handle a higher share of decentralized renewable energy generation and the recently evolving consumption patterns (Elzinga, 2011). This process is not primarily related to the development of radically new technology but to the recombination and integration of existing technology in order to achieve new functionality that would optimize the efficiency of the established system. If flexible consumption can be activated by the introduction of smart functionality, costly investments in the reinforcement of the distribution system can be moved into the future or avoided (Forskningsnetværket, Smart Grid, 2013). This may be a favorable outcome for the country as a whole but might undermine profits of established actors that would benefit from capacity increase of the system.

3.2 Danish smart grid research and aspirations

Denmark is already today counting the largest amount of R&DD projects within the smart energy area in Europe (Giordano et al., 2011, 2013). The extremely high ambition of the national energy agreement, passed by the government in 2012, targets a wind-power share of 50 percent by 2020, and the more recently announced Smart Grid Strategy sees the country as a European laboratory for innovative energy solutions (KEMIN, 2013).

Following the target setting of the policy package, a “Smart Grid Research Network” with key organizations from the technical universities and practitioners from the Danish TSO energinet.dk, the Danish Energy Association, and the energy group within the Confederation of the Danish Industry were established. In 2013 the network published a report commissioned by the Ministry of Energy, Utilities and Climate, which draws up a roadmap for the development of the Danish smart grid. The report identifies fields which will require considerable research efforts but also areas with strong Danish competences and experience that can attract foreign investment or contribute to technology export. Overall, it concludes that the development of the smart grid should be put first but not seen in isolation. Rather the interactions with the other energy related systems, such as heating, cooling, gas, and transport should be considered at all times.

In their latest inventory report Giordano et al. (2013) outline, that compared with other European countries, Denmark manages to develop a large amount of smaller projects which spurs technological diversity (Borup et al., 2013). This is in line with the findings by Jurowetzki (2015). Exploring the scope of the national smart grid and systems research he found that, research projects span from topics that are closely related to the pure electricity smart grid, such as consumption flexibilization to the interaction areas of different systems (e.g. the role of electric vehicles, heat pumps, and the district heating system).

That can be interpreted as a sign of successful niche development and the gradual merge of the electricity, gas, cooling, and heating systems into one smart energy system (Copenhagen Cleantech Cluster, 2014). This context also offers entry and influence opportunities for different types of established actors

At the core of this research is the question of whether public funded R&DD activities are well constructed to provide necessary shielding in order to develop and introduce the needed amount of technological variety in the changing energy grid sector. The here proposed evolutionary network analysis can not provide direct answers to this question. Yet, the evolving structure of the research network can shed light on the likely development of the technological field.

4 Modelling Network Evolution

4.1 Data

Network Data

As a source for public funded research projects, we utilize the database provided by *Energiforskning.dk*. Combining data from several energy technology research and development programs, this database represents the most comprehensive source for public funded energy research in Denmark, covering projects funded by the *Strategic Research Council*, *ForskEL*, *ForskNG*, *ForskVE*, *ELFORSK*, *Green Labs DK*, *Danish High Technology Foundation* and the *European Union*. For the current analysis records from the *smart grid and systems* category were exported containing information on projects from 2009 to 2012 on yearly basis – overall 75 projects with 277 participants, and 132 single firms. Among those actors we identify 27 incumbent firms and 21 research institutions with the rest being either established diversifier companies or new entrants[2].

[2]A detailed description of the applied classification methodology is described below

We include all private firms and other organizations that participated in at least one public funded R&DD project during the 2009 - 2012 period. Further Thereby we exclude actors which have unsuccessfully applied for public funding, actors who would have liked to join such a research project as partners but have not been selected, or have been selected in the initial project application but where for some reason excluded from the official consortium at the start of the project. When assuming such actors to be systematically different from successful project leaders and partners, this obviously introduces a selection bias and limits the concussions we are able to draw from this analysis. Consequently, we are able to analyze if public research grant allocation decisions *per se* favor actors with certain characteristics. Neither we can investigate the general mechanisms of partner selection in the "hypothetical" network of available research partners. Yet, working with the "revealed" network of realized cooperation still allows us – in line with our research objective – to analyze the emerging governance structure of public funded R&DD networks.

The directed edges in the network represent join affiliations with the same research project, which are active from the official -start until the end of the project, where they are set to be inactive again if no further joint project follows. Technically, we project the two-mode network of actors-to-project to a one-mode network of direct actor-to-actor affiliation. In line with our research objective to analyze governance structures in this network, we do not connect all participants of a project with each other, but only create one-directional edges between the assigned project consortium leader in direction of every other project partner.

In order to utilize models of network dynamics, the dataset under observation has to fulfill certain properties in line with the underlying assumptions of this model class. First, the network has to show some variation between its periods. However, too rapid changes indicate that the assumption of gradual change – compared to the observation frequency – is violated. To ensure the validity of the gradual change assumption, we consult the Jaccard index to be found in table D.3, a common measure of similarity between two networks.[3] Snijders (2002) suggest this index to be higher than 0.3 and never

[3]The Jaccard index as a measure of similarity between two network waves is computed by

drop beyond 0.2, which is given in our data. Overall, after a first preliminary inspection, the network data appears to have suitable properties in line with the assumptions of stochastic actor oriented models. Some further descriptive statistics on structural network measures and their development over time are provided in table D.4 in the appendix.

A graphical presentation of the network under observation and its change over time is provided in Figure D.2 in the appendix. On first glance, a formation of structural clusters around some incumbent actors can already be seen over time.

Actor Data

Data on firm characteristics, such as their age, size, legal form *et cetra* was extracted from the Danish firm database Navne & Numre Erherv (NNE). For additional information about firms' technological capabilities and their range of activity where gathered by studying annual reports, press articles, corporate websites *et cetra*.

4.2 Modeling network dynamics

Our attempt is to analyze the dynamics of interorganisational networks of joint participation in public funded research projects. In particular, we are interested in which firms over time move towards central positions in the network. The analysis of such dynamic networks represents an empirical challenge which calls for distinct statistical models and methods. The main problem stems from the very nature of social network formation processes. Many drivers of individual tie-formation decisions, such as transitivity, reciprocity, and popularity effects, by their very nature lead to endogeneity and dependencies of observations (Rivera et al., 2010), since multiple characteristics of the current network structure influence its future development. This usually violates the assumptions of most standard statistical model types at hand (Steglich et al., 2010).

The class of stochastic actor-oriented models (SAOM) originally developed by Snijders (1996) represents an attractive solution to address the inher-

$\frac{N_{11}}{N_{11}+N_{01}+N_{10}}$, where N_{11} represents the number of ties stable over both waves, N_{01} the newly created and N_{10} newly terminated ties in wave 2 (see Batagelj and Bren, 1995).

ent endogeneity problems of longitudinal network analysis, which scholars have lately started to deploy in the context of inter-organizational innovation networks (e.g. Balland, 2012; Balland et al., 2012; Buchmann et al., 2014; Giuliani, 2013; Ter Wal, 2013). At its core, a SAOM combines a random utility model, continuous time Markov process estimation procedures, and Monte Carlo simulation. Originally, SAOM was developed in a sociological context and designed to model group dynamics in interpersonal networks (e.g. Van De Bunt et al., 1999). However, actor-oriented modeling has also proven to be suitable to depict the interaction between macro outcomes and firms' micro choices (Macy and Willer, 2002; Whitbred et al., 2011) in inter-organizational alliance formation process. Here, structural change of the network is driven by individual firms' collaboration decision derived from a random utility model. Firms are assumed to observe the current network structure and characteristics of its population, and reorganize their ego-network in an utility-optimizing manner. Given the context of the study, we consider SAOM as the most suitable class of dynamic network models and deploy it for the empirical analysis to follow.

Snijders (1996) firstly proposed to address the problem of multiple endogeneity in the evolution of social network with transforming discrete datasets of panel waves into a continuous set of micro-changes (single reconfiguration decision) to be estimated by Markov-chain Monte Carlo simulation (MCMC).[4] Unobserved changes between the panel waves are simulated as continuous actor choices at stochastically determined points of time. Formally, following a Poisson function of rate λ_i, the actors (in our case, individual firms) are allowed to create, maintain, or dissolve ties until the network is transformed to the new structure χ. The decision of actor i to change the state of one tie to another actor j leads to a new overall state of the network χ, where the probability P_i for an actor choosing this structure is given by:

$$P_i(\chi^0, \chi, \beta_k) = \frac{\exp(f_i(\chi^0, \chi', \beta_k))}{\sum\limits_{\chi' \in C(\chi^0)} \exp(f_i(\chi^0, \chi', \beta_k))} \tag{D.1}$$

It technically resembles a multinomial logistic regression, modeling the

[4]Besides all its merits, the usage of estimations based on continuous-time Markov processes also has its drawbacks. It by definition does not allow for path dependencies. Yet, it is still possible to include variables aggregated over time to the current state.

probability that an actor chooses a specific (categorical) new network configuration P_i as proportional to the exponential transformation of the resulting networks objective function $f_i(.)$, with respect to all other possible configurations. The parameters' coefficients are stepwise adjusted by Monte Carlo simulation techniques in order to obtain convergence between the estimated and observed model, and finally, held fixed to allow their comparison and post-estimation analyses. The objective function contains actor i's perceived costs and benefits of a particular network reconfiguration leading to a network state χ, χ, which are represented by the random utility model:

$$f_i(\chi^0, \chi', \beta_k) = \sum_k \beta_k s_i(\chi^0, \chi, \nu_i, \nu_j, c_{i,j}, \epsilon, r) \tag{D.2}$$

It depends on the current state of the network χ^0, the potential new one χ, the ego i's and alter j's individual covariates ν_i and ν_j, their dyadic covariates c_{ij}, exogenous environmental effects ϵ, and a random component r capturing omitted effects. The underlying assumption is that the actors observe the current structure of the network χ^0 and the relevant characteristics of its actor set and make their collaboration decisions in order to optimize their perceived current utility (Jackson and Rogers, 2007).

4.3 Empirical Strategy

Theoretical considerations

We model the tie creation process between ego i (project consortium leader) and alter j (project partner) as unidirectional from $i \Rightarrow j$. Thus, existing ties do not have to be reciprocal – a characteristic we find in many real-life networks such as friendships, mentorship, or producer-consumer relationships. Since we are interested in the ability to steer technological development of public funded research networks, we assume project consortium leader to have a significantly higher influence on the project's content than other participants. From this point of view, the directed network resembles the governance structure of there networks, and the actors outdegrees can be interpreted as a measure of influence. In our case, this appears as reasonable since the leaders of such projects are usually the ones applying for the corresponding grant, determining most of it's content, and selecting further partners. We chose a unilateral confirmation setup, where tie creating is only conditional to the ego's – but not the alter's – choice. By doing so, we assume potential partners to automatically join research projects when invited. This appears as a strong, but realistic assumption. Such a participation represents a safe source of income (and potentially knowledge), where the main upfront work, such as the grant application and determination of the content, is mostly carried out by the project leader. SAOM usually model tie creating as well as tie dissolution, where actors might choose to break up ongoing relationships which turn out to now offer negative utility. Since in our case the timeframe research projects is determined *ex-ante*, we only model the creation of new ties, where we exclude egos with already existing collaborations from the ego's choice set.

The nature of our network data calls for further consideration. In order to create a direct network among actors, we first have to project the two-mode network between actors and research projects to a one-mode network in actor space. Our resulting network is unweighed, meaning that the relationship between a project-leader and all project-members has the same quality, independent of the number of members. One might obviously assume that the size of project consortia systematically differs in a way that certain actors (probably larger and/or more experienced) actors show a tendency to include more members than others, thus establish more outdegrees per project than others. Further, it has been argued that the quality relationship between actors arising from a joint association with a second-mode differs with the number of actors this affiliation is shared. Newman (2001) for example argues that the quality relationship and interaction arising from scientific cooperation via co-authored publications substantially decreases with the amount of co-author. To account for this effect, one could weight the projected edges by the number of edges of the second mode (Opsahl, 2013). While this is true for many types of relationships in different social settings, we do not believe it to be in our case. We explicitly aim to model governance structures emerging in public funded R&DD networks, given by the actors number of outdegrees. Consequently, the more alters a specific ego reaches increases their influence in determining research agendas, indecent of the fact that these outdegrees are established in one large or many small projects.

In addition, there undoubtedly exist some caveats when mapping networks based the common participation research consortia funded by public research grants. First, these networks only to some degree evolve naturally, since they are subject to a selection by the responsible public authorities. Selection criteria may be found, among others, in (i.) the reputation and credibility based on past performance and other forms of accumulated advantage of consortia members, (i.) the characteristics of the project such as the applied technology, (iii.) or the favoritism of certain consortia constellations. Second, since the actors are anticipating a selection according to these criteria, they have an incentive to consciously form consortia according to them. Thus, consortia formation are subject to selection biases *ex-ante* and *ex-post* to the project application. Consequently, the results have to be interpreted not as the outcomes of natural network evolution, but rather the channeled evolution in a socially constructed selection environment designed by public authorities, which might be subject to criteria (ii.). With the choice of the study's empirical context, we attempt to minimize systematic biases caused by criteria (ii.) and (iii.). First, Danish research funding in renewable energy technology is designed to generate the broad technological variety necessary for the sustainable transition of the energy system (Lund and Mathiesen, 2009), where favoritism of certain technology should explicitly be avoided. Second, by including several research funding programs of independent governmental and non-governmental agencies in Denmark and the EU, spanning different industries as well as preferred development stages of funded projects, we avoid systematic bias caused by preferences of particular programs or policy initiatives.

Dependent Variable

We model collaboration choices driving the evolution of the network as the outcome of the actors' mutual attempts to optimize their expected utility with respect to their own and their potential alters' covariates, and the current network structure. Thus, our model's dependent variable represents the probability P_i that the focal actor i chooses a reconfiguration of the own network that leads to a tie with a corresponding alter j. This tie is directed from the project-consortium leader (ego) to a participating project partner.

Independent Variables

In the following, we discuss our independent and control variables, where we integrate covariates referring to the characteristics of the actors, as well as effects referring to their position in the local and global network[5] Since we are primarily interested in what makes actors establish – rather than receive – new ties, all independent variables refer to the characteristics and network structure of the focal ego *i*. A detailed description of all independent variables – and their calculation – deployed is provided in table D.2, and all network related effects are illustrated visually in D.1.

Actor covariates: This set of variables represents the effect of individual actor characteristics on their likelihood to establish new ties with other organizations.

In order to examine the `role` of actors in the combined network, we use a set of industry experts[6]. We differentiate between three roles, where we are particularly interested in the role of energy incumbents and the strategic deviations of these actors as compared to other actors involved in smart grid research projects. `Role incumbent`: This category aims at grouping actors with an origin in the energy sector that have an vested interest in protecting the established infrastructure from significant change. The experts were asked to identify "firms with a strong background/track-record and stakes in the traditional energy sector". This includes utilities, producers of transmission and distribution infrastructure, and producers of measuring devises. Apart from the utilities that went through a Europe wide policy induced organizational restructuring process, companies were founded before 2000. `New Entrant`: This group summarizes companies which were mostly founded after 2000 and have their main activity in the energy sector. The firms provide a broad range of products and services. Many of the firms develop ICT related solutions for the envisioned communication structure of the smart grid. Another large share are technology consultancies that are often responsible for analysis and system integration. It, however, also includes mature firms from

[5]Where local and global refer to the network position of the actor and not to a geogaphical context.

[6]The experts are 3 energy related association managers from the Copenhagen Cleantech Cluster, Intelligent Energy alliance and the Lean Energy Cluster respectively

other fields diversifying in the energy sector. `Role Others:` This class contains private and public actors that have shown interest in the development of a new grid infrastructure by participating in a research project. Actors are rather heterogeneous and have not had a background in the energy grid sector. This set of actors represents the reference group.

The `size` of a firm is also supposed to influence it's capabilities of successfully obtaining research grants, as well as to occupy central and dominant position in the resulting research networks. However, `size` is difficult to compare between different forms of organizations such as private companies, public organizations and research institutions. Therefore we only use a rough categorical classification of small (up to 25 employees, `firm small`), medium sized (up to 100 employees, reference groups), and large organizations (more than 100 employees, `firm large`). Generally, we expect large firms to establish more outdegrees for a set of reasons, where the most obvious is their higher internal capacity and resources to manage more projects at once than their smaller counterparts.

While maturing, firms are able to increase their competences in how to successfully formulate a research grant application, establish an intensify formal and informal relationships to industry partners and public authorities, and develop routines how to manage research partnerships. Since we expect these benefits to increase with decreasing marginal effects, and furthermore the distribution of firm age in our sample is highly skewed (start-ups as well as traditional firms established over a hundred years ago), we use the natural logarithm of the ego's `age` in years instead as control variable, which we generally expect to have a positive impact on the establishment of further outdegrees. Yet, the opposite might very well be true, if older firms loose their innovative edge and participate less in R&D projects.

Some further descriptive statistics of these actor-oriented measures are provided in table D.5.

Local (ego) network effects: This set of variables captures structural characteristics of the actor's ego-network, which include dyadic and triadic tie-configurations with other actors. Literature suggests these effects to be among the most important driving forces of network dynamics. Given the context of our study, however, they mostly represent control variables and are not emphasized in the following analysis. Reason therefore is the local nature of these variables, referring to effects only in and on the close neighbourhood in the network space.

The most basic effect is defined by the `outdegree` of actor i, representing the basic tendency to form an arbitrary tie to possible alters j, regardless of their individual characteristics. Since most social network structures observed in reality are rather sparse (meaning their density is way below 0.5), this effect tends to be negative, meaning the costs of establishing a tie *per se* in absence of a particular beneficial characteristic outweigh the benefits if no further characteristics make this tie particularly attractive (Snijders et al., 2010b).

Another basic feature of most social networks is `reciprocity`, the tendency of an ego i to respond to a former $j \Rightarrow i$ with the establishment of an $i \Rightarrow j$ tie (c.f. Wasserman, 1979). In our context this effect captures a tendency of current project leaders to invite partners to join a project. In most social relationships such as friendship this effect has shown to be positive and of high explanatory power. Yet in our case of directed relationships, we expect this effect to be less pronounced, since project partners due to their characteristics might not necessarily qualify to be project leaders, thus might not have the chance for reciprocal action.

`Transitivity` is a measure for the tendency towards transitive closure, sometimes also called the clustering coefficient. Formally, it determines the likelihood a connection between $i \Rightarrow j$ and $i \Rightarrow h$ is closed by a connection between $j \Rightarrow h$ and/or $h \Rightarrow j$, or in other words that “partners of partners become partners” (e.g. Davis, 1970). In our case we make use of the measure for transitive triads, which measures transitivity for actor i by the number of other actors h for which there is at least one intermediary j forming a transitive triplet of this kind. In line with a large body of earlier research, we expect this effect to be positive.

Global network effects: Global network (or degree-related) effects express global hierarchies in a way that they reflect actors positions in the overall network. They capture the tendency of actors to send and receive ties according to their amount of out- and in-degrees, independent of their particular position in the network. Such effects can only be analyzed in a directed networks.

They are of particular interest against the background of our study, since they are – in contrast to commonly applied triadic measures – suitable to analyze the tendency of certain actors to establish central and dominant positions in the overall network structure. Therefore, in our analysis we primarily focus on outdegree-related global effects.

`Out-degree popularity` captures the reputation and social recognition effect of the network on the activities of actor *i*. A positive parameter indicates that actors sending a higher amount of ties are also considered as more attractive to receive them in terms of higher indegrees. It in a way represents the global version of the local `reciprocity` effect, leading over time to a convergence of in- and outdegrees. This can in our case be interpreted in a way that actors leading many research projects also happen to often get invited to become partners in other projects. From a governance perspective, a positive `Out-degree popularity` effect leads to a more even distribution of power, since actors participate more equally in leading as well as following positions in research projects. Yet, in the same way as we argue in the case of `reciprocity`, we leave the direction of this effect to be an empirical question.

Of particular interest for this study is the `Out-degree activity` effect, which is the tendency of actors with high outdegrees to establish even more. A positive parameter indicates a self-reinforcing mechanism leading to an increasing dispersion of out-degrees in the network (Barabási and Albert, 1999). It can be interpreted as the in network-structuralic impersonation of what is called the "Matthew Effect" (c.f. Merton, 1968, 1988), cumulative advantage (Price, 2007) or preferential attachment (Barabási and Albert, 1999). Networks driven by this effect tend to stabilize towards a core-periphery structure around some very central, well connected, and influential actors. In the case of public funded research network, a positive `Out-degree activity` will lead to an ongoing and reinforcing concentration of governance structure and agenda-setting around particular actors. Technically, it resembles the squared version of an ego's outdegrees.[7]

[7] In the interpretation of this effect, one should take in the understanding that the outdegree effect itself is also included, and the parameters will be estimated such that the balance between creation and termination of ties agrees with the data. Taking a given function and then adding a positive coefficient multiplied by a quadratic function of the outdegree, (and note that the added quadratic function will because of the estimation be centered at the value where the

Finally, we also include an interaction term between `Out-degree activity` and `role incumbent`, to test if the posited Matthew effect works particularly strong for incumbent actors.

Model Specification

To analyze the influence of actor characteristics and endogenous structural effects, we run a set of three models. All of them contain a set of standard structural dyadic and triadic ego-network control variables. Model I traditionally tests for ego (project leader) covariates, which are assumed to affect the capabilities of creating new outgoing ties. Model II instead tests for degree-related structural effects. In comparison to the set of dyadic and triadic structural effects, degree related effects are related to the overall number of in- and out-degrees of alter and ego, independent of their position in the others network. Thus, while the first set of controls refers to the local hierarchy of the actors ego network, degree related effects refer to a global hierarchy in the overall network. Finally, in model III we test for the joint effects of actor covariates and degree related effects simultaneously.

All parameters are estimated under full maximum likelihood according to the algorithm proposed by Snijders et al. (2010a), which has proven to be more efficient for small datasets. Technically, we make use of the SAOM application of SIENA (Ripley et al., 2013), a package for the statistical environment of R.

5 Results

Goodness-of-fit evaluation

As a first goodness-of-fit measure one can consider the t-convergence values of the parameters, indicating whether the simulated values deviate from the observed values. For a good model convergence, Snijders et al. (2010b) suggests to only include parameters with t-values of convergence between estimated and observed parameters below 0.1, what is given for all parameters

balance occurs) imply that for current low oudegrees, the push to lower values will be relatively amplified, while for high outdegrees, the push to higher values will be relatively amplified.

in all corresponding models. The values in general show better convergence in later models, which confirms the effectiveness of our applied forward-selection strategy of model choice (cf. Lospinoso and Snijders, 2011). Since the class of stochastic actor-oriented models is still under development, there exists no direct equivalent to the R^2 indicator of least squares regression models. Latest advances, however, offer a set of instruments to asses the model fit in stochastic settings. Score tests for each variable proposed by Schweinberger (2012), lead to overall satisfying results and gradually increased from model I to III. To account for changing dynamics over time, i.e. due to different policy focus and overall funding available, we carry out the test for time heterogeneity proposed by Lospinoso et al. (2011), which indeed shows a significant effect. As a result, an interaction term between year dummies and the actors outdegree is included in all models.

Also, we perform the Monte Carlo Mahalanobis Distance Test proposed by Lospinoso and Snijders (2011). Here we test the null hypothesis that auxiliary statistics such as indegrees, outdegrees and geodesic distance of observe data is distributed the results of Monte Carlo simulations on the estimated coefficients of our SAOM model, using the network in period one as point of departure. The purpose is to evaluate how well our stochastic model simulates transformation from the initial to the final network in terms of different degree distributions. The underlying logic is to evaluate if a simulated process of network evolution based on our estimated coefficients leads to a network embodying the same structural characteristics as the observed one, the underlying mechanics of network change are appropriately modeled.[8] We here use the classical structural characteristics proposed by Lospinoso and Snijders (2011) indegree (how many nodes receive $1, 2, \ldots, n$ incoming ties), outdegree (how many nodes establish $1, 2, \ldots, n$ outgoing ties), geodesic distance (who many actor-dyads have a shortest path of $1, 2, \ldots, n$ that connects them in the network), and triad census (how many actor-triads show a certain connection pattern). We thereby also provide first validation of the ability of our model to predict future developments of research networks based on our estimated coefficients. The results are illustrated in figure D.3.

The results suggest that our model is very well suited to predict the in-

[8]Note: We here do not compare the characteristics of individual nodes, but the aggregated characteristics of the whole resulting network.

degree and geodesic degree distribution, where the simulation results are very close to the observed values. Same holds for most forms of triad constellations. The only weakness of the model up to now appears to be the inconsistent identification of low outdegrees. While the model performs very well for high outdegrees, the simulated statistics for nodes with zero up to two outdegrees deviates highly from the observed values. However, since we are primarily interested in the distribution of the high degrees (the dominant nodes in the network), we consider the accuracy of prediction on the low end only as second priority.

Models of network dynamics generally have a tendency to suffer from colinearity problems, since a main share of variables originate from the same source, an actor's out- and indegrees.While building our models, we carefully checked for high correlations among the coefficients, where we in no case found a correlation of network related effects above 0.5. We also observed carefully the estimate stability when in- or excluding network-related variables, and found our models to be sufficiently stable.

SAOM regression models

Table D.1 reports a set of SAOM on the probability of ego *i* to establish a new outgoing tie, depending on the egos characteristics, ego network, and global degree related effects. In our context that means that a project consortium leading firm *i* establishes a collaboration with some project partner firm *j*.

In the first model we jointly test for basic ego-network and ego-characteristic effects. `The outdegree` effect shows, as in most real-life sparse social networks, a negative coefficient. The positive and significant coefficient for `transitive ties` indicates local clustering over time, when partners of "partners become partners" on their on. Actors of `size large` as well as of `size small` establish significantly more outdegrees than their peers of the `size medium` reference group, where the coefficient is higher for large firms. This might reflect the preference of grant allocation decision makers for more stable large firms leading research consortia, or just the higher resource endowments of large players enabling them to manage the coordination of multiple research projects simultaneously. The `age` of the firm, however, *ceteris paribus* manifests in decreasing outdegrees. Allocation preferences towards

Table D.1: Stochastic Actor-Oriented Model: Probability of Tie Creation Ego→Alter

	Model I		Model II		Model III	
Variable	Coef.	Std. Er.	Coef.	Std. Er.	Coef.	Std. Er.
Structural ego-network effects						
outdegree	−4.314***	0.540	−5.913***	0.342	−6.264***	0.453
reciprocity	1.143	0.622	1.411**	0.582	1.034	0.594
transitivity	1.791***	0.345	0.319	0.228	0.229	0.191
Actor level effects						
size small	0.990	0.873			1.601**	0.681
size large	2.644***	0.832			1.629**	0.726
role incumbent	3.424***	0.611			2.759***	0.476
age (*ln*)	−0.793**	0.267			−0.448**	0.227
Degree related effects						
out-pop			0.085**	0.029	0.077**	0.030
out-act			0.372***	0.047	0.413***	0.073
out-act ∗ role incumbent					1.430***	0.347

Note: *, **, *** indicate significance at 10, 5, 1 percent level, two-tailed

stable project leaders again should lead to favoring older firms not subject to the liability of newness and the associated high failure rate (Freeman et al., 1983). An explanation could instead be found on the demand side, when aging firms loose their innovative drive and stop engaging in early stage research. An interesting finding is the high positive and significant coefficient of `role incumbent`, providing first evidence that the smart grid research network indeed over time tends to be dominated by incumbent actors.[9] Since we are not able to disentangle supply and demand effects of public research funding, this finding again offers different explanations. First, it can be interpreted of revealed preferences of public authorities for consortia led by incumbents, possibly reflecting incumbents strategic advantage of infrastructure ownership or their exercised influence on policy making. On the other hand, it is also possible that incumbents actively strive for consortia leadership positions enabling them to influence early stage research on the future

[9]While we first categorized new entrants separately, we decided to in our final analysis only contrast incumbents with all other actors, who we assume to not share the same incentives to stabilize the existing system. Further, in an unreported analysis including also a dummy for new entrants, we find no significant effect for this variable.

energy grid infrastructure – possibly to preserve the "old regime".

In model II, we test for ego-network and global network degree-related effects. An interesting finding is that, after introducing global degree related network effects, the coefficient of `transitive ties` drops in magnitude as well as significance. This finding demonstrates the usefulness and additional insights of including degree related effects when analyzing directed networks. Since actors increasing high outdegrees, they naturally will also have more potential to form reciprocal ties in their choice set. However, in this case global centralization outweighs local clustering in the further evolution of the network, indicating the development towards a core-periphery rather than a small world like structure. Both `outdegree popularity` and `outdegree activity` show a high positive an significant coefficient, where `outdegree activity` dominates.[10] These findings indicate that the current selection environment in the technological niche of public funded smart grid R&DD indeed shows a tendency to develop towards a global hierarchy. This network-structural "Matthew Effect" over time leads to a development of the network towards a centralized network structure with a high dispersion of degrees. In such network structures, some actors continuously move in a reinforcing manner towards dominant positions. Such tendencies can be observed in many real-life networks. For instance, in a comparative analysis of different sectors of the Danish renewable energy research,

Therefore, in model III we jointly test for the impact of ego-characteristic and global degree related network effects on an actor's establishment of further outdegrees. While ego-network effects remain roughly unchanged compared with the former model, the investigation of actor level effects reveal some interesting insights. Again, the effects of `size large` and `role incumbent` are significant and show positive coefficients, even though with decreased magnitude. However, the degree related effects `outdegree popularity` and `outdegree activity` both remain positive and significant, where the latter even increases in magnitude. Thus, `outdegree-activity` appears to be a major driving force in the evolution of public funded smart grid research networks, an effect that appears to be even stronger when controlling for firm characteristics.

[10]Note that all parameters in SAOM are standardized (divided by their mean), thus making a direct comparison of their magnitude difficult within a model, but easier between models.

Overall, the results of this final model suggests incumbents indeed to be in a favorable position to inherit dominant roles in the research network over time. While they are generally more likely to establish outgoing ties, preferential attachment and accumulated advantages reinforces this tendency over time. Finally we introduce an interaction term between `outdegree-activity` and `role incumbent` to test if degree-related effects work particularly in favor of incumbent firms, which appears to be the case. It shows a high positive coefficient, significant at one percent level, providing further evidence for the advantageous effects incumbents enjoy in the development of their network position. Here we are able to provide evidence not only of the benefits incumbents *per se* in leading research consortia, but also that powerful mechanisms of network evolution work in their favor. If these effects are driven by the demand or supply side of public research funding can only be speculated. So may it be that incumbents due to factors like their political influence and ownership of the energy grid infrastructure are generally more successful in grant applications, but the ones who decide to massively exercise their influence on energy grid technology development will enjoy structural forces of network evolution supporting them to do so.

This process can easily be forecasted in a simple Monte Carlo simulation of network evolution using the parameters estimated in our SAOM for calibration. After 10 period, such a network already shows a very strong core-periphery structure, where the core is almost exclusively populated by incumbents.

Robustness tests

Our main results are primarily dependent on a correct classification of the actors' roles, which in our case is determined by the categorization of industry experts. To cross-validate these sensible results, we ran all models with alternative classification strategies. First we apply a simple subjective classification strategy similar to the one used by Erlinghagen and Markard (2012), where we determine incumbents by certain combinations of NACE codes, size, and age of an actor. However, a classification exclusively based on these objective measures would often fail to identify actors. Second, we use a computational approach, where we collected approximately 550 Danish industrial publications related to energy system topics from the period 1995-2000 and used a fuzzy string matching process to identify actors that appear in the analyzed research projects within the description parts. We assume that actors that appear in a "energy context" can be considered established in the industry.

Furthermore, as already discussed, the number of an ego's outdegrees can in the projection of a two-mode network (project association $\rightarrow$ actor) to an one-mode network (actors $\rightarrow$ actors) be influenced by the number of projects lead by an actor as well as the number of participants in such projects. To test for bias arising from the tendency of certain actors to establish smaller or larger project-consortia, we rerun all models including a variable representing the average number of members in projects the ego-actor participated in, in the current and last year. In all cases, the results point in the same direction but are less pronounced, which speaks in favor of using industry experts for the identification of nuanced roles such as energy industry incumbents. All additional regressions mentioned are – for the sake of brevity – not reported, but available on request.

6 Conclusion

In this paper, we studied the influence of incumbent firms on the structural dynamics of research networks in technological niches at the case of public funded research projects. Drawing from innovation system, sociotechnical transitions, and network evolution literature, we identify a set of structural – as well as firm-characteristic – effects that might enable incumbents over time to move towards dominant positions in the research network. These effects generally originate from the supply side of public grant allocation, for instance the preferences of public authorities towards certain firms, technologies, project types. In addition, we identify demand side effects related to strategic motives of incumbents to participate in technological niches, and draw implications for the rate and direction of technological change as an outcome of research network dominated by incumbents.

To do so, we conduct a stochastic actor-oriented network analysis, where we model the hierarchy and power structure in the network with directed ties between research project leader and partners. We assume the leader of such projects as mainly influencing the context of conducted research as well as the selection of further participants, thus strongly influencing the development of technological trajectories in such niche networks. In contrast to mostly pronounced function of "knowledge diffusion" in research and innovation networks, we focus on governance structures as a result of project leadership. By doing so, we are able to analyse up to now unobserved cumulative and self-reinforcing effects of network dynamics and relate them to firm strategies and vested interests.

Our results indicate path-dependent and cumulative effects of firm characteristics such as size, and degree-related "Mathew effects" in the development of the research network, which over time lead to a centralization of the network structure. While we find incumbents *per se* to enjoy benefits in establishing new outgoing ties, we find path-dependent effects to work particularly in their favor. Overall, the observed dynamics suggest a development of the network towards a structure where incumbents occupy the most central positions.

By emphasizing governance and influence related aspects combined with firm characteristics and strategies, we provide an alternative – and perhaps more critical – perspective on research and innovation networks, and the role of the state in their coordination. The development of the electricity grid into a smart grid is not envisioned as a radical process that threatens the existence of the established regime. Rather it is a process of upgrading and adaptation to new types of energy generation. Yet, the strong centralization effects in the network and the high probability of incumbent players to lead research projects are surprising, particularly against the backdrop of the literature arguing for niche protection when developing sustainable technologies. Methodologically, we demonstrate the richness of stochastic actor-oriented models to answer such questions by modeling collaboration decisions on actor level, and relating them to macro outcomes of structural network evolution. We further contribute to a more nuanced discussion on the role and behavior of incumbents in sociotechnical transitions by identifying which firm-characteristics and structural forces of network evolution facilitate them to - for the better or the worse - increase their influence in the formulation of early stage research agendas. Our findings also provide implications for policy. Whether these increasingly incumbent-dominated networks are favorable or not is a rather normative discussion, which would go beyond the scope of this research.

However, the here unveiled interplay between firm characteristics, strategy and network dynamics have to be considered carefully, since they are to some extent policy orchestrated and not fully subject to natural evolution. The supply side selection environment is subject to *ex-ante* biases of grant allocation preferences of public authorities, as well as *ex-post* biases of firms observing these preferences and probably optimizing their project constellation patterns. Further, demand side effects related to firm strategies and vested interests affect the extent to which they participate in public funded research projects or choose other forms of collaboration, and which positions they prefer in such projects. While we derive some suggestions from theoretical reasoning and existing (mixed) evidence, we are not able to analytically disentangle supply and demand side effects. Even though this is supported by prior results on the same data (c.f. Jurowetzki, 2013), we yet do not provide a direct analytic link between the identified structural change of research networks and outcome characteristics in terms of more radical or incremental innovation.

Consequently, we consider future research separating supply and demand side effects of public funded research network formation as a promising avenue for further research. Here, the combination of rich supply side data, such as evaluations of project grant applications together with firm-level data on motives and strategies appears to be particularly promising to disentangle supply and demand side effects in public funding of R&D and the resulting network dynamics. While the empirical link between the network structure and innovation outcomes can be – and has been – established using network data to explain innovation output measures such as patents, the link between micro-level actor behavior and network dynamics with macro-level outcomes faces some empirical challenges. One obvious challange is the endogeneity caused by interdependence of actor behavior and network position. Co-evolutionary models of networks and actor behavior as proposed by Snijders et al. (2007) and applied by Checkley et al. (2014); Steglich et al. (2010); Veenstra and Steglich (2012) could be an attractive solution. Furthermore, additional empirical cross-country and cross-industry evidence is needed to clarify the role of incumbents in research networks and sustainable transitions in general. We hope our work stimulates further work on this issue, which we consider as a promising avenue for future research.

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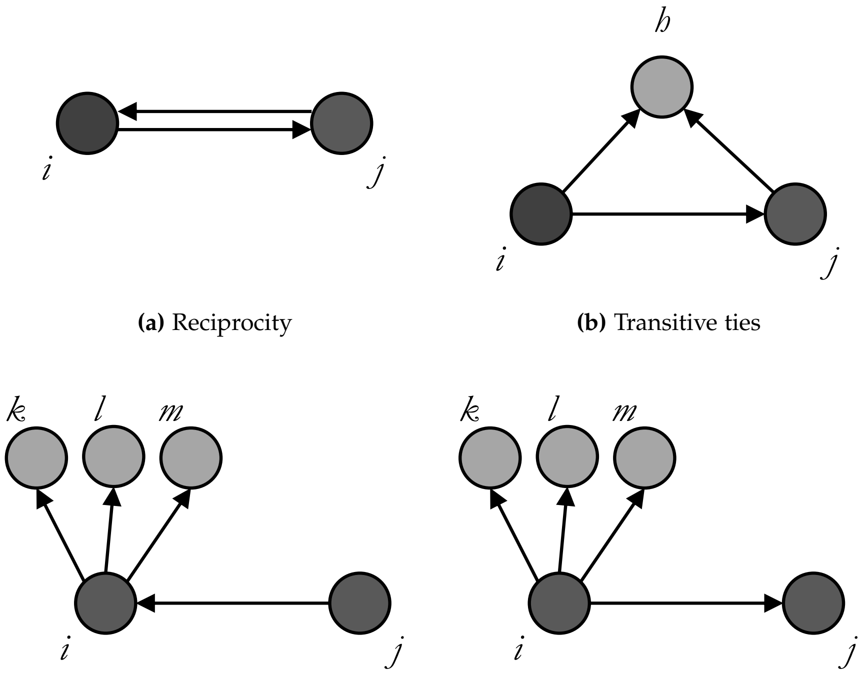
Appendix

Fig. D.1: Illustration of Ego-Network and Degree-Related Effects



(a) Reciprocity

(b) Transitive ties

(c) Outdegree popularity

(d) Outdegree activity

Note: The variables in the illustration are unrelated to the proposed model and analysis.

Table D.2: Variable Descriptions

Variable	Formal	Description
outdegree	$s^{net}_{i1}(\chi) = \sum_j \chi_{i,j}$	Sum of outdegrees of ego i
reciprocity	$s^{net}_{i2}(\chi) = \sum_j \chi_{i,j}\chi_{j,i}$	Sum of reciprocal ties between ego i and alter j
transitivity	$s^{net}_{i3}(\chi) = \sum_{j<h} \chi_{i,j}\chi_{i,h}\chi_{j,h}$	Number of transitive patterns in ego i's relations (ordered pairs of alters (j,h) to both of whom ego i is tied, while also j is tied to h)
size small		Dummy variable, taking the value of 1 if ego i is in size category small ($<$ 25 employees), 0 otherwise
size large		Dummy variable, taking the value of 1 if ego i is in size category large ($>$ 100 employees), 0 otherwise
role incumbent		Dummy variable, taking the value of 1 if ego i is categorized as incumbent, 0 otherwise
age (ln)	$ln(age^{year})$	Age of ego i in years, natural logarithm
out-pop	$s^{net}_{i15}(\chi) = \sum_j \chi_{i,j} \sum_h \chi_{j,h}$	the sum of the out-degrees of alters j to whom ego i is tied
out-act	$s^{net}_{i19}(\chi) = (\sum_j \chi_{i,j})^2$	the squared out-degree of the ego i

Table D.3: Network turnover frequency

Periods	$0 \Rightarrow 1$	$1 \Rightarrow 0$	$1 \Rightarrow 1$	Jaccard
$1 \Rightarrow 2$	22	3	42	0.627
$2 \Rightarrow 3$	30	2	62	0.660
$3 \Rightarrow 4$	53	39	53	0.366

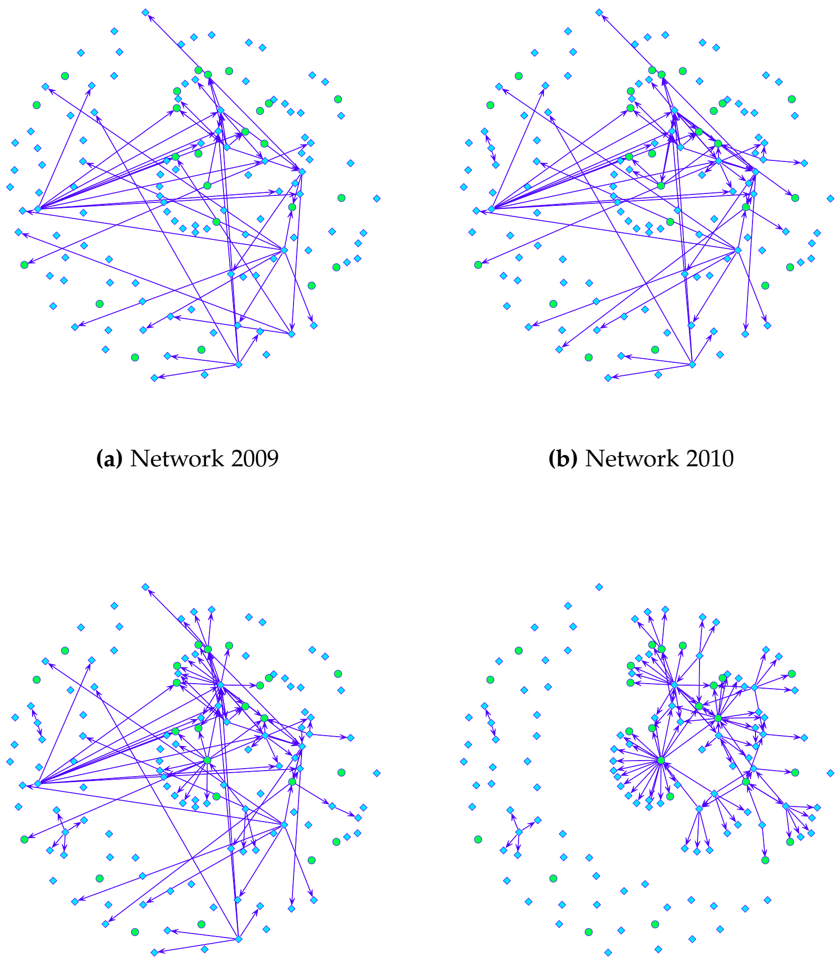
Table D.4: Network density indicators

Periods	1	2	3	4
Density	0.003	0.004	0.005	0.006
Average degree	0.341	0.485	0.697	0.803
Network rate	0.383	0.490	1.406	-
Number of ties	45	64	92	106
Mutual ties	0	2	4	3
Asymmetric ties	45	60	84	100

Table D.5: Descriptive Statistics

Variable	Min.	Max.	Mean	Std. Dev.
size small	0	1	0.356	0.481
size large	0	1	0.432	0.497
Role: Incumbent	0	1	0.182	0.387
Role: Newcommer	0	1	0.106	0.309
Firm age	1	110	22.437	22.130

Fig. D.2: Network Development in Public Funded R&D in Smart-Grid Research



(a) Network 2009

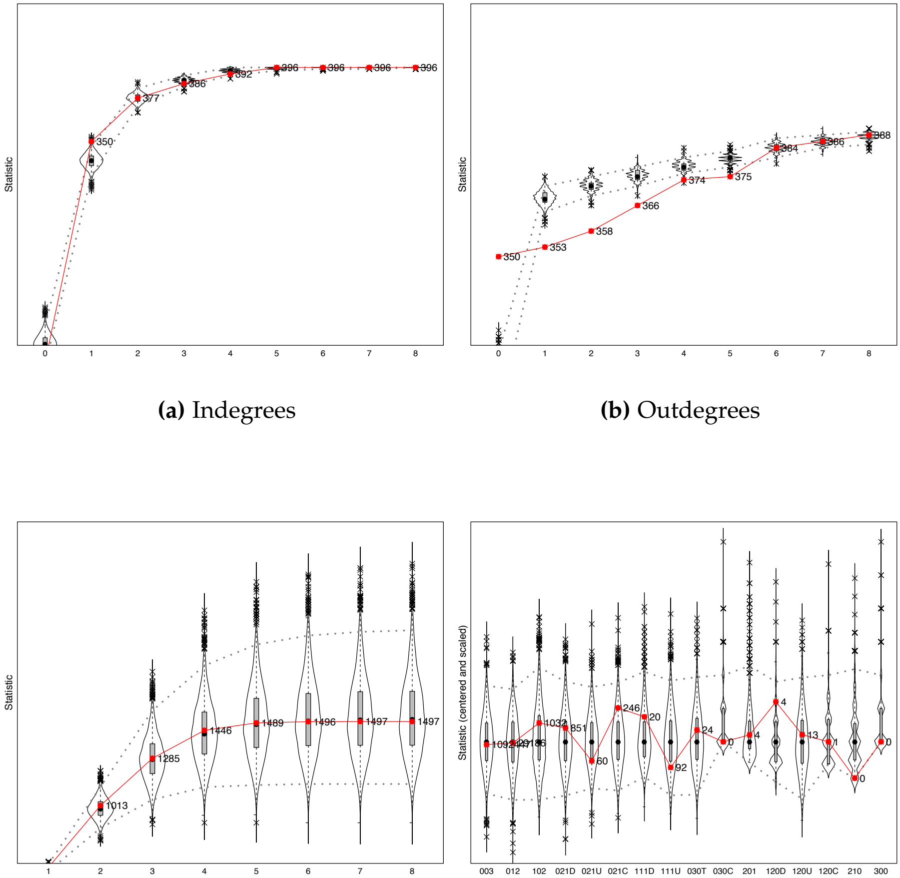
(b) Network 2010

(c) Network 2011

(d) Network 2012

Note: Research network on basis of joint public funded research projects. Ties are directed from project-leader ⇒ project partner. Circles represent incumbents, squares all remaining types of organisations. The graphical presentation was done with the R package *Igraph*.

Fig. D.3: Goodness-of-Fit: Monte Carlo Mahalanobis Distance Test



(a) Indegrees

(b) Outdegrees

(c) Geodesic

(d) Triad Census

Note: X-axis: P-value obtained by the Monte Carlo Mahalanobis Distance Test proposed by Lospinoso and Snijders (2011), testing null hypothesis that auxiliary statistics of observe data is distributed according to plot.
Y-axis: Value of auxiliary statistic (indegree, outdegree, geodesic distance, triad census). Solid red line the observed values equal auxiliary statistic.
“Violin plots” show simulated value of statistic as kernel density estimate and box plot of 95% interval.

Paper E

Mapping the (R-)Evolution of Technological Fields

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