THESIS FOR THE DEGREE OF LICENTIATE OF PHILOSOPHY

Watt’s next?

On socio-technical transitions towards future electricity system architectures

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Cover:
[The cover represents the backbone of our research: the visions of future electricity systems with different types and levels of interconnectedness]

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Abstract

In the effort to fight climate change, the electricity systems around the world are undergoing a transformation towards being based on renewable sources of energy. The criterion of one hundred per cent renewables can, however, be satisfied in several radically different ways, varying from global or continental super grids via local smart-grids to self-sufficient off-grid communities and households of electricity prosumers. At this point, the eventual system design is not a given.

The purpose of this research is to follow the emergence of new system configurations that satisfy the criterion of hundred per cent renewables globally, to identify possible development pathways, and to study the critical factors that influence the different directions of development. This thesis takes a step towards fulfilling this objective by answering the question of what determines the direction of the electricity system transition. While Article 1 presents findings about these directions and comprehensively describes them, Article 2 answers questions related to the causal relationships and buildup processes that influence the transition to take a specific direction. It takes the Multilevel Perspective (MLP) and Technological Innovation System (TIS) frameworks, as a theoretical starting point and places technological change, especially the emergence and diffusion of novel technologies, at the core of the analysis.

The research presented in this thesis contributes to the literature by clearly defining three alternative electricity futures, i.e., the Super-grid, Smart-grid, and Off-grid systems, that can be monitored in the form of structural components currently emerging and accumulating. Our findings show that all three alternatives have gained notable momentum over the last 15 years and provide evidence that a transition is underway. However, the emerging systems are not exclusive to the electricity sector, but instead, create links with and borrow components from other sectors, discourses, and societal trends. In addition, the results contribute to a better understanding of the causalities that may lead to a future of complete interconnectedness, i.e. the Smart-grid system by analysing important factors and processes determining the successful innovation processes leading to a development in this direction.

This thesis makes conceptual contributions by combining a number of socio-technical concepts and methodologies to clearly define a number of future configurations and their key structural components. Moreover, for the analysis of the Smart-grid scenario, this thesis proposes a variation of the conventional TIS framework, by integrating a categorization of the innovation system context and the role of entrepreneurial activities to better analyse developments at the micro-level.

Keywords: electricity system, socio-technical transition, technological innovation system, future configurations, transition pathways, innovation system context, entrepreneurial activities

List of included articles

ARTICLE 1

Hojčková, K., Sandén, B., & Ahlborg, H. (2017). Three electricity futures: Monitoring the emergence of alternative system architectures. Futures. Volume 98, 72-89.

ARTICLE 2 (MANUSCRIPT)

Hojčková, K., Sandén, B., & Ahlborg, H. (2018). Entrepreneurial use of contexts in technological innovation systems: the case of blockchain based Peer-to-Peer electricity trading systems.

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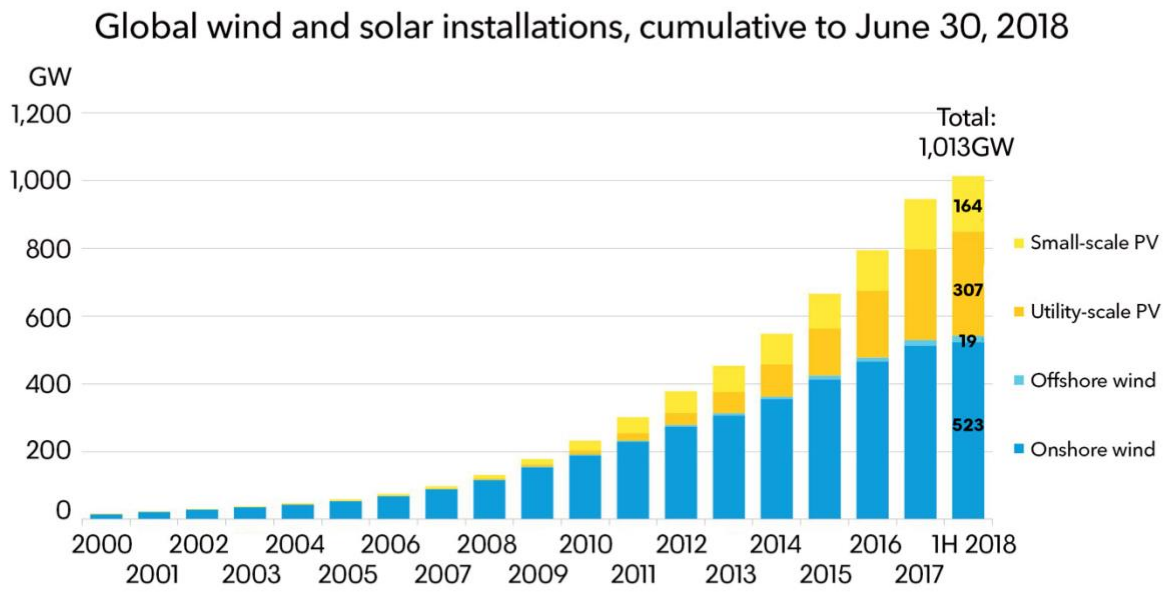
1 Introduction

The conventional electricity system built around central utilities is facing problems of aging grid infrastructure and plants, fossil fuel dependency, and environmental impact. These issues put pressure on the existing electricity system, which is consequently undergoing a transformation towards being based on renewable sources of energy.

As of 2018, one thousand gigawatts (GW) of wind and solar electricity generation capacity has been installed around the world. While it took several decades to get to this point, some predictions say that reaching another thousand GW will take only five years and will be about 50 per cent cheaper. Alongside falling prices for renewable electricity generation, more efficient power lines, grid balancing technologies such as batteries and smart meters, as well as digital grid solutions are becoming cheaper and more advanced (New Energy Outlook 2018).


Global wind and solar installations, cumulative to June 30, 2018

Source: Bloomberg NEF. Note: 1H 2018 figures for onshore wind are based on a conservative estimate; the true figure will be higher. BNEF tyipcally does not publish mid-year installation numbers.

While a strong consensus exists about the need to accelerate the transition towards an electricity system based on renewables, it is less clear what such a system will look like. In fact, given the modular character of renewable technologies, there are several radically different ways to build an electricity system that could satisfy the criterion of one hundred per cent renewables. Will we move towards a global Super-grid, distributed networks of Smart-grids or Off-grid communities? At this point, the eventual system design is not a given.

It is the uncertainty of this transition that motivates this research. Based on our understanding of the electricity system as a socio-technical system in transition, we set out to explore what the future system might look like.

1.1 Research domain

Electricity infrastructures as we know them today developed over a long time period into large socio-technical systems (Hughes 1987, Loorbach, Frantzeskaki et al. 2010, Markard 2011). Such large socio-technical systems consist not only of physical artefacts but also of social, economic, institutional, and organizational structures (Hughes 1987, Geels 2002, Loorbach, Frantzeskaki et al. 2010, Verbong and Geels 2010). Still, existing research into the future of the renewable electricity system predominantly focuses on the technical and economic aspects of the transition. While these perspectives are important, they often downplay the role of the closely interlinked socio-cultural, organizational, and institutional factors that often pose barriers to the transformation of the electricity grid and market structures. It is therefore useful to bring a social science perspective to studies of the ongoing transformation of electricity systems through the lens of socio-technical system-oriented concepts and frameworks, to create a more holistic understanding of the complex nature of technological innovation and change (Hughes 1987, Carlsson and Stankiewicz 1991, Geels 2004, Bergek, Jacobsson et al. 2008a). While there are multiple perspectives that can be identified as socio-technical, we apply the Multilevel Perspective (MLP) and Technological Innovation System (TIS) frameworks, which were formulated to analyse the dynamics of technological innovations related to large-scale systemic change. These perspectives are accordingly used as a theoretical point of departure for this research.

1.2 Empirical focus

Empirically, this thesis examines alternative future electricity system configurations that represent possible ways to build an electricity system powered by renewable energy technologies. While there are multiple ways to define the possible configurations, this research investigates three popular visions: the Super-grid, Smart-grid, and Off-grid systems, which point in very different directions (further described in Chapter 5). Although a renewable electricity system may eventually be a mainstream global system, the developments leading to this end are still in their early stages, emerging in the form of projects and experiments in different parts of the world, slowly gaining momentum, being scaled up, and working their way towards a complete system based on renewables. Consequently, the alternative configurations can at present be empirically analysed only as sets of local, national, or regional projects creating system prototypes intended to manifest certain versions of the future global system. This thesis is concerned with the empirical cases of the technologies, actors, and institutions that have emerged, accumulated, and co-developed, materializing in experiments and supporting the transition in specific directions given by three scenarios.

1.3 Research aim

The general purpose of the research is to explore different pathways the electricity system transition can take. As a step towards achieving the general purpose of this thesis, we aim to better understand what determines the direction of the electricity system transition. This aim is fulfilled by answering two research questions and related sub-questions:

1. In which direction(s) is the electricity system currently developing?
    a. What directions could this development take?
    b. How can development in a certain direction be monitored?
    c. What does such monitoring reveal?
2. What factors and processes support or block electricity system development in a certain direction?

Given the aim of this thesis, we intend to make an empirical contribution by better understanding various aspects of the transition towards a future renewable electricity system. We also aim to make a conceptual contribution by borrowing concepts from, developing and critically assessing the MLP and TIS frameworks, as well combining them with scenario methodologies.

Our research is presented in two appended articles. Article 1 is about scenarios that identify different directions the studied transition can take. It answers the first research question by identifying three idealized alternative system configurations, i.e., the Super-grid, Smart-grid and Off-grid systems, which then guide the monitoring of key structures, by describing the structures that support the transition towards different future systems. Furthermore, it reveals the structural overlaps between the existing dominant system structures and the new alternative systems. Article 2 then builds on the descriptions of the future scenarios and studies the processes and factors that determine the success of the transition towards one of the alternative configurations, the Smart-grid system, empirically represented by P2P electricity trading experiments.

2 Theoretical starting points

The foundations of this thesis are in the socio-technical understanding of innovation and societal change, which sees society and technology as co-evolving and shaping each other via a process characterized by uncertainty and complexity, in contrast to perspectives that understand technology as simply the material result of the human mind or deterministic views that see technology as controlling humans (Feenberg 1991). Following Feenberg (1991: 14), we see technology as an “ambivalent process of development suspended between different possibilities”. The “ambivalence” of technology opens a space for multiple future configurations, while technological development is not neutral, but a space for contestation.

Socio-technical perspectives place technological change, especially the emergence and diffusion of novel technologies, at the core of the analysis. These perspectives build on evolutionary economics, innovation studies, history of technology, sociology, and society, and technology studies, which together propose a view of technological change as a social phenomenon, i.e., a process in which social and technological aspects are interrelated and co-evolving (Geels 2004, Cherp, Vinichenko et al. 2018). Within the larger socio-technical domain, we operate within the smaller field of socio-technical transition and innovation studies, in which, over the past two decades, two major approaches have been developed and applied to study large-scale system transitions and their underlying innovation processes: the Multilevel Perspective (MLP) and Technological Innovation System (TIS) frameworks.

These frameworks are suitable considering the empirical object of this research: ongoing transition in electricity systems around the world. In the first part of the research, these perspectives are complemented by scenario methodology, used as a tool to explore different directions the transition in the electricity sector could take. While “the transition” is referred to in the singular, we do not assume that the future will give rise to a single dominant model or to different systems developing in parallel; instead, we are aware that hybridization is equally possible. The following chapter serves as an introduction to the above-mentioned approaches used in answering our research questions and conducting the chosen type of analysis. While this chapter reviews and synthesizes the state of the art and points to limitations, the concrete application and conceptual contributions are captured in Chapter 5.

2.1 A systems approach to understanding the transition and innovation processes

The components of large, mature socio-technical systems are numerous and mutually aligned, creating inertia and lock-in (Unruh 2000). While the process typically takes several decades, history shows that even such locked-in systems can and will be replaced, a phenomenon termed “socio-technical transition” (Rip and Kemp 1998, Geels 2002). Such transitions can be triggered by new discoveries that offer new opportunities, by efforts to address major problems with the old system, or, more likely, by both processes in combination (Rip and Kemp 1998, Geels 2002, Sandén and Jonasson 2005, Geels and Schot 2007).

The MLP and TIS frameworks that we build on here initially developed independently but they share theoretical origins and analyse similar phenomena, and there has been an ongoing effort to combine their strengths in order to better understand socio-technical system transitions (Markard and Truffer 2008). This research, borrows various elements and concepts from both these frameworks.

MLP was formulated to study how technological innovation induces complex large-scale structural change (Geels 2002, Geels 2004, Geels 2005, Geels 2011). This perspective describes transitions as non-linear processes that unfold through interaction among three analytical “levels”. The mature socio-technical system exists at the regime level, where a well-established set of institutions is shared by a large number of actors utilizing mature technologies to deliver certain goods or services. Second is the niche level, where new configurations emerge, grow, and gain momentum, and third is the landscape level, where broad societal trends unfold beyond the reach of actors at the regime and niche levels. From the landscape level, exogenous forces can put pressure on the existing regime, opening windows of opportunity for novel technologies to break through and initiate a transition (Geels 2004, Geels 2011).

Instead of studying the possible future system's end-states, MLP was developed to analyse the non-linear, evolutionary processes of transition from one socio-technical system to another conceptualized as *transition pathways* (Geels and Schot 2007). As defined by Turnheim et al. (2015), transition pathways are patterns of change unfolding over time in socio-technical systems that lead to new ways of realizing specific societal functions. Based on historical studies undertaken with the guidance of the MLP perspective, authors have argued that transitions entail reconfigurations at the three levels, changing the dominant set of technologies, market models, supply chains, as well as consumer preferences and behaviour, and occur only when developments at all three levels become aligned and mutually reinforcing (Verbong and Geels 2010). Geels and Schot (2007) developed a typology of transition pathways[1] based on how they differ in terms of the origins of the innovation processes and the nature of the multi-level interactions that lead to different transition dynamics and outcomes (Geels and Schot 2007). The motivation to study transition pathways comes from efforts to capture and understand ongoing transition processes and seize opportunities to intervene (Turnheim, Berkhout et al. 2015).

In an effort to better understand how to influence transition processes and open up space for alternative systems to influence system transitions, MLP scholars have identified two strategies (Raven 2007): niche accumulation and hybridization. Niche accumulation starts as radical innovation (e.g., new markets, technologies, actors, and institutions) at the niche level and from there strives for improvement, builds internal momentum, and prevents early rejection by keeping experimentation at the niche level until the system is strong enough to compete with the existing regime. Hybridization starts near the dominant regime but ultimately aims to achieve radical transformation by diverging from existing trajectories towards more desired ones. However, as Raven (2007) pointed out, the two strategies should be understood as extremes, and transitions often include a combination of both.

While MPL serves as a useful tool for studying large-scale systemic transitions resulting from interaction between the three levels, it does not pay particular attention to the dynamics that support new socio-technical systems in niches, helping them grow and mature into new dominant socio-technical regimes. More attention has been paid to these dynamics in the Innovation Systems (IS) literature, which applies a systems perspective to innovation and conceptualizes the development of system structure as a process of the reconfiguration and co-emergence of system components (Carlsson and Stankiewicz 1991). Within the field of IS, various models have been developed having different analytical foci and boundary settings: the national innovation system (NIS) and regional innovation system (RIS) perspectives define spatial boundaries (Lundvall 1988, Cooke, Uranga et al. 1997), while the sectoral innovation system perspective pertains to the sector of a particular product or product group (Malerba

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[1] This typology is based on previous work on transitions and regime change by (Smith, Stirling et al. 2005).

2002). The TIS framework then developed as a response to existing IS perspectives, focusing more on the technology-specific processes and less on the geographical or sectoral boundaries to give more technology specific policy advice (Carlsson and Stankiewicz 1991, Bergek, Jacobsson et al. 2008a, Van den Bergh, Truffer et al. 2011, Binz and Truffer 2017). In TIS, a transition process is conceptualized as resulting from innovation buildup processes that gradually grow and replace the established socio-technical system (or parts of it). This approach is intended to better assess the prospects and development of a particular technology or configuration of technologies assumed to be a more sustainable alternative to existing technological solutions (Markard and Truffer 2008).

A TIS study combines analyses of key structural components and of the innovation processes, i.e., functions (Bergek, Jacobsson et al. 2008a). While several ways to define the structural components exist, these all generally distinguish between technology, actors, networks, and institutions (Bergek, Jacobsson et al. 2008a, Sandén and Hillman 2011, Wieczorek and Hekkert 2012). *Technology* here refers to physical artefacts that make use of natural phenomena to produce a service (Arthur 2009), and to descriptions of the same process, commonly referred to as technical knowledge (Bergek, Jacobsson et al. 2008, Sandén and Hillman 2011). *Actors and networks* refers to an organizational dimension populated by people (Sandén and Hillman 2011), where *actors* refers to individuals or groups of individuals hierarchically linked in organizations, and *networks* to more loosely linked groups of actors. Organizations include not only firms but also knowledge institutions, industry associations, and governmental or non-governmental organizations. *Institutions* refers to rules that regulate interaction, mainly between actors, but sometimes also between artefacts (Bergek, Jacobsson et al. 2008a, Bergek, Jacobsson et al. 2008b). The category includes cognitive, normative, and regulative institutions (Scott 2001), i.e., commonly held positive and normative ideas about what is true, reasonable, good, and allowed, including beliefs and expectations about how the world works and develops, norms and attitudes concerning what is desirable, and hard regulations controlled by the juridical systems.

While traditional IS studies concentrate on the structure of the innovation system, in an effort to generate more insight into the dynamics of innovation, the TIS perspective complements this approach with a set of functions believed essential for a well-performing innovation system. Mapping these underlying processes (i.e., functions) serves to identify system weaknesses and give technology-specific advice to policy makers and other system actors. There is no single list of functions but rather various interpretations of a set of supporting innovation processes (Hekkert, Suurs et al. 2007, Bergek, Jacobsson et al. 2008a, Hekkert and Negro 2009, Perez Vico 2014). In this thesis, we start by using existing lists as analytical heuristics in constructing a list that fits our research purpose. The list of functions used in this thesis is presented in Table 1.

Table 1 TIS functions (Bergek, Jacobsson et al. 2008a, Hekkert and Negro 2009, Hekkert, Negro et al. 2011, Perez Vico 2014).

FUNCTION	DESCRIPTION
Entrepreneurial experimentation	This function captures the process of experimenting and implementing new technologies and business models to learn and improve and thus reduce uncertainty.
Knowledge development and diffusion	Process of creating new knowledge in the innovation system buildup through 'learning by searching' and 'learning by doing'. However, in a successful innovation process, knowledge further develops via diffusion and exchange across actor groups through processes of 'learning by interacting', at technology-specific conferences or workshops, or in case of user—producer networks, through 'learning by using'.
Network formation (Social capital development[2])	This function captures the process of building networks and coalitions, in which social relations are created and maintained. Social relations in these networks are built and maintained through trust, mutual recognition, dependence, authority and shared norms.
Legitimation	Process of creating formal and informal institutions to overcome resistance to change. An innovation is accepted and perceived as a relevant and appropriate new technology, application or business model or as a solution to an existing technological bottleneck or business crisis.
Guidance of search	This function accounts for the process of attracting and motivating new actors to enter the innovation system, providing a favourable selection environment for the focal novel configuration buildup, influencing market formation etc.
Market formation	At the stage of experimentation and early buildup, this function captures formation of demand that often takes place by creating niche markets with a competitive advantage for specific applications of the focal technology.
Resource mobilisation	Function that represents the process of accessing necessary resources, in the form of physical, financial and human resources.

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[2] This function has been added by Perez Vico (2014) as social capital development. We chose to name the function as 'network formation', which we find more appropriate as the focus is on the creation of a network of relationships instead of social capital as an asset.

Socio-technical perspectives on innovation are appreciated by a wide range of scholars from different fields and have mostly been used for historical studies, with a few examples of future-oriented studies. In fact, these frameworks are not well suited for prospective work, as socio-technical transitions are inherently complex and uncertain and cannot be addressed by a set of well-defined solutions (Andersson and Törnberg 2016). We contribute to the literature by combining these frameworks with scenario methodology to complemented them with other approaches developed specifically for prospective studies.

2.2 Scenario-making to explore the future of the electricity system

To say something about what determines the direction of the transition, one first needs to define what the different directions and possible future end-states can be. It is therefore useful to engage with the field of scenario-making.

While the scenario-making field is extensive, there is little agreement on the exact definition and typology of scenarios. This research adopts the typology of scenarios suggested by (Börjeson, Höjer et al. 2006), who define scenarios as descriptions of probable, possible, and preferable futures, corresponding to the predictive, explorative, and normative types of scenario-making.

This research takes a step towards predictive scenario-making, typical in *forecasting*, as we define a set of scenarios likely to happen based on the present situation and trends. However, forecasting that focuses on short-term, linear, step-wise causality is not suitable for studying the electricity system transition, which is inherently complex and uncertain and requires long-term thinking. The scenario-making method used here is closer to *backcasting*, a normative type of scenario method that uses as its starting point a desired future end-state, which is often deemed unreachable under the current status quo and serves as a tool for encouraging searches for solutions with no restrictions on what factors are internal and what are external (Robertson 2016). However, this research does not have such a normative starting-point and instead explores scenarios based not on what is likely, as in forecasting, or on what is desirable, as in backcasting, but on what is theoretically possible. This means that our interest is not in a specific target and how it can be reached, but instead in what various targets might be. Here the explorative scenario-making is productive in identifying a number of clearly defined alternative futures as starting points (Börjeson, Höjer et al. 2006).

The importance of scenario methods has also been acknowledged by scholars from the field of socio-technical transition studies, who claim that scenarios are a useful method that advances the exploration of large-scale systemic change, such as in the electricity system. However, as (Hofman, Elzen et al. 2004) pointed out, the prevailing scenario methods lack clear conceptual framing that would guide our understanding of how transition occurs. To better reflect the complexity of system innovations, they developed a new tool: socio-technical scenarios. Socio-technical scenario-making begins with the empirical analysis of aspects and processes that directly influence the focal object of study, and use MLP to conceive and write narratives about alternative scenarios in order to identify more generalisable patterns and mechanisms (Hofman, Elzen et al. 2004).

While socio-technical scenarios have previously been used to construct narratives about a course of events, patterns, and mechanisms, this research has taken a different approach and starts the scenario-making process by identifying future end-point systems that are used to organize and sort data on the current development. The method employed in our research is further discussed in Section 5.1.

3 The transformation of the electricity system is under way

In most places around the world, existing electricity grid architectures are built in a centralized, hierarchical, and one-directional fashion (Figure 1). Power is generated in large-scale power plants located far from the electricity demand points, transmitted over long distances, and then distributed to the end-users, i.e., customers (Hammons 2008).

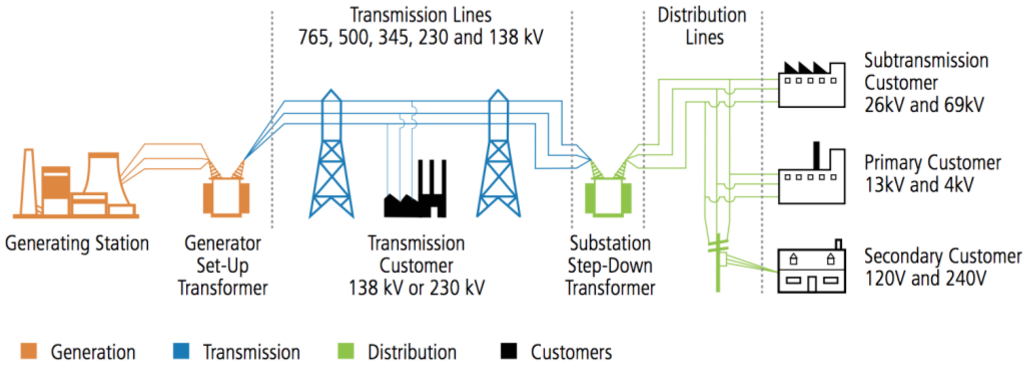


Figure 1 The electricity grid of today (source: US Department of Energy 2015).

This dominant structure of the electricity system is now being transformed under growing pressure to shift towards electricity systems based on renewable sources of electricity. In fact, it is anticipated that the future electricity grid will be restructured to incorporate a wide range of renewable energy (RE) sources. Although the push for renewable technologies is incentivized by the global effort to reduce reliance on fossil fuels, electricity production from renewables is intermittent and weather dependent, causing uncertainties about how to operate the grid to maintain stability of supply (Walker and Cass 2007, Hammons 2008, Swedish Agency for Growth Policy Analysis 2014, U.S. Department of Energy 2015). While a strong consensus exists about the need to restructure the electricity system to accommodate renewable electricity technologies and achieve grid stability, much less agreement exists about the actual design of such a system. Thanks to rapid innovation in grid-balancing technologies such as storage, efficient high-voltage cables, and smart meters, future electricity system structures may differ fundamentally from those we know today. Some believe that the future renewable electricity system will be dominated by centralized global transmission, some imagine a future of local electricity distribution, while others advocate self-sufficiency without the need for conventional electricity grid infrastructure (Battaglini, Lilliestam et al. 2009, Khalilpour and

Vassallo 2015, Funcke and Bauknecht 2016, Lilliestam and Hanger 2016). Though various terms are being used to describe the future electricity system, in the literature these ideas are often associated with the concepts of the Super-grid, Smart-grid, and Off-grid systems. Research interest in these future alternatives can be observed in the increasing knowledge production related to these concepts, especially in the last 15 years (see Figure 2).

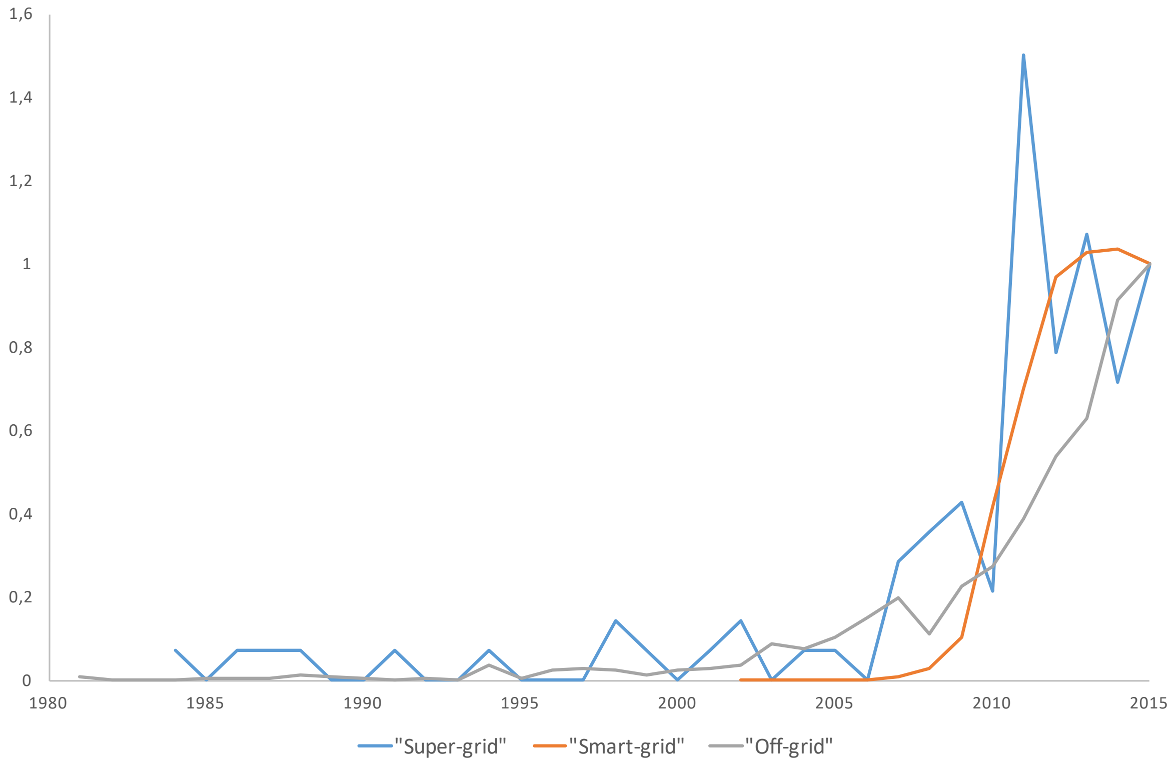


Figure 2 Relative growth of research interest in the three emerging systems. Annual number of articles was normalized with the number of articles in 2015. (source: Scopus).

The concept of building a large global system based on the transmission of renewable electricity around the world is often referred to as the Super-grid (Battaglini, Lilliestam et al. 2009, Dauncey 2009, Blarke and Jenkins 2013, Shuta Mano, Bavuudorj Ovgor et al. 2014, FOSG 2015, MacLeod 2015). The rationale underlying the Super-grid is the fact that RE sources are unevenly allocated around the world. While the Sahara Desert has an abundance of solar energy, the North Sea has enough wind to generate all of Europe’s electricity. The Super-grid would be built around large-scale renewable electricity installations and plants located in areas with abundant RE, while the variability of this power supply would be dealt with by optimizing transmission and distribution around the globe, without reliance on storage technologies (Meeuwsen J.J 2008, Battaglini, Lilliestam et al. 2009, Foxon 2013, Liu 2015). The logic underlying the Super-grid is similar to that of the current electricity system and can be described as the “greening of centralized production”. Constructing a secure and stable global electricity system requires international coordination and the experience of dominant actors in the electricity sector, especially incumbent utilities, transmission system operators, and energy companies such as ABB and Siemens (Foxon 2013, Liu 2015). In the Super-grid, existing electricity system actors are assumed to maintain their position, while electricity consumers remain a passive part of the system (Verbong and Geels 2010).

Another way to design the future electricity system is possible thanks to the modular character of renewable electricity technologies, which can be implemented in different physical sizes and generation capacities (Walker and Cass 2007). While conventional sources of electricity, such as coal power plants, cannot be installed on residential roofs, solar panels can. The great size range of RE technologies creates new opportunities for distributed electricity generation, in what is often referred to as the Smart-grid system (Battaglini, Lilliestam et al. 2009). A Smart-grid is based on small-scale RE technologies and the electricity is delivered over shorter distances (Foxon 2013). The idea is to build a "bi-directional electric and communication network that improves the reliability, security and efficiency of the electricity" (Hertzog 2010). In such local and information-centric electricity grid infrastructure, renewables need to be complemented with information and communication technologies (ICTs), smart meters, sensors and appliances, as well as storage technologies (Blarke and Jenkins 2013). By installing small-scale RE technologies, an increasing number of electricity consumers are becoming "prosumers" who both produce and consume electricity. This trend is not only changing the physical infrastructure but also destabilizing dominant organizational structures and regulatory frameworks, as direct customer participation in the system triggers changes in market design (Zinaman, Miller et al. 2015). While the incumbent actors currently operating the electricity system play an important role in building the Smart-grid, various new actors from other sectors as well as non-sectoral actors such as local governments and community groups are increasingly getting involved in electricity system development and operation (Foxon 2013). Compared with the centralized design, the Smart-grid suggests a flat organizational hierarchy in which everyone has the chance to contribute to the new electricity future. Consequently, values and expectations not typically related to electricity are created, such as local resilience, community ownership, sharing, and consumer empowerment (Verbong and Geels 2010).

While the Super-grid and Smart-grid systems are new ways to restructure the conventional grid infrastructure, some suggest that leaving the grid behind is the future of electricity systems (Zinaman, Miller et al. 2015). In fact, leaving the conventional grid to live off-grid has recently become a feasible option due to rapid declines in the prices of distributed energy technologies, in particular storage technologies that make self-sufficiency possible (Khalilpour and Vassallo 2015). Off-grid systems can range from living in self-sustaining residential units to small community microgrids (Zinaman, Miller et al. 2015). The ability to self-generate, store, and consume electricity makes the "prosumer" the key actor in this electricity system, making the existing organizational structure of the electricity sector irrelevant. Instead, private companies that provide solar plus battery packages for prosumers, already active on the market, would become important in building new Off-grid systems. Off-grid scenarios are often perceived as relevant to developing countries, where most of the people who still live without access to modern energy infrastructure are found, especially in remote rural areas (Doig 1999). Importantly, Off-grid solutions offer the opportunity to leapfrog conventional means of providing electricity and overcome the carbon-intensive, centrally controlled energy system by building electricity systems from the bottom up based on clean technologies.

Compared with the existing electricity system structure, Off-grid systems are often associated with expectations of achieving consumer- or community-level independence. In countries with well-developed electricity systems, striving for such independence is often driven by frustration with existing grid operators and utilities or, in some cases, by the desire to unplug from the grid that provides fossil-fuel based electricity (Bronski, Creyts et al. 2014). In many developing economies, on the other hand, Off-grid systems can represent a faster, cheaper, and more reliable alternative to the under-developed large-scale grid infrastructure (Ahlborg and Sjöstedt 2015).

4 Research design

This thesis is based on two studies presented in the form of appended articles. Although both studies are framed within the research project's general aim and explore the future of renewable electricity systems from a socio-technical perspective, they differ in research focus, use different aspects of the same analytical concepts, draw different system boundaries, and use different sources of data. This is because the analysis in Article 1 served as the basis for the research aim and empirical focus of Article 2, which represents the next stage of a research process addressing the same underlying phenomenon. This thesis is a synthesis of what was learned from both studies, learning that informs the conclusions and suggestions for future research (see Figure 3).

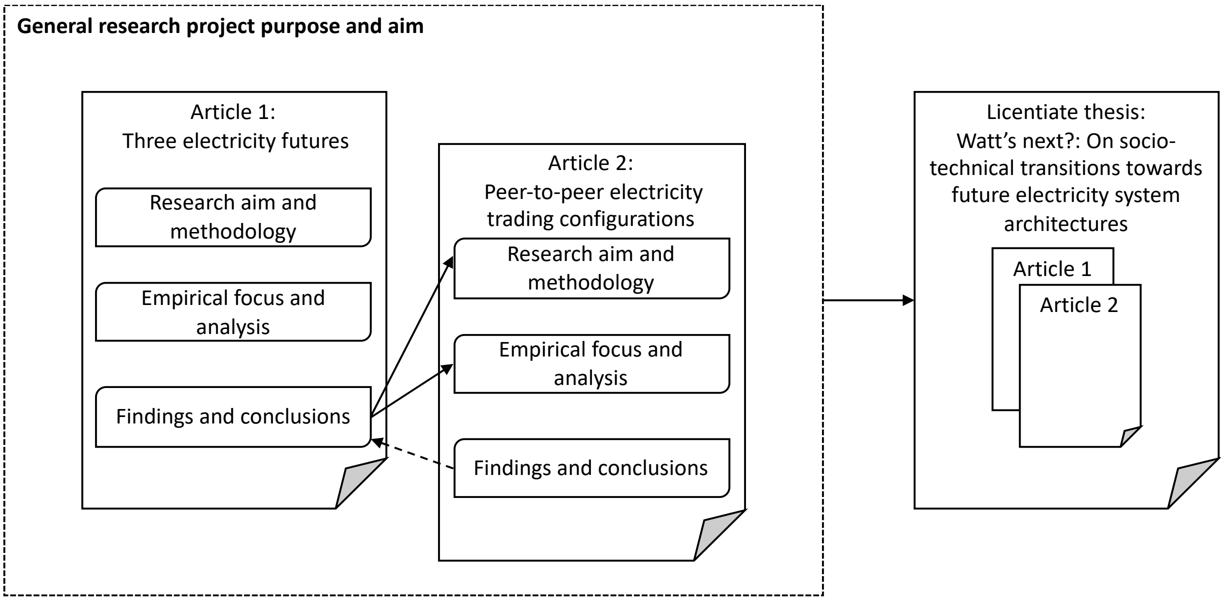


Figure 3 Relationship between articles 1 and 2 (appended) and with the thesis as a whole.

The general purpose of this research project is to follow the emergence of new system configurations that satisfy the criterion of 100 per cent renewables globally, to identify possible development pathways, and to study the critical factors that influence the different directions of development. Both appended articles partially address the overall project aim. Article 1 focuses on the first part of the project aim and identifies several alternative pathways towards future electricity configurations by combining scenario methodologies. The scenario-making exercise outlined three idealized end-states of future electricity systems (i.e., the Super-grid, Smart-grid, and Off-grid systems) that, using the TIS structural framework, were described in terms of key components that are currently emerging, accumulating, and co-evolving. Mapping the structures of the envisioned futures also guided our understanding of how these are linked or decoupled from the existing electricity system, other sectors, and trends. The scope of Article 1 was kept spatially open, with boundaries set at the global level, to allow explorative mapping of structural components directly involved in electricity generation, storage, and transmission. Building on the empirical findings in Article 1, the scope of Article 2 was narrowed in order to study one specific scenario and to analyse the causal relationships and processes that may lead in a particular direction: the Smart-grid system, empirically represented by two local technology demonstration projects. While Article 1 borrowed various socio-technical concepts to describe the three alternative futures, Article 2 exclusively applied the TIS functional framework, which was further developed to better account for the importance of the context and entrepreneurial agency that became apparent when studying the emergence of small, local experiments. Table 2 summarizes the research purposes, system boundaries, analytical strategies, and contributions of the appended articles.

Table 2 Summary of the research purposes, system boundaries, concepts, and contributions of the appended articles.

Research aim	**Article 1: Three electricity futures**	**Article 2: P2P electricity trading configuration**
Empirical	Identify alternative pathways leading towards future electricity configurations and map technological artefacts, actors, networks and institutions that characterize them and accumulate at present and how these are linked or decoupled from the existing electricity system.	Better understand the processes may influence the prospects for a radical Smart-grid scenario, and shape its trajectory by investigating two empirical cases of P2P electricity trading projects as two socio-technical transition efforts.
Conceptual	Use existing socio-technical and scenario methodology to monitor complete sets of socio-technical components identified in relation to a number of scenarios leading towards idealized forms of alternative futures.	Contribute to the existing TIS literature by (i) developing and testing a conceptualisation of influential contextual structures; and (ii) analysing how entrepreneurs utilize the context to stimulate structural buildup, overcome blocking factors and how this—in turn—affects their encounter with the local incumbent sector.
System boundaries		
Socio-technical	Technologies, actors and institutions that are directly involved in electricity generation, storage and transmission.	Peer-to-peer electricity trading via blockchain that lead to the construction of the future 'Smart-grid' system.
Spatial	Global innovation system related to the electricity sector.	The geographical boundaries have a starting point at the local level development projects and from there we explore a variety of contextual factors whereof some may become internalized locally.
Temporal	2000-2016	2016-2018
Analytical strategy		
Concepts used	TIS Structural components, MLP: niche accumulation and hybridization, socio-technical scenarios	TIS functional framework extended with conceptualization of the context and entrepreneurial activities.
Contributions		
Empirical contributions	Typology of idealized scenarios: the Super-grid, Smart-grid and Off-grid and related components emerging and accumulate at present and their relation to the electricity sector, other sectors and trends.	A better understanding of a P2P electricity trading system buildup in two exemplary local developments projects studied as novel system configurations.
Conceptual contribution	The MLP and socio-technical scenarios are used as a tool to clearly define extreme end-points (future alternatives) in combination with the TIS structural framework to map the specific set of components supporting these end-points.	By using and further developing the TIS 'functions' framework by analysing the innovation system buildup while proposing a typology of contexts and accounting for the special role of entrepreneurial activities in this process.

4.1 Data collection and methods

The research presented here applies a qualitative methodology based on a case-study approach (Flyvbjerg 2006, Yin 2017). While the credibility of quantitative research rests on the objective quality of the research, in qualitative research, the researcher him or herself is the instrument affecting the results via his or her own subjective views (Kvale 1994, Brinkman and Kvale 2015). Therefore, the reliability and validity of the data collected using qualitative techniques in this research was improved by adopting a systematic analytical procedure, triangulating the different data sources, and continuously discussing the results with fellow researchers.

While both articles appended to this thesis are qualitative in nature and contribute to the same overarching research aim, they differ in the specific research designs, scales of observation, data collection techniques and sources, and analytical methods applied. They also differ in their analytical focus. While Article 1 answers the first research question by mapping the complete structures of alternative future electricity systems, Article 2 answers the second research question by analysing the important aspects of the innovation system buildup of smart-grid-related developments in different parts of the world.

4.1.1 Article 1: Descriptive study of the direction of future electricity systems

The first paper appended to this thesis presents the first stage of the research process, with the objective of getting an overview of developments related to the future of the electricity sector. The article was designed as a descriptive study and was intended to uncover new facts and meanings related to possible pathways towards future electricity systems. This approach can answer “what is” and “what was” questions and describe variables rather than analyse relationships between them (Yin, Bickman et al. 1998). The data for Article 1 were collected from secondary data sources, including scientific literature, websites, reports, newspaper articles, and online datasets. The process of data analysis was qualitative content analysis, following the traditional steps in qualitative research going from data selection, through understanding the data, and eventually clarifying the larger meaning of the data (Creswell 2013).

In Article 1, the conclusions were reached in three steps. First, several alternative future electricity systems repeatedly mentioned in the literature were identified, clearly defined, and labelled as follows: the Super-grid, Smart-grid, and Off-grid systems. These alternative systems were then conceptualized as visions that do not yet exist in reality but can be traced as emerging sets of new technologies, actors, and institutions (Bergek, Jacobsson et al. 2008a). As suggested by Bergek, Jacobsson et al. (2008a), a bibliometric analysis was carried out to determine how much scientific knowledge has been amassed in recent decades in relation to the concepts of the super-grid, smart-grid, and off-grid systems (Figure X). In the second step, the distinctions between the three alternatives were used to construct three idealized system scenarios that can be positioned in a two-dimensional design space as three extreme future system end-points. In the third step, after outlining the systems of interest, we reviewed the socio-technical transition literature and conceptualized the three extreme systems as alternative socio-technical systems, i.e., structures of novel systems developing at the niche level. Here, we used MLP to position the alternative systems in relation to the regime and landscape levels in the context of the ongoing transitions in global electricity systems. After gaining a deeper understanding of the potential future electricity systems, we characterized the main structural components of the alternative systems using the structural analysis borrowed from the TIS framework. We looked for the actual actor constellations, novel technologies, and driving institutions paving the way towards alternative future electricity systems in a range of websites, reports, newspaper articles, and online datasets in order to find "what is out there". By doing this, we expected to find patterns of structural accumulation indicating the direction of the ongoing transition in electricity systems around the world.

4.1.2 Article 2: Comparative case study analysis of the important factors and processes supporting a specific scenario

The second paper presents the next stage in our research processes. Based on the findings of Article 1, Article 2 set out to analyse one of the directions: the Smart-grid scenario. Here, the research was designed as a comparative case study analysis, based on a qualitative research design in order to analyse the innovation processes leading to the build-up of a potential future Smart-grid system. The strategy of inquiry in Article 2 was based on a case study approach intended to explore "a program, event, activity, process of one or more individuals" (Creswell, 2009: 13). More precisely, Article 2 presents a comparative analysis of two local development projects for P2P electricity trading, an innovation driving the transition in the direction of the Smart-grid scenario. Comparative analyses are undertaken to find "puzzles" that can be difficult or even impossible to identify without making a comparison (Pennings et al. 2006).

In this study, we used the TIS framework as part of the research design to advance the empirical research, as an analytical scheme to guide the data collection, analysis, and interpretation, as well as to retain analytical coherence and clarity. The conventional TIS analytical framework used in Article 2 was further developed to incorporate the important role of the wider TIS context and agency, better reflecting our empirical observations from the field.

We based the analysis on data from interviews, participatory observations, and desktop research. Interviews were chosen as a primary source of data to ensure good control over the relevance and quality of the data, which is not always possible for secondary data such as documents, reports, and statistics (Palm and Glad 2011). In total, 28 semi-structured interviews were conducted with various participants directly involved in the P2P electricity trading demonstration projects, including entrepreneurs, researchers, representatives of large energy companies and small technology companies, and other key informants. The number of interviews was limited by the researcher's time in the field and the ability to access key informants involved in the studied projects.

The interview questions were open ended, framed in accordance with the key themes based on the "functions" defined in the TIS framework. We selected semi-structured interviews to allow for flexibility. This way we could build on the initially selected themes but also react to unexpected and interesting answers by asking further questions and encouraging reflection (Mikkelsen 2009).

The data gathered in the field were divided according to the case studies and treated separately in the analysis. Data collection in the field was followed by data analysis, which was an iterative process of transcription, reflection, pattern seeking, data categorization, drawing causal maps, as well as sharing findings with relevant stakeholders and research fellows, to refine the analysis based on the input gained from them. Visual Understanding Environment (VUE) software was used as a coding tool to categorize the data into structures and functions while also making causal connections and noting relations developing over time. The data analysis was based on deductive coding, in which themes were identified based on tracing the innovation process, actor motivations and capabilities, the encounter with the regime, and contextual factors. The data analysis process involved recurrent triangulation between the interviews, observations, and various case-related documents. Finally, the data were conveyed using a retrospective narrative approach (Clandinin and Connelly 2000).

While the methodological choices in Article 2 supported our analysis, it is important to note that these choices entail certain limitations. An important limitation comes with studying systemic innovation processes over short time periods, as analysing developments paving the way to different future alternative systems requires research over longer time periods. Even though Article 2 presents a narrative of the system buildup related to the Smart-grid, it assesses only the very early stages of the transition towards a future Smart-grid system and considers only two cases of experimentation. The time horizon captured in this study is too short to enable us to draw conclusions about the actual impact of the development of P2P electricity trading on the transition in the electricity sector and how that relates to other alternatives. Furthermore, using open-ended interviews as the primary data source limited us to collecting data from fewer respondents in the form of key individuals. Semi-structured interviews can lead to accidentally omitted topics and reduced comparability of responses compared with more quantitative data collection methods. Therefore, combining qualitative and quantitative methods would be beneficial to strengthen the empirical findings in Article 2.

4.1.3 Case selection

Before conducting the comparative analysis, significant effort was put into reflecting on the relationship between the compared cases. The two cases were selected as relevant to the research questions, meaning that they have more in common than they differ from each other in relation to the research questions. The selected cases are homogeneous in that both use blockchain technology to enable P2P electricity trading, yet heterogeneous in the geographical location and institutional environment in which the P2P trading was being developed. Specifically, we chose two local demonstration projects: the Brooklyn Microgrid in New York, USA, and the White Gum Valley demonstration project in Fremantle, Western Australia. These projects were selected based on their similarities and differences, similarities being: (1) blockchain-based trading platforms for P2P electricity trading, (2) the set of technological components required for this technology to function, (3) the key role of small entrepreneurial firms, (4) size and year started, and (5) vision of the future electricity system. The cases differ in (1) their political, institutional, and geographical contexts, (2) the existing physical setting in which they have developed, and (3) the actors actively engaged in the projects.

The decision to study P2P electricity trading supported by blockchain relates to the definition of the Smart-grid system presented in Article 1. Blockchain has been identified as the technological component that can enable an idealized form of Smart-grid in which every consumption unit is also a production unit and all units interact within a perfectly interconnected grid without relying on a third party or intermediary. Theoretically, in such a P2P trading network, small-scale producers act as both electricity prosumers and traders on a free market. Individual households can become small energy suppliers and every consumer has the chance to switch suppliers on a near to real time basis (Murkin J., Chitchyan R. et al. 2016).

Several existing energy companies have created “peer-to-peer” marketplaces, though these still involve retailers that mediate the market and interact between the customers, making them “peer-to-retailer-to-peer” systems. For example, Open Utility in the UK, PowerPeers in the Netherlands, and P2Power in New Zealand are facilitating virtual markets that match existing RE suppliers with buyers. Individual electricity suppliers at the household or commercial level, however, cannot directly act as sellers or buyers in these platforms (Engerati 2016, P2Power 2017).

A grid in which prosumers can trade electricity in a direct P2P fashion could be enabled by blockchain, which would provide a suitable digital infrastructure that supposedly allows a network of decentralized actors to reach consensus around a shared data state (e.g., transaction data) without the need for a central coordinator or the involvement of an intermediary, such as a utility or energy retailer (Burger, Kuhlmann et al. 2016, Murkin J., Chitchyan R. et al. 2016, PwC 2016, Sousaa, Soaresb et al. 2018). At the inception of the study in 2016, there were only two demonstration projects of blockchain-based P2P trading systems in the world, i.e., the Brooklyn Microgrid in New York, USA and the White Gum Valley demonstration project in Fremantle, Western Australia; these were accordingly selected to serve as cases.

5 Results and discussion

Based on their theoretical starting points and methodological approaches, the appended papers address the overall research aim proposed in this thesis and provide partial answers to the same overarching question: What determines the direction of the electricity system transition? While Article 1 presents findings about these directions and comprehensively describes them, Article 2 answers questions related to the causal relationships and buildup processes that influence the transition to take a specific direction. This chapter summarizes the empirical results and conceptual contributions of the appended papers, synthesizing them in relation to the overall aim of this thesis.

5.1 Findings in Article 1

Article 1, “Three electricity futures: Monitoring the emergence of alternative system architectures”, establishes a foundation for the research process. The empirical findings in this paper are based on a mapping process providing insights that address the aim of the paper: to systematically monitor key structural system components that constitute building blocks of differently configured future electricity systems. Addressing the aim of this paper resulted in the identification of three idealized electricity futures, i.e., the Super-grid, the Smart-grid, and the Off-grid systems, that not only shaped our understanding of the transition pathways but also created a basis for subsequent research endeavours.

While much has been written about how the future electricity system will or should be constructed (see Chapter 3), the research in Article 1 contributed to the literature by clearly distinguishing and describing a number of theoretically possible alternative future systems that are mutually exclusive in their extreme forms, and each of which could become the ultimate global electricity renewable electricity system architecture. Based on reviewing the literature, we found that the level and type of interconnectedness can be decisive in differentiating future alternative electricity systems into systems of dependent, interdependent, and independent electricity consumers (Figure 4), corresponding nicely with visions of the Super-grid, Smart-grid, and Off-grid systems articulated in the literature.

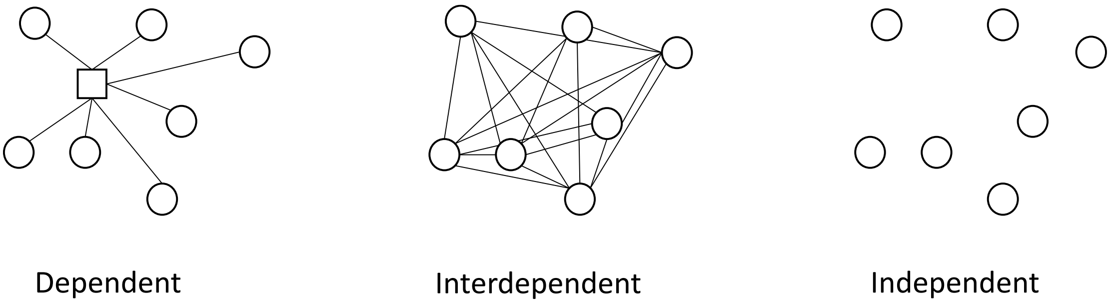


Figure 4: Different system organizations of electricity consumers and producers representing the Super-grid, Smart-grid, and Off-grid scenarios.

Such categorization can be taken further and a clearer distinction can be made by creating a design space (Stankiewicz 2000) described by two variables, i.e., the number of production units and the number of independent grids in the world, related to a constant, which is the number of consumers (see Figure 5). In this design space, the three alternative systems can be positioned at the very corners, making them mutually exclusive.

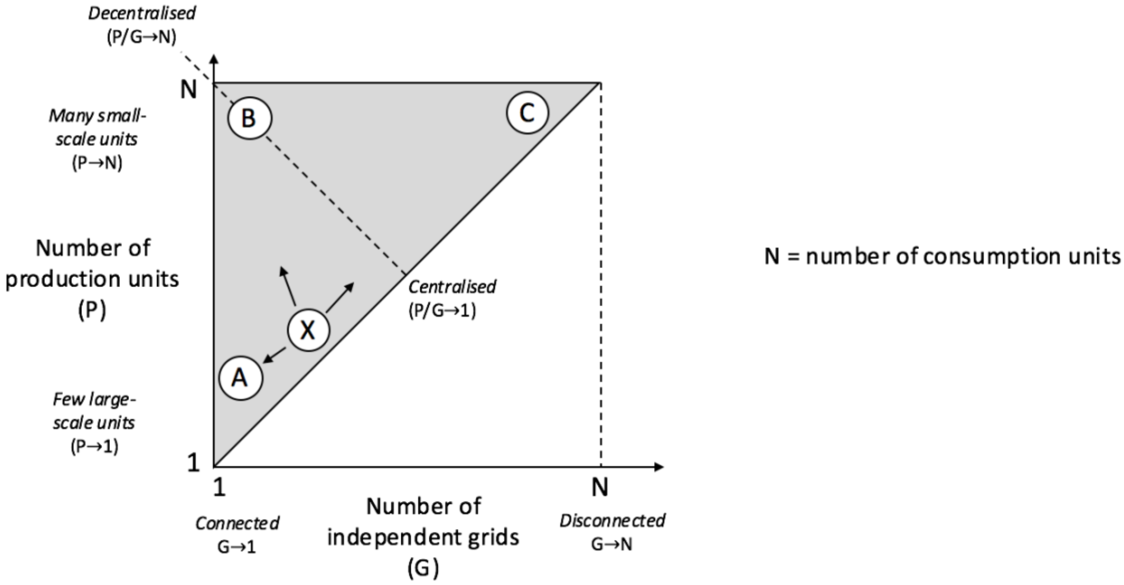


Figure 5: Three scenarios in one design space, where the letter X stands for the current electricity system, A for the Super-grid scenario, B for the Smart-grid scenario, and C for the Off-grid scenario.

The Super-grid scenario represents a global electricity grid architecture interconnected with high-voltage transmission lines delivering electricity from large-scale centralized renewable sources of electricity far from the consumer centres. The Smart-grid system also represents a globally interconnected electricity grid infrastructure, yet the renewable electricity generation is small in scale and installed at the demand level, making every consumer a prosumer. The Off-grid system is a configuration in which consumers around the world defect from the conventional grid infrastructure and instead build self-sufficient units or microgrids.

While we are aware that the future system may combine these alternatives, creating clarity by defining three extreme system configurations is analytically interesting, enabling a clear focus in monitoring and trend analysis, which can be used to determine which of these systems are starting to materialize at present. Table 2 presents an overview of the socio-technical components of the three systems identified in an extensive desktop data collection process.

Table 2: Socio-technical components of the three idealized scenarios.

	Super-grid	**Smart-grid**	**Off-grid**
Key technical components	Large-scale RE technology installations or plants HVDC cables Voltage source converters Large-scale storage	Small-scale RE technology Flexible AC transmission systems ICT, smart metering, and smart sensors Small-scale storage Electric vehicles	Small-scale RE technology Small-scale storage Microgrids
Main actors	National governments & international organizations Transmission system operators Large, often state-owned vertically integrated utility companies Incumbent power system companies	Regional & national governments Distribution system operators Incumbent firms and new entrants from other sectors (e.g., the ICT and automotive sectors) Prosumers	Prosumers Private device developers and maintenance providers
Supporting institutions	Collaboration and harmonization between governmental, regional, and international projects Multilateral agreements Tenders Vision statements and roadmaps	Collaboration along the new supply chain Standardization Feed-in tariffs Expectations translated into demonstration projects	Mistrust in existing electricity market actors Norms related to independence, self-sufficiency, and direct contribution to climate neutrality Innovative financing practices (e.g., microfinance and pay-as-you-go)

In addition to describing alternative systems and tracing the emergence and accumulation of a range of socio-technical components developing at the niche level, we found that having complete sets of components provided insights into how these structures relate to the incumbent electricity regime, other sectors, and trends. For this purpose, we used the concepts of niche accumulation and hybridization (Raven 2007) when interpreting our observations.

Accordingly, we found that the Super-grid system develops close to the existing electricity system, encompassing predominantly hybridization processes. The transition towards a Super-grid seems to involve replacing large-scale fossil fuel-based plants with plants and installations based on renewable electricity generation and incremental technological innovation in transmission. The Super-grid is supported by the actors dominating the existing electricity system, such as the national governments, research institutions, and dominant energy firms with the capabilities to coordinate such a megaproject. In this centralized, border-crossing transition, the actors rely on comprehensive visions and roadmaps that create the basis for their collaboration as the global Super-grid is being constructed. The motivations driving the transition towards a global Super-grid closely relate to those dominating the existing electricity system: top–down system control, efficiency, economies of scale, and the idea of globalizing the electricity sector.

The Smart-grid scenario seems to be emerging out of a combination of hybridization and niche accumulation processes bringing the dominant electricity sector together with niche developments, mostly in other sectors and supporting systems. The Smart-grid deviates from the existing system by creating a distributed grid configuration enabled by small-scale renewables and innovations in communication, metering, and storage technologies, developed in other sectors, discovering niche market applications in Smart-grid-related developments. Additional examples of important smart-grid components from other sectors are the blockchain from the financial sector and electrical vehicles from the automotive industry. While incumbent actors such as distributed system operators, local utilities, and large power system companies are often in charge of carrying out and financing demonstration projects in collaboration with research institutions, new entrants are increasingly contributing a variety of innovative Smart-grid technologies and solutions. Furthermore, private, public, and commercial building owners are becoming increasingly important in this scenario, initiating and participating in smart-grid experiments. The vision of the Smart-grid system seems to be inspired by other systems based on networks of users, such as the Internet, and by ideas about the free market and the sharing economy.

The Off-grid system has developed away from the existing electricity sector. We found that the transition towards the Off-grid system involves leaving the conventional electricity grid and related markets. We observed that this system is enabled by niche developments in small-scale and storage technologies that historically found a niche and developed economic strength in remote areas of developing countries, but also in applications in satellites, mobile phones, and electrical vehicles. Prosumers become the key actor in this system, choosing to leave the grid to avoid reliance on the conventional grid and utilities as well as to achieve individual independence and environmental responsibility.

The key result related to the electricity system transition reported in Article 1 is the evidence that the different scenarios have gathered momentum over the last 15 years through the development of new technologies, actors, and institutions and by creating links and borrowing from other sectors, discourses, and societal trends. We also found that to get closer to understanding in which direction the transition will develop, each direction needs to be further studied in terms of causal relationships between the structural components and by analysing the processes that support or hinder the success of the specific alternatives.

In summary, Article 1 suggests that the possible pathways taken by the electricity system transition can be better described by creating a new combination of complementary concepts borrowed from the neighbouring fields of socio-technical innovation and transition, namely, MLP and TIS, and from scenario methodology. After mapping the conceptual background, we chose those concepts that gave value to the explanation of the phenomena of interest. The MLP framework served as a heuristic mind map that supported our thinking about how regime change comes about, and about the interaction between incumbents and new actors challenging the established structures. In contrast, the TIS structural framework was used to zoom in on and specify the alternative socio-technical systems emerging in niches, by mapping complete sets of future system structures. Such use of the concepts is rather unusual, considering that the MLP framework is commonly used to create narratives and identify patterns and mechanisms in order to provide insight into why certain transition dynamics occur. Even more uniquely, this research has taken a different approach and started the scenario-making process by identifying a number of future end-point systems and identified a set of socio-technical system components existing at present instead of telling a narrative about a course of events or about patterns and mechanisms. The same is the case for the TIS framework, in which the structural analysis is not usually employed to map the structure of a future system but instead establishes the groundwork for analysing innovation processes and for identifying what is missing or is impeding system development in a certain direction.

5.2 Findings in Article 2

Article 2, “ Entrepreneurial use of contexts in technological innovation systems: the case of blockchain based Peer-to-Peer electricity trading systems”, builds on the empirical findings of Article 1 and aims to improve our understanding of how the early buildup of innovation systems influences the prospects and problems of a radical Smart-grid scenario and shapes its trajectory (Hojčková, Sandén et al. 2017). This aim is fulfilled by investigating two empirical cases of P2P electricity trading projects as two socio-technical transition efforts, both using the same innovative technology – the blockchain – with the common goal of promoting the radical “Smart-grid”, then existing only in the form of local demonstration projects. The analysis was conducted by employing the TIS framework as a lens for studying novel system developments as small socio-technical systems in the process of becoming. Beside the empirical contributions, Article 2 also suggests a variation of the TIS framework that better accounts for innovation processes in micro-level developments, where context and entrepreneurial agency play key roles in the system buildup. Consequently, Article 2 also has the conceptual aim of contributing to the TIS literature by i) developing and testing a conceptualization of influential contextual structures and ii) analysing how entrepreneurs utilize the context to stimulate innovation system build-up and how this affects the encounter with the local incumbent electricity sector.

The conceptual contributions of Article 2 integrate a number of concepts important for the system buildup, concepts lacking in the conventional TIS framework. First, despite the fact that the context appears to be crucial for early TIS development, for the “shaping” (Andersson et al. 2018) and overall prospects of a novel configuration, it has been under-theorized in the TIS framework, lacking a nuanced conceptualization of the geographical and socio-technical context of emerging configurations (Coenen and Díaz López 2010, Coenen, Benneworth et al. 2012, Bergek, Hekkert et al. 2015, Hansen and Coenen 2015, Truffer, Murphy et al. 2015).

The context was elaborated on to better understand why certain innovations develop successfully in some contexts while failing in others. After reviewing the existing context-related debate in the literature, we found many different ways of understanding the context and sorted these along two dimensions: the *spatial dimension of the context* and the *socio-technical dimension of the context*, which were integrated into the two-dimensional matrix presented in Figure 6.

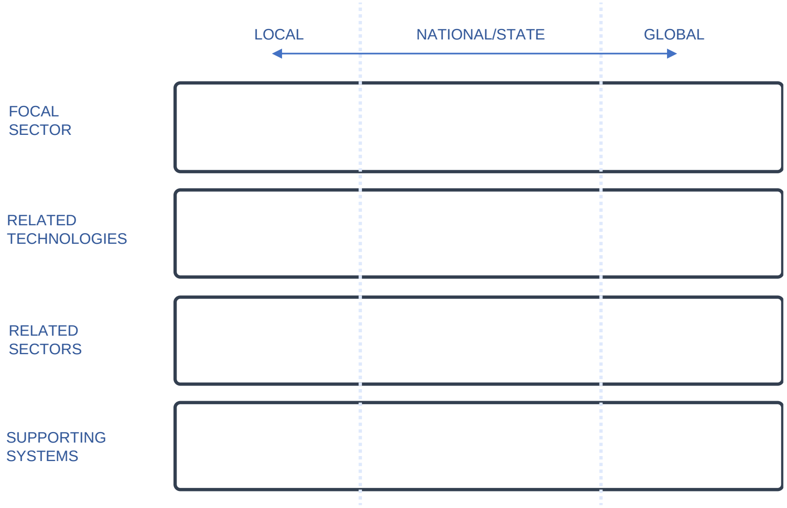
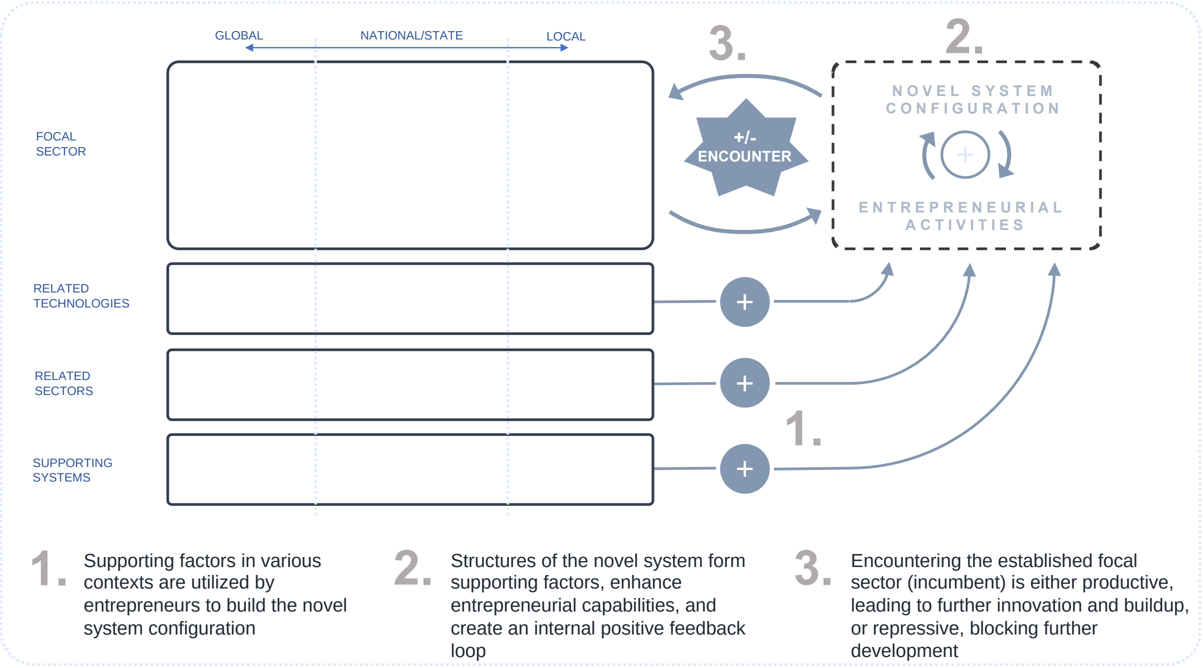


Figure 6: A two-dimensional conceptualization of the context of emerging configurations.

In addition to the important role of the context, entrepreneurial agency seemed particularly important when considering innovation processes, i.e. functions (Table 1) at the level of the local demonstration project, where the role of individual actors in utilizing available resources and mobilizing collective action becomes more apparent. Therefore, the micro-level foundation is often neglected and too little attention is paid to entrepreneurial activities (Alkemade, Negro et al. 2011). Hence, at the micro level we position entrepreneurial activities as the micro embodiment of the functions, navigating supporting factors from various contexts (see Figure 7).

While both the role of the context and the importance of entrepreneurs have previously been described as crucial for successful system building, these have been kept analytically separate here. Article 2 makes a conceptual contribution to the TIS framework by bringing a more nuanced definition of TIS context and entrepreneurial agency together, to gain a deeper understanding of why certain innovation systems succeed while others fail when encountering the incumbent sector that they are trying to transform. The version of the TIS framework that guides the analysis in Article 2 is represented in Figure 7.



1. Supporting factors in various contexts are utilized by entrepreneurs to build the novel system configuration

2. Structures of the novel system form supporting factors, enhance entrepreneurial capabilities, and create an internal positive feedback loop

3. Encountering the established focal sector (incumbent) is either productive, leading to further innovation and buildup, or repressive, blocking further development

Figure 7: Process of the TIS build-up that incorporates various contexts and accounts for the role of agency in utilizing them to support the internal momentum.

Given the analytical framework used in Article 2, the analysis provides a number of findings related to the important factors and processes that support or hinder development towards P2P electricity trading systems. First, we found that a favourable local electricity sector-related context, such as favourable policies or a large rooftop solar market, matters for innovation but does not automatically lead to a successful local demonstration project when encountering the locally embedded incumbent sector. To challenge the locally embedded incumbent electricity sector, finding opportunities in the context of other sectors, such as the housing sector in the case of the White Gum Valley project, appears to be particularly helpful in building a sufficient basis for a P2P electricity trading system as a way to create an opportunity for initial real-world application and experimentation. We also found that while strategic utilization of contextual aspects outside the local level, at the global and national levels, can serve as a means to mobilize resources and support legitimacy, these aspects are insufficient for achieving a productive encounter with the local incumbent sector. Instead, building a local actor network and creating a local supply chain that combines local and global knowledge can confer a better competitive position at the point of the encounter.

We also found that the role and positioning of the entrepreneurs matter. Our empirical cases provide evidence that entrepreneurs with local connections, with the *ability to access the tacit knowledge*, and familiar with the local context had an easier time translating their ideas into innovation processes. In the White Gum Valley project, the pre-existing local connections of the key entrepreneur proved to be crucial in building the local advocacy coalition that managed to realize the ambition to innovate the electricity market. On the other hand, in the case of the Brooklyn Microgrid, New York's electricity sector-related context seemed open to external entrepreneurs but de facto prioritized the local utilities, perceived as more credible in managing the local transition.

It also appears that the importance of the contexts outside the local level, at the national and global levels, may be utilized by key entrepreneurs for different reasons. While the entrepreneurs in the White Gum Valley project decided to go global as a result of being successful locally, in the case of the Brooklyn Microgrid, the move to the global level was triggered by the unsuccessful negotiations with the local incumbent sector. Consequently, some entrepreneurs use the global and national contexts to move and replicate their innovation systems in another context to cope with the local inertia, while others use them to grow their businesses from being local to being global solutions.

5.3 The three electricity futures revisited and potential future research

The findings presented in this thesis have implications for the overall purpose of this research, for the original categorization of the three alternative future scenarios, as well as for the initial assumptions about the Smart-grid system in Article 1, suggesting interesting avenues for future research.

Related to the initial description of the smart-grid scenario in Article 1, Article 2 provides evidence confirming that the Smart-grid scenario involved a combination of niche accumulation and hybridization processes, as its successful buildup relied on collaboration between incumbents and new entrants, especially from other sectors. The incumbents contributing to the Smart-grid system buildup, did not have to come from the electricity sector but instead came from another sector, such as the housing sector, that provided a niche for an innovation that was likely to fail in encountering the regime it was aiming to transform. In other words, entrepreneur-driven Smart-grid-related developments need to find a niche opportunity for initial testing and experimentation in order to build their strength before engaging with the incumbents from the electricity sector.

Furthermore, the analysis in Article 2 confirms the important role of local governments and entrepreneurs from novel firms in developing the Smart-grid system, though we also found that they played different roles in the system buildup process. Our cases show that local and national governments are important in providing legitimacy, in the form of favourable policies and financial resources, but that it is the entrepreneurs who can navigate the contextual opportunities and mobilize collective action to build actor networks that support the system buildup. While the incumbent utilities seem to be supporting Smart-grid-related innovation in an effort to better accommodate distributed renewables in the existing grid, they tend to hybridize the innovation to maintain their position in the transition process, potentially hindering developments towards the idealized Smart-grid configuration that fundamentally questions dominant practices and routines.

Consequently, our analysis shows that the Smart-grid scenario, which at first glance could be envisioned as the most realistic path, supported by both existing and novel structures, in fact leads to considerable friction as it requires complex restructuring processes, often imagined differently by the dominant actors and new entrants involved in Smart-grid related development. More research attention should therefore be directed to the individual expectations and roles within actor networks supporting Smart-grid-related developments, to better manage the complex negotiation process. While the Smart-grid system requires complex negotiations, these processes are assumed to differ in the case of the Super-grid scenario, which is mostly about incremental changes in electricity generation and transmission supported by incumbents, or in the Off-grid scenario, which is about new actors leaving the existing system behind and building a new one instead.

Related to our findings in Article 2, more empirical work is needed to better understand the role of the prosumers, who are expected to play a key role in the transition towards the idealized Smart-grid scenario. Quite paradoxically, the P2P electricity trading developments analysed in Article 2 had very little direct involvement of prosumers, who are seen as the core of this distributed system. The involvement of prosumers will become increasingly important as development projects scale-up to real-world applications across the regulated electricity network, directly affecting the first P2P network participants. The characteristics of prosumers who are willing to contribute to experiments, learn about P2P electricity trading, or even become co-designers of the technology will be important determinants of the success of the transition towards the Smart-grid system.

Moreover, it is important to realize that the empirical findings in Article 2 are specific to the selected local demonstration projects. Although they are likely to have some more general validity, especially for similar projects, the results could be improved by studying other focal technologies than blockchain-based P2P electricity trading and in different parts of the world, driven by different actors. Furthermore, while the results might be generalizable to other small demonstration projects, this might not be the case as systems grow and mature. Additional studies are therefore needed to reassess our conceptualization of the TIS framework for studying system build-up processes at other levels of aggregation and maturity.

To this point, the empirical findings presented in this thesis are largely limited to the determinants of the transition towards the Smart-grid scenario. A more robust understanding of the ongoing transition processes could be achieved by studying the important factors leading to Super-grid or Off-grid-related developments, to learn whether these confirm or contradict the initial assumptions made in Article 1. Furthermore, comparing the results of studies analysing alternative future systems would constitute a next step in exploring what determines the direction of the transition.

Finally, the present findings are based on the conceptualization of the three alternative future systems formulated in Article 1, which differentiates between systems with different levels and types of interconnectedness. In the future, the original two-dimensional matrix could be further developed, complemented by a third dimension. After gaining more insight into existing projects, especially at sector-specific and industrial conferences, we noticed that large-scale technological components can be owned by small-scale actors or groups of them, and that the reverse can also be true, that small-scale systems can be centrally owned by a big investor. A third dimension could therefore be related to system ownership. A promising area for research would then be to study directions of the transition based on the kind of technology ownership in these systems.

6 Conclusions

This thesis aimed to improve our understanding of what determines the direction of the electricity system transition. Conceptually, the research takes socio-technical transitions and innovation frameworks as the theoretical starting point for studying innovation in the electricity system as a transition from the dominant fossil-fuel based system to a new system based on renewables. The appended papers both apply a socio-technical perspective to studying empirical phenomena and provide partial contributions to the aim stated in this thesis: What determines the direction of the electricity system transition? Article 1 provides a categorization and descriptions of the different directions the transition might take, while Article 2 analyses the processes and important factors that determine a specific direction.

Empirically, the present research contributes to the literature by clearly defining three alternative electricity futures, i.e., the Super-grid, Smart-grid, and Off-grid systems, that can be monitored in the form of structural components currently emerging and accumulating. This research shows that all three alternatives have gained notable momentum over the last 15 years and presents evidence that the transition is underway. The emerging systems are not exclusive to the electricity sector, however, but instead create links with and borrow components from other sectors, discourses, and societal trends. Moreover, the Smart-grid system was not only defined in terms of key components but also analysed in terms of important factors and processes, to gain a better understanding of the causalities that lead to a future of complete interconnectedness. For a more comprehensive understanding of the direction this transition might take, the alterative scenarios need to be further analysed and compared. This opens up a number of interesting avenues for future empirical research.

This thesis has made several conceptual contributions. First, a unique combination of socio-technical concepts was created and used to clearly define a number of future scenarios. Second, the TIS framework was further developed by emphasizing the role of the contexts and entrepreneurial agency in innovation system buildup to better suit analyses of context-dependent developments at the micro level. These contributions can inform future applications of the TIS framework, but also suggest new interesting areas for further conceptual development.

Though the present research is predominantly explorative, its findings are of general relevance for people interested in the transformation of the electricity sector, such as researchers, entrepreneurs, policy-makers, prosumers, and many others who hope to find more clarity amidst the messy changes that affect everyone as electricity systems around the globe change.

7 References

Ahlborg, H. and M. Sjöstedt (2015). "Small-scale hydropower in Africa: Socio-technical designs for renewable energy in Tanzanian villages." Energy Research & Social Science **5**: 20-33.

Alkemade, F., et al. (2011). "Towards a micro-level explanation of sustainability transitions: entrepreneurial strategies." Innovation Studies Utrecht (ISU)—Working Paper Series **11**.

Andersson, C. and P. Törnberg (2016). "Innovation and the anatomy of wickedness." article under revision.

Arthur, B. (2009). The nature of technology. New York, Free Press.

Battaglini, A., et al. (2009). "Development of SuperSmart Grids for a more efficient utilisation of electricity from renewable sources." Journal of cleaner production **17**(10): 911-918.

Bergek, A., et al. (2015). "Technological innovation systems in contexts: Conceptualizing contextual structures and interaction dynamics." Environmental innovation and societal transitions **16**: 51-64.

Bergek, A., et al. (2008a). "Analyzing the functional dynamics of technological innovation systems: A scheme of analysis." Research policy **37**(3): 407-429.

Bergek, A., et al. (2008). "'Legitimation' and 'development of positive externalities': two key processes in the formation phase of technological innovation systems." Technology Analysis and Strategic Management **20**(5): 575-592.

Bergek, A., et al. (2008b). "'Legitimation'and 'development of positive externalities': two key processes in the formation phase of technological innovation systems." Technology Analysis & Strategic Management **20**(5): 575-592.

Binz, C. and B. Truffer (2017). "Global Innovation Systems—A conceptual framework for innovation dynamics in transnational contexts." Research policy **46**(7): 1284-1298.

Blarke, M. B. and B. M. Jenkins (2013). "SuperGrid or SmartGrid: Competing strategies for large-scale integration of intermittent renewables?" Energy Policy **58**: 381-390.

Börjeson, L., et al. (2006). "Scenario types and techniques: Towards a user's guide." Futures **38**(7): 723-739.

Brinkman, S. and S. Kvale (2015). Interviews: Learning the craft of qualitative research interviewing, Thousand Oaks, CA: Sage.

Bronski, P., et al. (2014). "The economics of grid defection: When and where distributed solar generation plus storage competes with traditional utility service." Rocky Mountain Institute.

Burger, C., et al. (2016). Blockchain in the energy transition. Berlin.

Carlsson, B. and R. Stankiewicz (1991). "On the nature, function and composition of technological systems." Journal of Evolutionary Economics **1**(2): 93-118.

Cherp, A., et al. (2018). "Integrating techno-economic, socio-technical and political perspectives on national energy transitions: A meta-theoretical framework." Energy Research & Social Science **37**: 175-190.

Clandinin, D. J. and F. M. Connelly (2000). Narrative inquiry, San Francisco: Jossey-Bass.

Coenen, L., et al. (2012). "Toward a spatial perspective on sustainability transitions." Research policy **41**(6): 968-979.

Coenen, L. and F. J. Díaz López (2010). "Comparing systems approaches to innovation and technological change for sustainable and competitive economies: an explorative study into conceptual commonalities, differences and complementarities." Journal of cleaner production **18**(12): 1149-1160.

Cooke, P., et al. (1997). "Regional innovation systems: Institutional and organisational dimensions." Research policy **26**(4-5): 475-491.

Creswell, J. W. (2013). Research design: Qualitative, quantitative, and mixed methods approaches, Sage publications.

Dauncey, G. (2009). Build a Supergrid. The Climate Challenge: 101 Solutions to Global Warming, New Society Publishers.

Doig, A. (1999). "Off-grid electricity for developing countries." IEE review **45**(1): 25-28.

Engerati (2016). "Peer-to-peer energy trading pioneers in Britain." 2017, from https://www.engerati.com/article/peer-peer-energy-trading-pioneers-britain.

Feenberg, A. (1991). Critical theory of technology, Oxford University Press New York.

Flyvbjerg, B. (2006). "Five misunderstandings about case-study research." Qualitative inquiry **12**(2): 219-245.

FOSG (2015). "FOSG joins forces to communicate on Supergrid research." FOSG Newsletter.

Foxon, T. J. (2013). "Transition pathways for a UK low carbon electricity future." Energy Policy **52**: 10-24.

Funcke, S. and D. Bauknecht (2016). "Typology of centralised and decentralised visions for electricity infrastructure." Utilities Policy.

Geels, F. W. (2002). "Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study." Research policy **31**(8): 1257-1274.

Geels, F. W. (2004). "From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory." Research policy **33**(6): 897-920.

Geels, F. W. (2005). Technological Transitions and System Innovations: A Co-evolutionary and Socio-technical Analysis, Edward Elgar Publishing, Incorporated.

Geels, F. W. (2011). "The multi-level perspective on sustainability transitions: Responses to seven criticisms." Environmental innovation and societal transitions **1**(1): 24-40.

Geels, F. W. and J. Schot (2007). "Typology of sociotechnical transition pathways." Research policy **36**(3): 399-417.

Hammons, T. J. (2008). "Integrating renewable energy sources into European grids." International Journal of Electrical Power & Energy Systems **30**(8): 462-475.

Hansen, T. and L. Coenen (2015). "The geography of sustainability transitions: review, synthesis and reflections on an emergent research field." Environmental innovation and societal transitions **17**: 92-109.

Hekkert, M., et al. (2011). "Technological innovation system analysis." A manual for analysts. To be found on: http://www. innovation-system. net/wpcontent/uploads/2013/03/UU_02rapport_Technological_Innovation_System_Analysis. pdf,[Accessed: 02.10. 2013].

Hekkert, M. P. and S. O. Negro (2009). "Functions of innovation systems as a framework to understand sustainable technological change: Empirical evidence for earlier claims." Technological Forecasting and Social Change **76**(4): 584-594.

Hekkert, M. P., et al. (2007). "Functions of innovation systems: A new approach for analysing technological change." Technological Forecasting and Social Change **74**(4): 413-432.

Hertzog, C. (2010). Smart Grid Dictionary.

Hofman, P. S., et al. (2004). "Sociotechnical scenarios as a new policy tool to explore system innovations: Co-evolution of technology and society in the Netherland’s electricity domain." Innovation **6**(2): 344-360.

Hojčková, K., et al. (2017). "Three electricity futures: Monitoring the emergence of alternative system architectures." Futures.

Hughes, T. P. (1987). The evolution of large technological systems. W. E. Bijker, T. P. Hughes and T. J. Pinch. Cambridge, Massachusetts, MIT Press.

Hughes, T. P. (1987). "The evolution of large technological systems." The social construction of technological systems: New directions in the sociology and history of technology: 51-82.

Khalilpour, R. and A. Vassallo (2015). "Leaving the grid: An ambition or a real choice?" Energy Policy **82**: 207-221.

Kvale, S. (1994). "Ten standard objections to qualitative research interviews." Journal of phenomenological psychology **25**(2): 147-173.

Lilliestam, J. and S. Hanger (2016). "Shades of green: Centralisation, decentralisation and controversy among European renewable electricity visions." Energy Research & Social Science **17**: 20-29.

Liu, Z. (2015). Global Energy Interconnection, Academic Press.

Loorbach, D., et al. (2010). "Introduction to the special section: infrastructures and transitions." Technological Forecasting and Social Change **77**(8): 1195-1202.

Lundvall, B. A. (1988). "Innovation as an interactive process: from user-producer interaction to the national system of innovation." Innovation As An Interactive Process: From User-producer Interaction to the National System of Innovation: 349-369.

MacLeod, N. e. a. (2015). A Technological Roadmap for the Development of the European Supergrid. Lund, Sweden. https://library.e.abb.com/public/323e5c246dee456c8219f05d9b58ae55/A%20Technological%20Roadmap%20for%20the%20Development%20of%20the%20European%20Supergrid.pdf.

Malerba, F. (2002). "Sectoral systems of innovation and production." Research policy **31**(2): 247-264.

Markard, J. (2011). "Transformation of infrastructures: sector characteristics and implications for fundamental change." Journal of Infrastructure Systems **17**(3): 107-117.

Markard, J. and B. Truffer (2008). "Technological innovation systems and the multi-level perspective: Towards an integrated framework." Research policy **37**(4): 596-615.

Meeuwsen J.J, M. J. M. A., Verbong G.P.J, Kling W.L, Blom J.H (2008). "Electricity networks of the future : various roads to a sustainable energy system." Proceedings of the Conseil International des Grands Réseaux Électriques (CIGRE) Session 2008. - Paris : CIGRE, 2008.

Mikkelsen, B. (2009). Methods for development work and research: A new guide for practitioners, SAGE Publications Inc. .

Murkin J., et al. (2016). Enabling Peer-to-Peer Electricity Trading. 4th International Conference on ICT for Sustainability (ICT4S), Amsterdam, The Netherlands.

New Energy Outlook (2018). BloombergNEF. https://about.bnef.com/new-energy-outlook/.

P2Power (2017). from https://p2power.co.nz/#.

Palm, J. and W. Glad (2011). Interviews. Interdisciplinary energy system methodology: A compilation of research methods used in the Energy Systems Programme. M. Karlsson, J. Widén and J. Palm.

Perez Vico, E. (2014). "An in-depth study of direct and indirect impacts from the research of a physics professor." Science and Public Policy **41**(6): 701-719.

PwC (2016). Blockchain - an opportunity for energy producers and consumers? http://www.pwc.com/gx/en/industries/energy-utilities-mining/power-utilities/publications/opportunity-for-energy-producers.html.

Raven, R. (2007). "Niche accumulation and hybridisation strategies in transition processes towards a sustainable energy system: An assessment of differences and pitfalls." Energy Policy **35**(4): 2390-2400.

Rip, A. and R. Kemp (1998). Technological change, Battelle Press.

Robertson, S. (2016). "A longitudinal quantitative–qualitative systems approach to the study of transitions toward a low carbon society." Journal of cleaner production **128**: 221-233.

Sandén, B. A. and K. M. Hillman (2011). "A framework for analysis of multi-mode interaction among technologies with examples from the history of alternative transport fuels in Sweden." Research policy **40**(3): 403-414.

Sandén, B. A. and K. Jonasson (2005). Variety creation, growth and selection dynamics in the early phases of a technological transition: The development of alternative transport fuels in Sweden 1974-2004, Chalmers University of Technology.

Scott, W. R. (2001). Institutions and organizations. Thousand Oaks, Calif., Sage.

Shuta Mano, et al. (2014). Gobitec and Asian Super Grid for Renewable Energies in Northeast Asia. http://www.energycharter.org/fileadmin/DocumentsMedia/Thematic/Gobitec_and_the_Asian_Supergrid_2014_en.pdf.

Smith, A., et al. (2005). "The governance of sustainable socio-technical transitions." Research policy **34**(10): 1491-1510.

Sousaa, T., et al. (2018). "Peer-to-peer and community-based markets: A comprehensive review."

Stankiewicz, R. (2000). The concept of 'design space'. Technological innovation as an evolutionary process. J. M. Ziman. Cambridge, Cambridge University Press**:** 234-247.

Swedish Agency for Growth Policy Analysis (2014). Drivers and Barriers for a transition to a Sustainable Energy System. Drivers and Barriers for a transition to a Sustainable Energy System. E. Deiaco, Swedish Agency for Growth Policy Analysis.

Truffer, B., et al. (2015). "The geography of sustainability transitions: Contours of an emerging theme." Environmental innovation and societal transitions **17**: 63-72.

Turnheim, B., et al. (2015). "Evaluating sustainability transitions pathways: Bridging analytical approaches to address governance challenges." Global Environmental Change **35**: 239-253.

U.S. Department of Energy (2015). Chapter III: Modernizing the electricity grid. QER Report: Energy Transmission, Storage, and Distribution Infrastructure**:** 1-33.

Van den Bergh, J. C., et al. (2011). "Environmental innovation and societal transitions: Introduction and overview." Environmental innovation and societal transitions **1**(1): 1-23.

Verbong, G. P. and F. W. Geels (2010). "Exploring sustainability transitions in the electricity sector with socio-technical pathways." Technological Forecasting and Social Change **77**(8): 1214-1221.

Walker, G. and N. Cass (2007). "Carbon reduction,'the public'and renewable energy: engaging with socio-technical configurations." Area **39**(4): 458-469.

Wieczorek, A. J. and M. P. Hekkert (2012). "Systemic instruments for systemic innovation problems: A framework for policy makers and innovation scholars." Science and Public Policy **39**(1): 74-87.

Yin, R., et al. (1998). "Handbook of applied social research methods." Handbook of applied social research methods.

Yin, R. K. (2017). Case study research and applications: Design and methods, Sage publications.

Zinaman, O., et al. (2015). "Power Systems of the Future." The Electricity Journal **28**(2): 113-126.