

THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

## **Emerging networks of power**

Exploring sociotechnical pathways towards future electricity systems based on  
renewable energy technologies

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Gothenburg, 2020

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ISBN 978-91-7905-397-0

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Doktorsavhandlingar vid Chalmers tekniska högskola

Ny serie nr 4864

ISSN 0346-718X

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Chalmers digitaltryck

Gothenburg, Sweden 2020

*“Knowledge is life with wings”*

William Blake



# Emerging networks of power: Exploring sociotechnical pathways towards future electricity systems based on renewable energy technologies

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## ABSTRACT

In the effort to fight climate change, electricity systems around the world are undergoing a transition from fossil-fuelled to renewable energy-based production of electricity. The transition can, however, be attained in several radically different ways, ranging from global or continental super-grids, via local smart-grids, to self-sufficient off-grid communities and households of electricity prosumers. How the transition will unfold and what the eventual system will look like remains uncertain. By shifting focus away from simply increasing the share of renewable energy production to the specific configurations of renewables, we can better navigate the complex technological landscape, better target investment, and help inform the governments, businesses, and citizens that are shaping the future of the electricity system.

This thesis aims to study the emergence of alternative electricity system configurations that could satisfy the criterion of one hundred per cent renewables globally. Positioned in the broader innovation and sustainability transitions literature that share the sociotechnical systems perspective on technological change, the thesis improves the existing knowledge about two main aspects of the electricity system transition: 1) alternative electricity system end states, and 2) the dynamics of the transition towards them.

The research presented in this thesis contributes to the literature by constructing a ‘design space’ of clearly distinguishable electricity system alternatives, 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. The monitoring reveals that all three alternatives have gained notable momentum over the last 15 years and that the alternative configurations are not exclusive to the electricity sector but are also linked to and borrow components from other sectors, discourses, and societal trends.

The design space of alternative futures also guides the case study selection of two contrasting configurations for an electricity system powered by renewables: the global high-voltage transmission Super-grid and Smart-grid experiments in the shape of local blockchain-based peer-to-peer trading in Australia and the US. The in-depth case studies provide findings about drivers of and barriers for alternative electricity system configurations, as well as conceptual contributions to ongoing debates in the innovation and sustainability transitions literature relating to system definition, maps of alternative futures, agency of actors supporting new technologies, the role of context, and the encounter between the novel system and established structures.

By thinking about possibilities and understanding what it takes to get there, this thesis improves the existing knowledge by providing a deep understanding of the activities and roles of different system builders, strategies of momentum building, and macro-level trends that together influence the direction of change. This thesis challenges myopic and siloed thinking about the future of the electricity system and calls for collective action in addressing the transition-related unknowns and trade-offs. For practitioners and policymakers, the design space of alternative futures and the empirical findings can guide communication and negotiation on the complex path towards a low-carbon electricity future.

**Keywords:** electricity system, renewable energy, sociotechnical systems perspective, Technological Innovation System, Multilevel Perspective, transition pathways, context, entrepreneurs, energy users, incumbents

## LIST OF PUBLICATIONS

This dissertation thesis presents an extended summary of the six appended papers listed below.

The papers are referred to in the text by Roman numerals.

- PAPER I** Hojčková, K., Sandén, B., & Ahlborg, H. (2018). Three electricity futures: Monitoring the emergence of alternative system architectures. *Futures*. 98, 72–89.
- PAPER II** Hojckova, K., Ahlborg, H., Morrison, G., & Sandén, B. (2020). Entrepreneurial use of context for technological system creation and expansion: The case of blockchain-based peer-to-peer electricity trading. *Research Policy*. 49. 104046.
- PAPER III** Wilkinson, S. J., Hojckova, K., Eon, C., Morrison, G., & Sandén, B. (2020). Is peer-to-peer electricity trading empowering users? Evidence on motivations and roles in a prosumer business model trial in Australia. *Energy Research and Social Science*. 66. 101500.
- PAPER IV** Hojckova, K. (2020). The challenge of peer-to-peer electricity trading pilots: Review of innovation systemic problems in the US and Australia. Manuscript submitted to *Energies*' special issue on Smart Local Energy Systems.
- PAPER V** Hojckova, K., Ahlborg, H., & Sandén, B. (2020). Building a global Super-grid: A sociotechnical analysis. Manuscript submitted to *Renewable & Sustainable Energy Reviews*.
- PAPER VI** Andersson, J., Hojckova, K., & Sandén, B. (2020). Clarifying the focus and improving the rigour of sustainability transitions research on emerging technologies. IST 2020 Conference paper.

Authors' contributions to the co-authored papers:

I: Authors collectively developed the conceptual framing of the study. I collected and analysed the data with the support of Sandén, B. and Ahlborg, H. All three authors were involved in preparing and revising the paper.

II: I selected the object of study and identified case studies. I also collected, transcribed, and analysed the empirical data. Sandén, B. and Ahlborg, H. were closely involved in developing the conceptual framework and revising the manuscript. Morrison, G. provided access to the empirical case study and gave advice regarding the empirical analysis and findings.

III: Wilkinson, S., Eon, C., and I were involved in formulating the study topic and research questions as well as in collecting the empirical data. Wilkinson, S. and Eon, C. analysed the empirical data and I was in charge of conducting a literature review and developing a theoretical framework for the study. Wilkinson, S. and I prepared and revised the manuscript. Morrison, G. and Sandén, B. provided senior guidance and advice.

V: My contribution was in identifying the object of study and case studies. I also collected, transcribed, and analysed the empirical data. Sandén, B. and Ahlborg, H. were closely involved in developing the conceptual framework and revising the manuscript.

VI: Sandén, B. identified the topic of the paper. All three authors were involved in discussing the topic, while Sandén, B. and Andersson, J. were in charge of drafting the initial manuscript and formulating its main ideas. I contributed by conducting a literature review and providing input on the conceptualisation of the main ideas. All the authors were involved in revising the manuscript.

## ACKNOWLEDGEMENTS

It is hard to put into words how grateful I am for this journey and all the amazing people I had the privilege to work with and learn from. Undertaking this PhD has been a truly life-changing experience for me, and it would not have been possible without the support and guidance of many people.

I owe a great deal to my dear colleagues at the Division of Environmental Systems Analysis, for creating a welcoming and inspiring work environment. Thank you all for sharing your positive energy, knowledge and support. I have missed you dearly over the last few months and I am hoping we can all reunite and celebrate together soon in a post-pandemic world.

I would like to extend my deepest gratitude to my supervisors Helene Ahlborg and Björn Sandén. My biggest role models. Your ability to mentor me while encouraging me to discover my own answers has shaped me not only as a researcher but also as a person. I could not have asked for more inspiring and generous supervisors and I have always tried my best to make you proud through my work.

I would like to extend my sincere thanks to Peter Altmann for sharing his wisdom, for challenging me and encouraging me to take a step out of my comfort zone. Thank you for the endless talks, the energy and laughter.

A sincere thank you also goes to Greg Morrison and his team at Curtin University Sustainability Policy Institute in Perth for treating me as one of their own and generously sharing their knowledge and time with me. Special thanks to Sam Wilkinson, for the fantastic teamwork and genuine support.

I am grateful to my family that despite having little clue about the content of my work has always been amazingly supportive not only throughout writing this thesis but also in my life choices in general. To my beautiful friends, who I miss so much. I am forever grateful for your patience and understanding. I can't wait to reconnect with each of you.

And finally, this work would not have been possible without the emotional support of my significant other, my amazing partner Ancrum, who has stayed with me through this roller coaster, taught me how to find balance in life and reminded me to believe in myself. Without you by my side, I never would have made it till the end.

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# 1 Introduction

Most electricity systems built throughout the 20<sup>th</sup> century are facing problems of ageing grid infrastructure and fossil-fuel dependency, making the electricity sector one of the biggest contributors to global carbon emissions (IEA, 2019a). Environmental concerns coupled with falling prices of small-scale renewable energy technologies (RETs) and changing customer needs have put pressure on the established electricity sector to make profound changes. As the global community demands a transition towards a decarbonised, reliable, and affordable electricity system for all, many believe that this will require complex, radical changes that challenge the status quo of the traditional centralised electricity sector based on fossil fuels.

While a strong consensus is emerging about the need to achieve this transition, it is less clear what kind of future system can fulfil this objective. In fact, as the shift to renewable energy generation gathers momentum, the diversity of ways to decarbonise the electricity system seems to be increasing. Given the modular character of RETs and the rapid innovation in grid-balancing technologies such as efficient high-voltage cables, energy storage, and smart meters, there appear to be several radically different ways to build an electricity system that could satisfy the criterion of one hundred per cent renewables.

The actual design of a system powered by renewables remains unknown, and opinions on the direction of change differ greatly (Verbong and Geels, 2010). Some believe that the renewable electricity system will be dominated by centralised global transmission, some imagine a future of local electricity distribution, while others argue for self-sufficiency without the need for a conventional electricity grid (Battaglini et al., 2009; Funcke and Bauknecht, 2016; Khalilpour and Vassallo, 2015; Lilliestam and Hanger, 2016). As a consequence, high-voltage transmission lines are being extended to supply electricity from large-scale remote wind parks; in parallel, local communities are building self-sufficient microgrids supplied by small-scale renewables and storage. The development of a diversity of competing system designs makes policy and investment decisions increasingly uncertain.

How can we better understand the direction of the transition towards an alternative electricity system the design of which is as yet unknown? The thesis helps answer this question by using a sociotechnical systems lens to identify and describe the end states of different alternative

electricity systems. From the same sociotechnical perspective, the thesis improves the conceptualisation of how the transition towards alternative systems can be understood. The sociotechnical perspective gives us a base from which to empirically study the ongoing transition as well as to say something about how new technologies and business models are transforming the established electricity system.

## 1.1 Research aim and purpose of the thesis

The overall aim of this thesis is to explore different pathways of the electricity system transition. While there is no single comprehensive way to do this, this thesis uses a sociotechnical systems perspective to improve the understanding of two main aspects of the transition: alternative end states, and the dynamics<sup>1</sup> of the transition towards these.

The purpose of this thesis is fulfilled by answering research questions that make both empirical and conceptual contributions (Figure 1):

	Theory	Empirics
End states	<b>How can one conceptualise alternative configurations?</b> Papers I and VI	<b>What configurations are developing?</b> Paper I
Dynamics	<b>How can one conceptualise factors influencing the build-up of alternative configurations?</b> Papers II and III	<b>What is driving or hindering developments towards alternative configurations?</b> Papers II – V

**Figure 1.** Matrix of research questions and the papers that address them.

The papers presented in this thesis make partial contributions to the overall aim. Some papers focus on the conceptual framing of the empirical investigation, whereas others go more deeply into crucial aspects of the transition, such as the growth of new system structures, the importance of context, actors and their agency, and the encounter with the incumbent electricity

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<sup>1</sup> The terms dynamics of ‘transition’, ‘system change’ and ‘system build-up’ are used interchangeably throughout the thesis.

system. This thesis synthesises what we are learning as we study empirical evidence and uncover similarities, differences, and overlaps between the alternative configurations and the transition dynamics towards these.

## 1.2 Scope of the thesis

The choice of the empirical domain and conceptual starting point determined the scope of the thesis. First, the empirical domain is the global electricity sector. More specifically, this thesis considers possible ways to transform the established electricity sector so that it will be powered by renewable energy technologies. To that end, this thesis defines and explores three idealised future systems. While these systems can be theoretically defined as versions of the mainstream global electricity system at some point in the future, at present, these can only be empirically analysed as a set of local, national, or regional projects creating system prototypes. This thesis is therefore concerned with the empirical cases of technologies, actors, and institutions that emerge, accumulate and align in specific projects and experiments that are propelling the electricity system transition in the direction of a centralised, distributed<sup>2</sup>, or disconnected system.

Second, the conceptual starting point is a sociotechnical systems perspective on the electricity system in transition. While most research into the future renewable electricity system concentrates on the technical and economic aspects of the transition to it, such research often downplays the role of the sociocultural, organisational, and institutional factors that are closely linked and often pose barriers to the transformation of the electricity grid and market structures. However, the technical dimension should not be underestimated, since the changing of material systems such as electricity production and transmission is largely enabled and constrained by the physical and technical artefacts in place or under development. It is, therefore, useful to view electricity systems through the lens of sociotechnical perspectives in order to understand the co-evolution of technology and society (Bergek et al., 2008a; Carlsson and Stankiewicz, 1991; Geels, 2004). We follow previous research that treats electricity infrastructures as large sociotechnical systems that consist not only of physical artefacts, such as power plants and grid infrastructure, but equally of actors, organisations, and institutional structures that govern and maintain them (Geels, 2002; Hughes, 1987; Loorbach et al., 2010; Markard, 2011; Verbong

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<sup>2</sup>Labels ‘distributed’, ‘decentralised’ and ‘small-scale’ are used interchangeably in this research to refer to similar technologies and configurations that are small in scale and usually have a decentralised ownership.

and Geels, 2010). While numerous perspectives identify themselves as sociotechnical, we draw inspiration primarily from Large Technical Systems studies (LTS) (Hughes, 1987), the Technological Innovation Systems (TIS) approach (Bergek et al., 2008a; Hekkert et al., 2007), and the Multilevel Perspective (MLP) (Geels, 2004, 2011), which have been used specifically to analyse the emergence of innovative technologies and the transformation of large sociotechnical systems.

The scope is limited by the primary interest in the *causes* of emergence and growth of the alternative systems, rather than the *effects*. Hence, the assessment of the alternatives in terms of their actual ability to decarbonise the electricity supply, contribute to affordability, or improve accessibility is not assessed in this thesis.

### 1.3 Overview of the papers and their contributions

The thesis presents an extended summary of six appended papers. While the individual papers focus on specific questions, together they highlight different aspects of the ongoing changes in electricity systems around the world. The analyses in Papers I and VI provide conceptual and empirical contributions by defining the alternative end states as idealised technological systems and by providing methodological guidance on identifying these. Regarding the dynamics of system change, Paper VI presents a constructive critique of the TIS approach used as a theoretical lens in most of the empirical investigations in this thesis.

Paper I establishes a foundation for the consequent empirical investigations in Papers II–V. These papers analyse real-world cases that make partial contributions to our understanding of the macro- and micro-level transition dynamics in electricity sectors locally and globally. Beside empirical findings, Papers II and III make conceptual contributions to our understanding of factors that influence the build-up of alternative electricity system configurations.

### 1.4 Notes on key terminology

The terms ‘configuration’, ‘system’ and ‘technology’ are used extensively throughout the thesis and deserve some clarification. A configuration is in this thesis used to describe a collection of system elements. The configuration is a descriptive account of the system, which is defined as an interconnected set of elements that is coherently organised in a way that

achieves something (Meadows, 2008). Accordingly, a system must be constituted of three things: elements, interconnection, and a purpose. The fact that a system has a purpose does not mean that the system is ‘conscious’ or has a ‘will’; neither does it mean that the system’s elements are aware of the system’s purpose. Instead, the system’s purpose is in the eyes of the beholder. Understanding something as a system implies that an observer can identify at least one overarching purpose that ‘unifies’ the system’s elements.

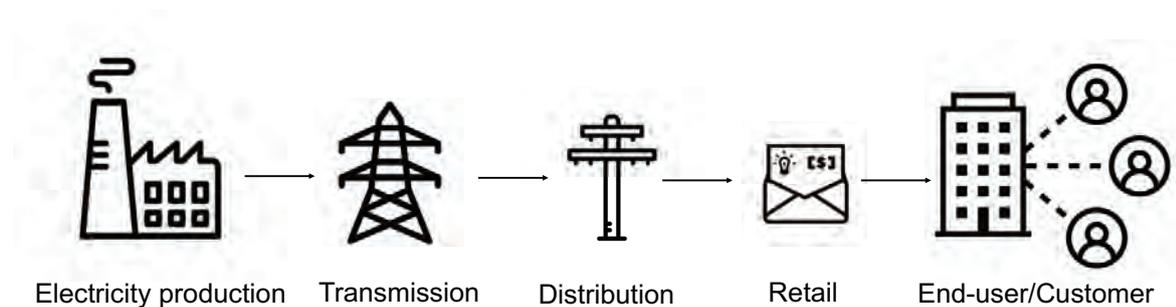
The systems studied in this thesis are oriented around activities involving developing and using new technologies for a variety of purposes. What is meant by ‘technology’ merits discussion. While the term technology is often used to refer to a tangible product such as a windmill or a PV panel, the thesis takes a broader view on technology as ‘a means to an end’, i.e. means to fulfil human purposes (Arthur, 2009). As Arthur (2009) explained, technology can be a material product, a car for example, that has a clearer purpose than does a nonmaterial technology, such as a software program, which can have multiple and changing purposes. Regardless of the nature of the technology, it organises humans and artefacts into ‘production systems’ designed to achieve its purpose. But for a technology to be perceived as a means to an end, it needs to be demanded and used. Hence, the technology is a production–consumption system in which a production system is a designed system that converts a means to an end and the consumption system makes use of the same end.

In contrast to perspectives that understand technology as a material result of the human mind or as an autonomous force controlling humans, I recognise that technology is not neutral, i.e. it is not outside human control but not completely within human control either. Following Feenberg (1991), I view technology as an ambivalent process of development suspended between different possibilities. Accordingly, technology is a double-edged sword: it is more than just human intention; rather, it has an emergent quality and impact on society beyond human control. The sociotechnical perspective applied in this thesis emphasises the embedded character of technology, which means it is not detached from politics, culture, and the organisational structure of society.



## 2 Conceptual starting points and knowledge gaps

In most places around the world, the existing electricity grid architectures have evolved since the early 1900s into centralised, hierarchical, and one-directional systems. In this dominant system model (Figure 2), the power is generated in large-scale power plants located far from the electricity demand, transmitted over long distances, then distributed and sold to the end-users and customer (Hammons, 2008).



**Figure 2.** The dominant electricity system model.

The dominant structure of the electricity system is now being challenged by the growing pressure to replace old power plants and incorporate a wide range of modular and intermittent RETs. But the push for RETs comes with new challenges caused by variable electricity production, raising the question of how to structure and operate the electricity grid to maintain its stability and reliability of supply (Hammons, 2008; Mian et al., 2017; Swedish Agency for Growth Policy Analysis, 2014; U.S. Department of Energy, 2015; Walker and Cass, 2007).

The appended papers review scholarly work addressing the electricity system transition from multiple fields and disciplinary perspectives. Together, they establish an overview of the state of the art when it comes to changes in the global electricity system and alternative end states. The appended papers show that although contributions come from many fields, the bulk of work, in absolute terms, comprises various technical or techno-economic assessments of system structures and their components (Battaglini et al., 2009; Blarke and Jenkins, 2013; Funcke and Bauknecht, 2016; Meeuwssen et al., 2008; Tröndle et al., 2020). Another prominent category of studies is positioned in various strands of economics and social science and focuses on specific market mechanisms (Castaneda et al., 2020; Nordensvärd and Urban, 2015), public policies (Sinsel et al., 2020; Xin-gang et al., 2020), and the agency of specific companies

(Boute and Willems, 2012; Sheng, 2020) and organisations that play a role in driving the transition towards an electricity system based on renewables (Lilliestam and Hanger, 2016).

Relevant contributions are also found in the literature on innovation and sustainability transitions,<sup>3</sup> which contributes sociotechnical scenarios and narratives of alternative transition pathways for electricity systems in Europe (Foxon, 2013; Verbong and Geels, 2010) as well as analyses of emerging technologies with lower environmental impact than that of established alternatives (Andersson et al., 2018; Jacobsson and Karltorp, 2013; Negro and Hekkert, 2012; Truffer, 2011; Wieczorek et al., 2013).

The research in this thesis sets its conceptual starting point in two analytical frameworks that have been applied extensively in the innovation and sustainability transitions literature,<sup>4</sup> i.e. the Multilevel Perspective (MLP) for studying sociotechnical system transitions and the Technological Innovation System (TIS) framework for analysing the emergence of novel sociotechnical systems (Köhler et al., 2019; Markard et al., 2012).

## 2.1 The innovation and sustainability transitions literature

My motivation for situating this research within the innovation and sustainability transitions literature stems from some of the *core ideas* that make this line of inquiry particularly suitable for studying change processes in the electricity sector.

1. The notion of sociotechnical systems
2. System change as a complex, co-evolutionary, nonlinear, and multi-actor process
3. The dynamic relationship between stability and change
4. The directionality of system change

To begin with, these perspectives share the ontological view of ‘sociotechnical systems’ that are constituted by physical artefacts, societal actors, and institutions that are co-dependent and

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<sup>3</sup> Scholars often refer to the innovation and sustainability transitions literature as the field of ‘Sustainability Transitions’. Here, I choose to refer to innovation and transitions literature separately since they have different intellectual roots and address different aspects of systemic change.

<sup>4</sup> Strategic Niche Management (SNM) and Transition Management (TM) are also considered founding frameworks in this field. However, the research in this thesis has not used these perspectives on sociotechnical change and has therefore excluded them from the review.

co-evolving to fulfil a societal goal (Hughes, 1987; Loorbach et al., 2010; Markard, 2011). The sociotechnical systems concept is useful for capturing the interaction between physical artefacts, networks of actors, and institutions (Geels, 2004; Sandén and Hillman, 2011) and can be particularly useful for understanding processes of fundamental change in the electricity sector (Markard, 2011). Hughes (1987) was the first to describe electricity networks as Large Technical (sociotechnical) Systems (LTS). Through studying the electricity system development in the western cities of Berlin, London, and Chicago at the beginning of the 20<sup>th</sup> century, he demonstrated how society shaped the technological design in different ways. His major insights that technological innovation cannot be understood in isolation from societal contexts (Geels, 2004; Hughes, 1987) and that *system change* unfolds as a co-evolutionary, nonlinear, and multi-actor process (Köhler et al., 2019), remain at the heart of the innovation and sustainability transitions perspectives.

While being largely inspired by Hughes' work, the analytical focus of innovation and sustainability transitions research goes beyond factors that create new systems to those that lead to the destabilisation of mature, often environmentally unsustainable systems, through the development and diffusion of new, purportedly more sustainable ones. The analytical focus of LTS research has expanded to encompass the dynamic relationship between system stability and change in analysing how technological novelties breakthrough and challenge dominant systems (Köhler et al., 2019). Both the MLP and the TIS literature highlight the dynamic relationship between the development and diffusion of innovative technologies, services, and practices (e.g. renewable energy technologies, car-pooling, or recycling practices) and the forces of path-dependence and lock-in effects in dominant systems (e.g. fossil-fuelled electricity generation, car culture, and throw-away consumption practices) (David, 1988; Unruh, 2000).

The process of analytical expansion can be attributed to the increasingly cross-disciplinary background of scholars who have borrowed and combined concepts from related disciplines. As a result, the TIS framework combines ideas from innovation system studies and industrial economics, while MLP has roots in evolutionary economics, institutional theory, and the sociology of innovation. Through interaction across disciplines, transition scholars have enriched innovation studies with the notion of normative directionality, which is the idea that innovation is not just about growing the economy, but rather about growing it in a certain, more desirable direction. The influence of transition thinking has thus contributed to a 'normative

turn' in innovation studies (Elzen et al., 2011). Accordingly, the role of innovation in systemic change is not merely to achieve faster growth in one dimension, but rather to grow to achieve a fundamental change from one sociotechnical system or dynamic equilibrium to another (Rotmans et al., 2001).

For more than two decades, the MLP and TIS literature have been evolving in close proximity. While both MLP and TIS scholars view a transition as a shift from one sociotechnical system state to another, they analyse transitions from slightly different perspectives. Put simply, MLP focuses more on the system being replaced, whereas TIS focuses on the system that is replacing. Some scholars have attempted to integrate the MLP and TIS approaches (Markard and Truffer, 2008b), but with limited success. The approaches continue to develop relatively separately, although constantly exchanging ideas and mobilising new concepts from different fields and theories to address knowledge gaps related to various aspects and sub-topics of sociotechnical transitions (Köhler et al., 2019).

The **Multilevel Perspective** focuses on how to break the lock-in of an established system structure. This perspective describes transitions as nonlinear processes that unfold through interaction among three analytical levels: regime, niche, and landscape. The mature sociotechnical system exists at the regime level, where a well-established set of institutions is shared by a large number of actors utilising 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 that trigger systemic change unfold beyond the reach of actors at the regime and niche levels (Geels, 2004, 2011). A systemic transition is deemed completed when the social, technological, institutional, and economic dimensions of the old system configuration are reorganised in a new way to fulfil its societal function. Because systemic change is a nonlinear process, it can take multiple directions, i.e. transition pathways (Foxon, 2013; Geels and Schot, 2007; Rosenbloom, 2017; Verbong and Geels, 2010), that lead to a variety of system configurations.

The **Technological Innovation Systems** approach is generally concerned with the emergence and growth of particular new technologies, products, and related industries, rather than with changes in a broader economic sector. Studies applying the TIS approach have predominantly focused on environmental technologies (Markard et al., 2012), while the approach's popularity can partly be attributed to its usefulness in identifying 'blocking factors' (Bergek et al., 2008a),

or ‘system problems’ (Negro et al., 2012), that hinder the development and diffusion of technology, thereby guiding policy interventions. The TIS approach consists of structural and functional analysis (Bergek et al., 2008a; Hekkert et al., 2007). First, technology is defined as a system composed of heterogeneous components, typically categorised as technology, actors, networks, and institutions (Bergek et al., 2008b). Second, the innovation processes, termed ‘functions’, are used to analyse the growth of the system around a particular technology. Many separate but overlapping lists of functions have been developed by TIS scholars, but most concentrate on a limited number of distinguishable processes such as the development and diffusion of knowledge, entrepreneurial experimentation, market formation, resource mobilisation, legitimation, and the direction of search processes (Bergek et al., 2008a, 2008b; Hekkert et al., 2007). Functions represent processes that support the entrance of new actors, the development of knowledge and physical artefacts, and the alignment of institutions. Accordingly, the transition is conceptualised through the endogenous process of ‘cumulative causation’, viewed as links between agency and the structural development of the new system, or as links between functions, which are organised in loops and influenced by exogenous (i.e. contextual) factors. If an important structural element (e.g. a regulation, technological component, or actor network) is missing from the system, or if an external trend or event (e.g. war or pandemic) is hindering development, the functions are weakened and the structural development will slow or stop (Hekkert et al., 2011; Hillman and Sandén, 2008).

## 2.2 Knowledge gaps

In line with the trends in the innovation and sustainability transitions literature, this work has not avoided crossing disciplinary boundaries and engaging with other perspectives, especially if these help in better addressing case-specific aspects and analytical goals. The empirics have continuously informed and shaped the development of the conceptual framing. Conceptual developments were achieved through borrowing and combining concepts and methodologies from related fields (Papers I and III), elaborating on specific aspects (Paper II), and ‘tweaking’ the original framing (Papers IV and V), which in turn improved the guidance of the empirical analysis. The appended papers together contribute to ongoing debates in the innovation and sustainability transitions literature relating to a) system definition b), alternative system end states, and c) certain dynamics that influence the transition towards these, namely, the agency of actors supporting new technologies, the role of context, and the encounter between the novel system and established structures.

The first debate concerns aspects of how systems should be defined. There is still a lack of clarity regarding what is meant by novel system structure, the components it consists of, and the purpose it fulfils. While the TIS framework has been used as a tool to identify structures that support the emergence and growth of new technologies, the existing literature provides ambiguous descriptions of a growing system being called a 'TIS'. Because the literature contains both social and sociotechnical system definitions of the system that both creates and is created in the innovation process, this can lead to analytical difficulties and confusion, especially for scholars entering the field. Although this issue has already been discussed by Markard and Truffer (2008b), subsequent TIS studies have failed to create more clarity.

Second, what is still missing is a framework for identifying the structure and components of alternative configurations, such that we can also identify the pathways leading to them. While transition scholars recognise that innovation can take different 'transition pathways' leading to different sociotechnical system configurations, these pathways were constructed to frame the process of change in a vaguely defined 'low-carbon fashion' (Rosenbloom, 2017, p.39). As a consequence, we still lack more specific descriptions of clearly distinguishable alternative end states that could all be categorised as low-carbon. Defining an analytical space of alternative configurations could complement research on transition pathways and facilitate future-oriented analysis and policy advice.

Third, multiple aspects of the dynamics of the novel system build-up have been the target of scholarly critique. In this thesis, I address some of the more articulated points of criticism, such as biased or weak conceptualisation of the geographical, sectoral, and institutional contexts of novel systems (Coenen et al., 2012; Coenen and Truffer, 2012), lack of attention to agency and micro-level processes (Alkemade et al., 2011; Farla et al., 2012; Markard and Truffer, 2008a; Musiolik et al., 2018; Planko et al., 2017), the insufficient conceptualisation of incumbent industries and their encounter with new entrants (Blanchet, 2015; Hellsmark and Hansen, 2020; Hess, 2020; Kungl and Geels, 2018; Mühlemeier, 2019), and lack of attention to user roles (Randelli and Rocchi, 2017; Schot et al., 2016; Sopjani and al, 2019; Truffer, 2003).

### **3 Research design and methods**

The research presented in this thesis applies an abductive case study approach based on qualitative data collection and analytical methods (Flyvbjerg, 2006; Yin, 2017). In line with Thomas (2011), the case study is not viewed as a research method itself, but rather as a research design frame that incorporates a number of methods selected based on the available research data (Thomas, 2011).

The choice of a case study approach in this thesis is motivated by the aim to study complex phenomena of the electricity system transition. Given the research aim, this research takes an interest in studying interesting and revealing examples, rather than a representative sample. Case studies also provide a unique opportunity for conceptual contributions through deep insight into unique and new empirical phenomena, such as real-world cases of novel technological configurations in the electricity sector.

#### **3.1 Research process and case study selection**

The reciprocal iteration between theory and empirical analysis is typical of abductive research and is also known as ‘systematic combining’ (Dubois and Gadde, 2002). It involves the constant shifting between the empirical world and its analytical representation. The appended papers, through their aims, analytical strategies, and contributions (see Table 1), together with this overarching thesis, generate a synthesis addressing the research goals and aims as formulated here.

**Table 1.** Summary of appended papers.

Paper title and type	Aims	Analytical strategies	Conceptual contributions	Empirical contributions
<p><b>I: Three electricity futures: Monitoring the emergence of alternative system architectures</b> /Empirical and conceptual study/</p>	<p>Empirical: to monitor key structural system components that support different scenarios of electricity system change. Conceptual: to develop a methodological framework for monitoring the emergence of alternative configurations based on a literature review.</p>	<p>Combine (a) concepts of ‘niche accumulation’ and ‘hybridisation’ from MLP and (b) ‘design space’ concept from scenario methodology to identify idealised system configurations that can be monitored in terms of (c) structural components from the TIS framework to identify structural overlaps.</p>	<p>The methodological framework for identifying idealised electricity system configurations.</p>	<p>Found evidence that alternative configurations are currently developing by monitoring their key components and their overlaps with the established electricity sector, other sectors, and societal trends.</p>
<p><b>II: Entrepreneurial use of context for technological system creation and expansion: The case of blockchain-based peer-to-peer electricity trading</b> /Empirical and conceptual study/</p>	<p>Empirical: to better understand the emergence and build-up of blockchain-based peer-to-peer (P2P) electricity trading (‘Smart-grid’ system) and its encounter with the incumbent sector. Conceptual: to develop and test a conceptualisation of innovation contexts and how entrepreneurs utilise them to support the new system build-up and overcome resistance from incumbent actors.</p>	<p>Apply the TIS framework to study the emergence and growth of two P2P electricity trading pilot projects.</p>	<p>A variety of the TIS framework that links a two-dimensional matrix of contexts with the role of agency.  The TIS framework applied to a case of early-stage innovation around a software-based technology.</p>	<p>Identified the importance of protective spaces combined with the destabilised position of incumbents in achieving a productive encounter between new entrants and incumbents in a new system expansion.</p>
<p><b>III: Is peer-to-peer electricity trading empowering users? Evidence on motivations and roles in a prosumer business model trial in Australia</b> /Empirical and conceptual study/</p>	<p>Empirical: to investigate the motivations and roles of users in developing P2P electricity markets. Conceptual: to construct a framework of user roles based on a literature review.</p>	<p>Define P2P electricity markets as a ‘niche business model innovation’ and use MLP to position our case study in a broader electricity system transition. Complement the transition literature with user-centred perspectives.</p>	<p>An analytical framework for analysing user roles in all phases of innovation that integrates both the system-wide and micro-level agency of users in a single framework.</p>	<p>Found that a consortium of innovators continues to treat all users as ‘consumers’ but overlooks their contribution as transition-shaping agents that can design and legitimise the novel solution.</p>
<p><b>IV: The challenge of peer-to-peer electricity trading pilots: Review of innovation systemic problems in the US and Australia</b> /Empirical case study/</p>	<p>To identify systemic problems that are experienced in P2P electricity trading pilot projects.</p>	<p>Apply the ‘scheme of systemic problems’ to two cases of P2P electricity trading pilots.</p>	<p>A scheme of systemic problems applied to real-world pilot projects.</p>	<p>Found that established market structures need to change to allow new actors to enter without depending on an incumbent. New entrants can gain institutional support and access to physical infrastructure in protective spaces and regulatory sandboxes.</p>
<p><b>V: Building a global Super-grid: A sociotechnical systems analysis</b> /Empirical case study/</p>	<p>To understand the build-up of the ‘Super-grid’ system and to identify the bottlenecks of a global-level innovation effort.</p>	<p>Apply a sociotechnical systems perspective inspired by the TIS functional approach to study Super-grid-related development globally.</p>	<p>Sociotechnical systems lens applied to a case of a hard-linked technological system with a global system boundary.</p>	<p>Found that the Super-grid is hindered by lack of consideration of the political reality of technological change, especially the nation-level path-dependency of electricity system planning and development.</p>
<p><b>VI: Clarifying the focus and improving the rigour of sustainability transitions research on emerging technologies</b> /Conceptual study/</p>	<p>To clarify the focus and improve the rigour of sustainability transitions research on emerging technologies by adopting a systems perspective on technological change.</p>	<p>Review TIS foundational papers followed by a review of all TIS literature from 2007 to 2018 to evaluate how the ‘system’ and its purpose are defined.</p>	<p>To clarify the focus and improve the rigour of the TIS approach with deductive reasoning.</p>	<p>Provided a clear methodology for improving knowledge accumulation throughout the TIS literature.</p>

Given the overall aim to study various directions the electricity system transition could take, the research process in Paper I started with ‘what could be’ based on ‘what is out there’ to identify variables of alternative configuration end states. By combining findings from a literature review with our own logical reasoning, we identified basic characteristics that distinguish alternative visions of electricity systems powered by renewables: the Super-grid, Smart-grid, and Off-grid systems. These characteristics were then turned into variables in a design space of possibilities, with idealised end states placed in its corners. Having identified the idealised forms of alternative configurations, we could better map and categorise real-world structures that support the transition towards different end states.

Findings from Paper I guided our search for empirical cases that closely resembled visions of idealised end states. In Papers II–IV, the Smart-grid system was analysed through empirical cases of two blockchain-based peer-to-peer (P2P) electricity trading pilots. The case of P2P electricity trading was found to be the closest real-world representation of the idealised Smart-grid, in which every consumption unit is also a small-scale production unit and all units interact within a perfectly interconnected grid network. With blockchain technology, P2P trading of electricity can, in theory, be operationalised without a third party or intermediary, such as an electricity retailer. These cases present unique efforts to make fundamental changes in the established electricity system architecture. The selected pilot projects were conceptualised as small technological systems studied through the lens of the TIS approach.

As is often the case in abductive research, the empirical investigation in Paper II resulted in conceptual contributions to the TIS approach, by elaborating on the role of context and agency in innovation processes. Moreover, the data collection for Paper II also motivated further empirical investigation of blockchain-based P2P electricity trading. Papers III and IV are directly connected to Paper II in that they use data from the same empirical cases, and as such improve our understanding of the build-up dynamics of the Smart-grid system. Paper III applies a user-focused analytical lens, while Paper IV analyses P2P electricity trading pilots in terms of the ‘scheme of systemic problems’ (Negro et al., 2012).

The empirical investigations in Papers II–IV also shaped my understanding of the TIS framework, leading to contributions to Paper VI, which sharpened the analytical space of the three alternative end states.

After intense research on the Smart-grid system, I decided to analyse the dynamics leading towards the Super-grid system in Paper V. The Super-grid is empirically represented by the case of a high-voltage transmission-enabled global electricity grid that connects remote large-scale production units with consumers over long distances. While the global-scale Super-grid exists only as a vision, there are several regional and continental Super-grid case studies. The decision to conduct a case study of the idealised Super-grid might appear unconventional as it builds on multiple smaller cases viewed as a part of the bigger case. As a result, this study analyses and contrasts many cases at smaller geographical levels to draw conclusions about the global Super-grid. The advantage of such a case study design is that by analysing many cases, we can see to what extent continental and regional Super-grids differ or relate to one another, and also how they relate to the vision of the global Super-grid. As in Paper II, case studies were analysed as technological systems through the lens of the TIS approach.

The decision to study the Super-grid rather than the Off-grid system was influenced by my previous interaction with advocates of the Super-grid vision and by the relatively easy access to relevant publicly available data. Due to the limited timeframe of the PhD process, a separate study of Off-grid-related dynamics is not included in this thesis.

### 3.2 Data collection

The research in this thesis is informed mainly by qualitative data sources. Qualitative data collection methods were chosen given our interest in complex and emerging social phenomena, which are difficult to measure or count. It should also be noted that the data collection was limited by time, resources, and access to relevant data sources. While all the papers appended to this thesis are mostly qualitative in nature and contribute to the same overarching research aim, they differ in the type of analysis, system boundaries, data collection techniques, and data sources.

Before elaborating on individual papers, I would like to briefly reflect on the limitations of qualitative data collection methods. Qualitative data collection has been criticised for lack of rigour, lack of strict guidelines, the possibility of altering data to prove a point, and the influence of the researcher's subjective bias (Brinkman and Kvale, 2015; Kvale, 1994). I have used strategies to address inherent subjectivity and minimise bias in my research, primarily by triangulating between various data sources, such as semi-structured interviews, field

observations, and secondary documents. To mitigate the influence of my own bias, I have continuously discussed the findings from my data with fellow researchers.

## **Paper I**

This study is designed to use historical and current data to describe and present a foresight of alternative electricity systems. The analytical boundaries are set around the sociotechnical components along with the whole electricity production–consumption chain. The spatial boundaries are set at the global scale. In terms of the temporal boundaries, the study captures data from the period between 2000 and 2016. The data for Paper I were collected from secondary data sources, including scientific literature, websites, reports, newspaper articles, and online datasets. The data were collected in two steps. First, alternative configurations were identified in a literature review. To improve the conceptual clarity of the visions articulated in the literature, we constructed a ‘design space’ to clearly distinguish between idealised versions of the alternatives. We conceptualised alternative visions as sociotechnical configurations that comprise physical artefacts, actors, and institutions. In the second step, we used the design space to search for additional data on various websites, industry reports, newspaper articles, and online databases.

## **Paper II**

Paper II presents a study that aims to understand innovation dynamics, in order to inform relevant stakeholders and other similar cases. The analytical boundaries of this study are set around those technological components that are part of the production–consumption chain of blockchain-based technology for P2P electricity trading. Spatially, the analytical boundaries are not predefined, but rather change across spatial scales. We set the starting point at local-level development projects, the Brooklyn Microgrid (BMG) and the White Gum Valley project (WGV), but we include factors from other spatial levels to improve our understanding of system build-up at the local level. From a temporal perspective, we capture data between 2016 and 2018. The data for this study were gathered via semi-structured interviews, participatory observations, and desktop research. Semi-structured interviews were chosen as a primary data source to ensure good control over the relevance and quality of the data, which is not always possible when dealing with secondary data such as documents, reports, and statistics (Karlsson et al., 2011). In total, 28 semi-structured interviews, 14 from each case, 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 reflects the limited time in the field and the accessibility of 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.

### **Paper III**

Similar to Paper II on which this study builds, Paper III is designed to explain and evaluate the role of users in Smart-grid system build-up, in order to inform relevant stakeholders. Compared with Paper II, this study is designed as a single-case study seeking in-depth findings about a specific case rather than making comparisons with another case. Analytical boundaries are set around the RENEW Nexus pilot project in Fremantle, Western Australia, which also sets the spatial boundaries of the study. From a temporal perspective, it is worth noting that this project is a continuation of the WGV project (Paper II), which started in a small housing development but expanded to the city level. The study captures data from 2018 to 2019. Data for this study were collected in three separate rounds, using mixed-methods including surveys and group discussions with self-nominated participants. Both the surveys and focus group discussions were developed to test the analytical framing of the study, initially inspired by Schot et al. (2016). The reason for relying on primary data sources lies in the lack of secondary data about the user perspective on P2P electricity trading in similar projects.

### **Paper IV**

Paper IV is designed to evaluate P2P electricity trading pilots, in order to identify current weaknesses of the Smart-grid system and advise policymakers and industry actors. The study evaluates multiple cases, using data gathered for Papers II and III. The analytical boundaries are set around the blockchain-based P2P trials analysed in Papers II and III. The geographical locations of these projects also set the spatial boundaries of the study. The temporal boundaries are set to the years 2016–2019.

### **Paper V**

This paper’s analysis evaluates historical developments to identify the strengths and weaknesses of Super-grid system build-up in order to advise policy and industry actors about the barriers that impede its ongoing development. The analytical boundaries are set around the production–consumption chain involved in building and implementing high-voltage transmission connections between the production and consumption of electricity. Spatially, our

primary scale of interest is the global one but, as mentioned earlier, we also consider developments at smaller geographical scales that are conceptualised as sub-systems growing towards the global system. In terms of time, the study captures data from the 1920s up to the beginning of 2020. Data for this study were collected via semi-structured interviews, participatory observations, and desktop and document analysis. During 2019, 15 semi-structured interviews were conducted with transmission industry experts from leading companies, researchers, and representatives of transnational industry organisations. The interview questions were structured to assess expert opinions about what drives and hinders the development of long-distance transmission construction and integration.

## **Paper VI**

This study is a theoretical and methodological contribution, representing an attempt to strengthen the original TIS approach. The paper first reviewed existing TIS literature by using both qualitative and quantitative review techniques. A qualitative analysis of the most-cited ‘foundational’ papers was performed by a co-author, followed by a quantitative review of 159 publications, by counting and categorising publications based on their TIS definitions. While counting of social and sociotechnical system structure definitions was possible, it proved to be more challenging when it came to system purpose, which led us to collect clear examples of diverging definitions. This paper aims to build a TIS model deductively, starting from first principles and logical reasoning, in contrast to the original TIS approach, which was developed inductively through an extensive literature review.



## 4 Results

Given the purpose of this research, the papers presented in this thesis address different aspects of the electricity system transition: the alternative end states, and the dynamics of their build-up. Accordingly, our results are divided into two parts. First, Papers I and VI present conceptual and empirical results about future electricity system end states. Second, Papers II and III present conceptual findings about the dynamics that influence the development of alternative futures, whereas Papers II–V contribute empirical findings about what drives and hinders the development in a specific direction.

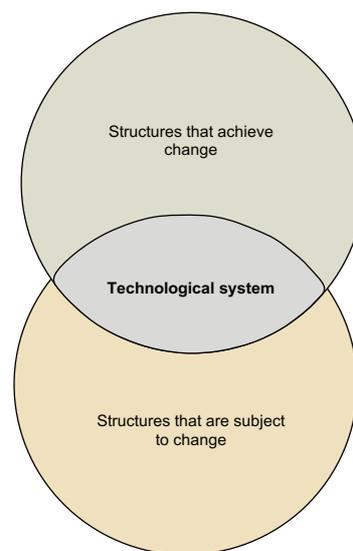
### 4.1 Identifying alternative electricity system end states

The first research question to answer is conceptual: *How can one conceptualise alternative electricity system configurations?*

While Paper VI, ‘Clarifying the focus and improving the rigour of sustainability transitions research on emerging technologies’, is our latest contribution, it is the product of years of work with the innovation and sustainability transitions literature and contributes important reflections on the analytical starting points of this research. The paper builds on the literature review that indicates persistent ambiguities in how the ‘system’ is defined in terms of its structural elements and purpose. The literature defines systems as composed of social structures only, or of both social and material structures. Given these ambiguities, Paper VI argues for a sociotechnical system structure in order to analytically capture how technical artefacts are not only created through the interaction of actors but also enable and constrain their actions. In relation to the research aim, conceptually clarifying what is included in the system structure of the alternative configurations is necessary in order to then monitor the build-up process empirically.

Moreover, as the literature review in Paper VI shows, the system definitions presented in the literature are often sufficiently vague to allow for two interpretations: one that views the system as an entity that *achieves change* through innovation activities, and another that also includes the production and consumption activities that are *subject to change*. Paper VI argues that the system purpose that unites the analysis of sociotechnical components should be centred on the purpose of the technology in focus, including all structures that can be considered ‘specific’ to this technology. A technology-centred perspective implies that the analytical system boundary

ought to include structures that perform production and consumption activities as well as structures that both influence and are influenced by innovation activities (Figure 3). Here, we call the technology-specific system a ‘technological system’ (TS), inspired by Hughes (1987) and Hillman and Sandén (2008). The TS is used as a specific label of a sociotechnical system that takes its starting point in a certain technology.<sup>5</sup> We reserve the term ‘technological innovation system’ (TIS) for the theoretical model that describes the emergence, development, and diffusion of a technological system, and not the technological system itself.



**Figure 3.** Simplified illustration of the technological system.

This main result of Paper VI is the system definition that is adopted in this thesis:

*A technological system is a set of social and technical structures, that perform the function of a specific technology, and that exist in a given spatial region and time period.*

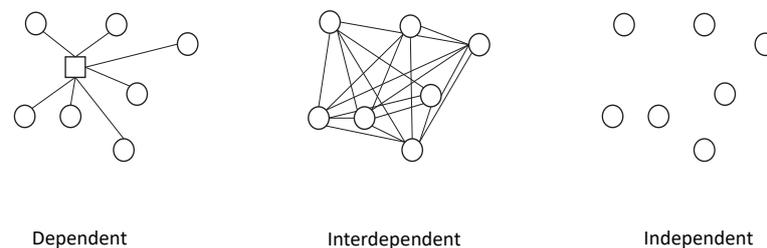
While Paper VI guides our thinking about electricity system alternatives in terms of ‘technological systems’, Paper I makes a conceptual contribution to the existing knowledge by proposing the construction of an analytical map, or a ‘design space’, that guides the identification of idealised versions of technological systems.

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<sup>5</sup> Another option is arguably to use the term ‘sociotechnical system’, which probably has a similar meaning for many scholars. In our view, sociotechnical system is a more general concept that can be analysed in different ways. The label ‘technological system’ should not be confused with technical system, which is composed only of the material structures.

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. However, given the inherently complex and uncertain nature of any transition, involving wicked problems that cannot be addressed by a set of well-defined solutions, sociotechnical system perspectives are seldom used for prospective analyses (Andersson and Törnberg, 2016). In Paper I, ‘Three electricity futures: Monitoring the emergence of alternative system architectures’, sociotechnical transition thinking is combined with scenario methodology to explore what the future of an electricity system built around renewables could look like. By borrowing ideas from scenario-making methodology, Paper I identifies in two steps a number of clearly distinguishable technological system configurations (Börjeson et al., 2006).

First, a literature review reveals that *the level and type of interconnectedness* can be decisive in differentiating among systems of dependent, interdependent, and independent electricity consumers (Figure 4), corresponding to visions of the Super-grid, Smart-grid, and Off-grid systems articulated in the literature (see Figure 5).



**Figure 4.** Alternative system configurations of electricity consumers based on the level and type of system interconnectedness, representing the Super-grid, Smart-grid, and Off-grid scenarios.

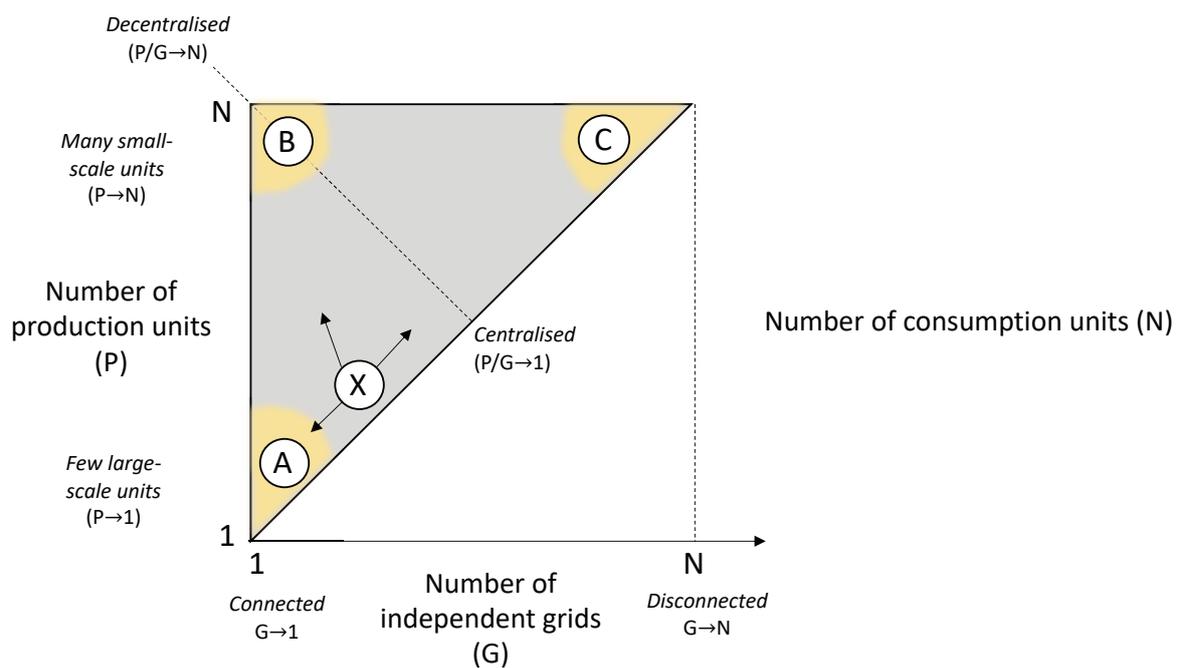
In the second step, the literature findings are used to define the Super-grid, Smart-grid, and Off-grid systems in their idealised forms, each of which could become the end state of a global electricity system powered entirely with renewable energy technologies.

The ‘design space’ of possible configurations is the main contribution of Paper I (see Figure 5). Taking the technology-centred perspective (Paper VI), the design space is constructed around two variables,<sup>6</sup> i.e. the number of production units (P) and the number of independent

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<sup>6</sup> These variables resulted from our reflections on what defines the electricity system. Production units, number of grids, and number of consumers worked well to differentiate between systems of complete dependence, interdependence, and independence. However, we are aware that these variables only describe system design in

grids (G) globally, related to a constant, which is the number of electricity consumers<sup>7</sup> The three alternative systems identified in the literature (Figure 4) can be positioned at the corners of the design space (illustrated by the yellow corners in Figure 5), representing their idealised forms. If we assume that the number of production units does not exceed the number of consumption units, any system configuration can be positioned within the design space (illustrated by the grey triangle in Figure 5). A rough estimate of the position of the current electricity system configuration dominated by centralised national grids is represented by X.



**Figure 5.** The design space of future alternative electricity systems.

The extreme form of a dependent system, the Super-grid (A), represents a step from the current system towards a system with only one centralised production unit in one global grid. All consumers are dependent on this one production unit. The extreme Smart-grid (B) configuration also has maximum global connectedness but has as many production units as consumption units. Every consumer is also a producer, i.e. a ‘prosumer’, and they are all interdependent. The extreme Off-grid (C) system is a completely disconnected system having as many independent grids as production and consumption units, and every consumer is

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the technical dimension, and to some extent in the spatial dimension, but not in the institutional and organisational dimension, which would include varieties of ownership and operation.

<sup>7</sup> While the analytical focus is often on electricity market players such as energy companies and governments, electricity consumers seldom serve as a starting point. However, electricity consumers are the constant in the electricity sector, because without them the electricity system has no purpose.

independent. The idealised Super-grid and Off-grid scenarios have one attribute in common, that is, centralisation, i.e. each independent grid is hierarchically organised around one production unit ( $P/G = 1$ ). The idealised Smart-grid scenario represents a grid that provides an ‘ideal market’ for all the production units with no hierarchy or top–down control.

An important contribution of the design space of idealised possibilities is that it allows for an empirical investigation not limited by currently dominant market structures, technological trends, or political discourses. Hence, Paper I also makes an empirical contribution to the research aim, by answering the question *What electricity system configurations are developing?*

Based on the literature review, Paper I includes an empirical mapping of the components associated with these three end states that currently exist (Table 2).

**Table 2.** Sociotechnical components of the three idealized technological systems that currently exist.

	<b>Super-grid</b>	<b>Smart-grid</b>	<b>Off-grid</b>
<b>Key technical components</b>	<ul style="list-style-type: none"> <li>• Large-scale RET parks and plants</li> <li>• HVDC cables</li> <li>• Voltage source converters</li> <li>• Large-scale storage</li> </ul>	<ul style="list-style-type: none"> <li>• Small-scale RE technology</li> <li>• Flexible AC networks</li> <li>• ICT, smart metering, smart sensors</li> <li>• Small-scale storage</li> <li>• Electric vehicles</li> </ul>	<ul style="list-style-type: none"> <li>• Small-scale RE technology</li> <li>• Small-scale storage</li> <li>• Microgrids</li> </ul>
<b>Main actors</b>	<ul style="list-style-type: none"> <li>• National governments &amp; international organizations</li> <li>• Transmission System Operators</li> <li>• Large, often state-owned vertically integrated utility companies</li> <li>• Incumbent power system companies</li> </ul>	<ul style="list-style-type: none"> <li>• Regional &amp; national governments</li> <li>• Distribution System Operators</li> <li>• Incumbent firms and new entrants from other sectors (ICT, automotive sector)</li> <li>• Prosumers</li> </ul>	<ul style="list-style-type: none"> <li>• Prosumers</li> <li>• Private device developers and maintenance providers</li> </ul>
<b>Supporting institutions</b>	<ul style="list-style-type: none"> <li>• Collaboration and harmonization between governmental, regional, international projects</li> <li>• Multilateral agreements</li> <li>• Tenders</li> <li>• Vision statements, roadmaps</li> </ul>	<ul style="list-style-type: none"> <li>• Collaboration along new supply chains</li> <li>• Standardization</li> <li>• Feed-in-tariffs</li> <li>• Expectations translated into demonstration projects</li> </ul>	<ul style="list-style-type: none"> <li>• Mistrust in the existing electricity market actors</li> <li>• Norms related to independence, self-sufficiency or direct contribution to climate neutrality</li> <li>• Innovative practices for financing (microfinance, pay-as-you-go)</li> </ul>

Through the process of structural monitoring, we found that having comprehensive sets of sociotechnical components can also provide insights into how these alternative futures relate to the incumbent electricity system, other sectors, and trends. Paper I finds that the ‘Super-grid’ system develops close to the existing electricity system, predominantly encompassing hybridization processes. The ‘Smart-grid’ scenario seems to be emerging as a combination of hybridization and niche accumulation processes bringing the dominant electricity sector together with niche developments, mostly in other sectors. The Off-grid system is a clear example of niche accumulation as it develops away from the existing electricity sector. Consequently, the transition towards the Off-grid system involves leaving the conventional electricity grid and related markets.

The key result reported in Paper I is the evidence that the idealised future systems have gathered momentum over the last fifteen years through the development of new technologies, actors, and institutions and by creating links to and borrowing from other sectors, discourses, and societal trends. Paper I concludes that to improve our understanding of the direction in which the transition will develop, each direction needs to be further studied to understand the processes that support or hinder the success of the specific alternatives.

#### 4.2 Factors influencing the build-up of alternative technological systems

Defining the idealised future alternatives and each one’s system structure is only a first step. The next step is to study the emergence and growth of alternative technological systems in order to uncover what enables or hinders the transition towards a specific configuration. Here, Papers II and III make conceptual contributions.

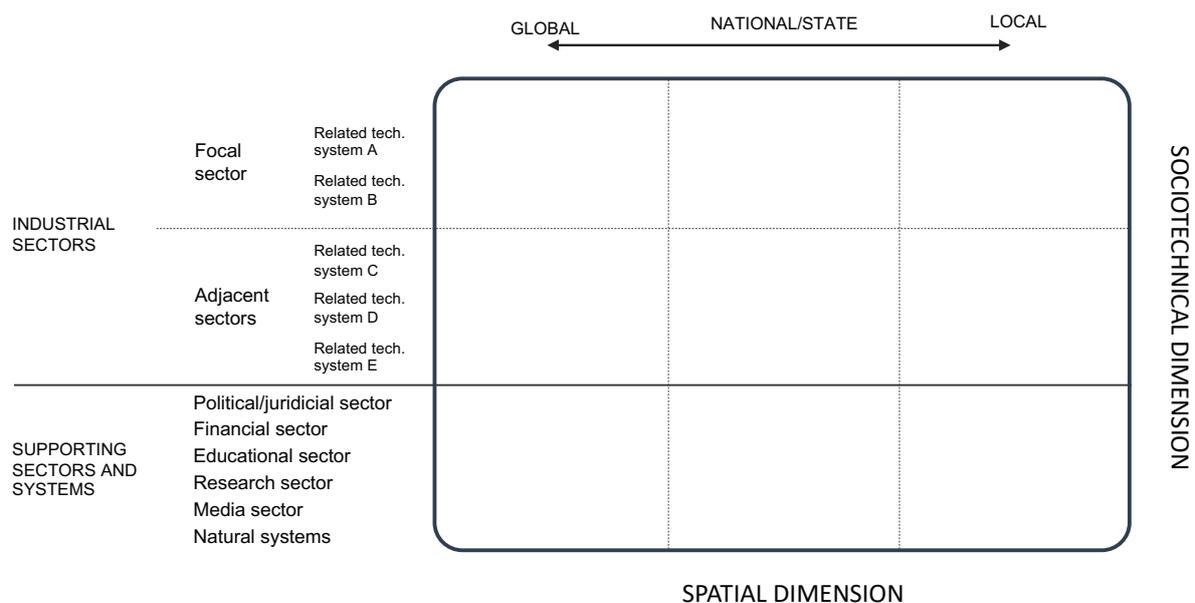
The research question answered here is: *How can one conceptualise factors influencing the build-up of alternative electricity system configurations?*

Paper II, ‘Entrepreneurial use of context for technological system creation and expansion: The case of blockchain-based peer-to-peer electricity trading’, contributes by improving our conceptualisation of context, entrepreneurial agency, and the encounter between established actors and new entrants in an elaborated version of the TIS approach. Paper III, ‘Is peer-to-peer electricity trading empowering users? Evidence on motivations and roles in a prosumer

business model trial in Australia’, provides a comprehensive framework of user roles in the novel system build-up.

#### 4.2.1 The role of contextual factors in the system build-up

The investigation of early-stage P2P electricity trading projects in Paper II reveals that the external environment, or context, is crucial for the prospects of a novel system. This is because immature systems are heavily dependent on contextual factors, as their internal structure has not yet developed and provides only weak support. However, in the literature review, we find that existing definitions differ in their assumptions and boundary setting, with the resulting analytical biases often receiving criticism. Hence, a key contribution of Paper II is a two-dimensional matrix that systematises what can be considered context (Figure 6). This matrix permits analytical and empirical richness, encouraging explorative framings rather than a priori assumptions about what contextual factors matter for the growth of a new technological system.



**Figure 6.** The two-dimensional matrix of contexts of the focal technological system. Contextual factors supporting or blocking the focal technological system can be located in any part of the matrix, for example, in the local focal industry sector or the global financial sector.

As illustrated in Figure 6, there are two main ways in which the wider innovation system literature conceptualizes context. First, there is the *spatial dimension* of the context, in which contextual factors reside at a certain level along a spatial scale, resulting in differentiation between factors from the local to global, with many possible relevant levels in between; for simplicity, these are visualized in Figure 6 as the local, national, and global levels. Second,

factors can be positioned along a *sociotechnical dimension* of the context, resulting in differentiation between industrial sectors and supporting sectors and systems. Industrial sectors are subdivided into a focal industrial sector and adjacent industrial sectors. These can be further subdivided into more narrowly defined technological systems to enable visualisation of the influence of specific related technological systems on the focal system. Similarly, supporting sectors and systems can be subdivided into more specific categories (e.g. political/juridical, financial, educational, research, media, and natural systems). Note that these do not necessarily only support the development of the novel configuration but may also host blocking factors. The matrix in Figure 6 emphasises that spatial factors crosscut the sociotechnical dimensions of the context. For example, the housing sector and political/juridical systems also have a spatial dimension, as they can range from local to global.

#### 4.2.2 *Entrepreneurial agency in novel system build-up*

In addition to the important role of the context, the entrepreneurial agency<sup>8</sup> seems particularly important when considering innovation processes at the level of local demonstration projects, where the role of individual actors in utilizing available resources and mobilizing collective action becomes apparent. Based on the insight from the empirical cases, we confirm the observations of Planko et al. (2017) that entrepreneurs enact substantial agency through their strategic actions in the early phases of system build-up when only a few actors are involved.

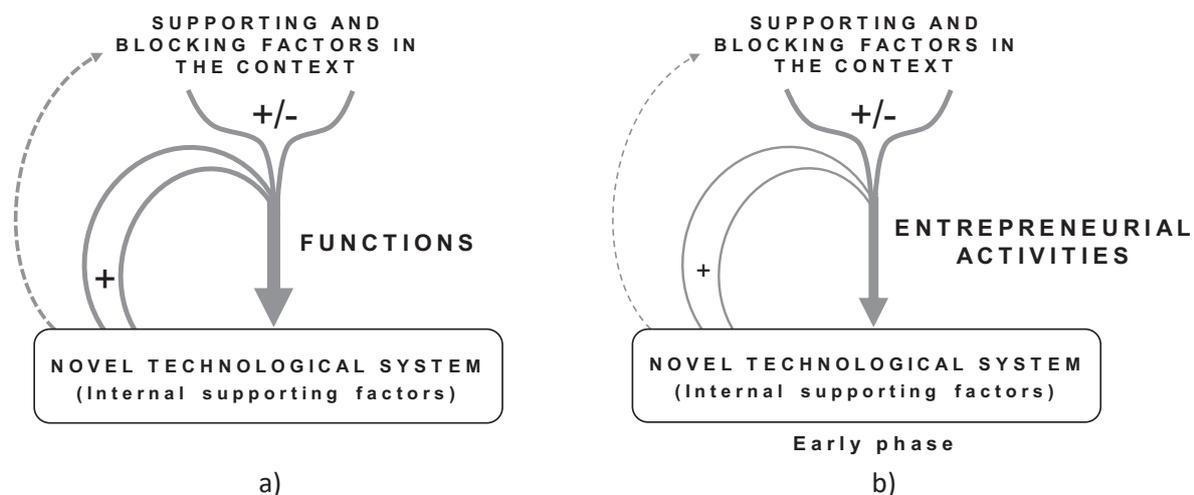
The important role of entrepreneurs is reflected in the ‘entrepreneurial experimentation’ (Bergek et al., 2008a) or ‘entrepreneurial activities’ functions (Hekkert et al., 2011) of the TIS approach. Yet, the presence of this function is usually measured quantitatively by counting the number of involved entrepreneurs (i.e. firms) (Bergek et al., 2008a; Hekkert et al., 2007). The number of entrepreneurs can arguably be an important indicator of novel system growth, but the micro-level foundation of entrepreneurial agency in mobilising collective action remains weak in the TIS approach (Alkemade et al., 2011). The micro-level role of entrepreneurs in innovation, especially their strategies to grasp new opportunities to initiate system building, has been extensively discussed in the broader field of entrepreneurship studies (Baker and Nelson, 2005; Gartner, 1988; Ghezzi, 2019; Sarasvathy, 2007; Sarasvathy, 2001; Shane, 2000;

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<sup>8</sup> The concept of ‘entrepreneurs’ is limited to the founders of start-ups or the managers of large firms. Entrepreneurs are understood in a broader sense as individuals who see and pursue new opportunities in the expectation of future rewards (monetary or non-monetary). Entrepreneurs can exist inside private firms, governmental departments, research institutions, and trade associations (Van de Ven, 1993).

Shane and Venkataraman, 2000) that, like the TIS approach, build on the Schumpeterian notion of ‘innovators’ (Schumpeter, 1942). However, the entrepreneurship literature is seldom acknowledged in the TIS literature, indicating that there is a clear knowledge gap to be addressed.

To address the lack of micro-level processes in the TIS approach, we propose to conceptualise entrepreneurs as agents that embody all functions (Figure 7a), as they use supporting internal and external factors in building the system while being hindered by blocking factors (Figure 7b). In doing so, we can study how entrepreneurs combine novel system-internal resources (e.g. new novel technological knowledge) with external means and opportunities (e.g. open-source software-based crowdfunding) across spatial and sociotechnical contexts (Figure 6) in the effort to build a new system and counteract negative influences (i.e. blocking factors) in the context.



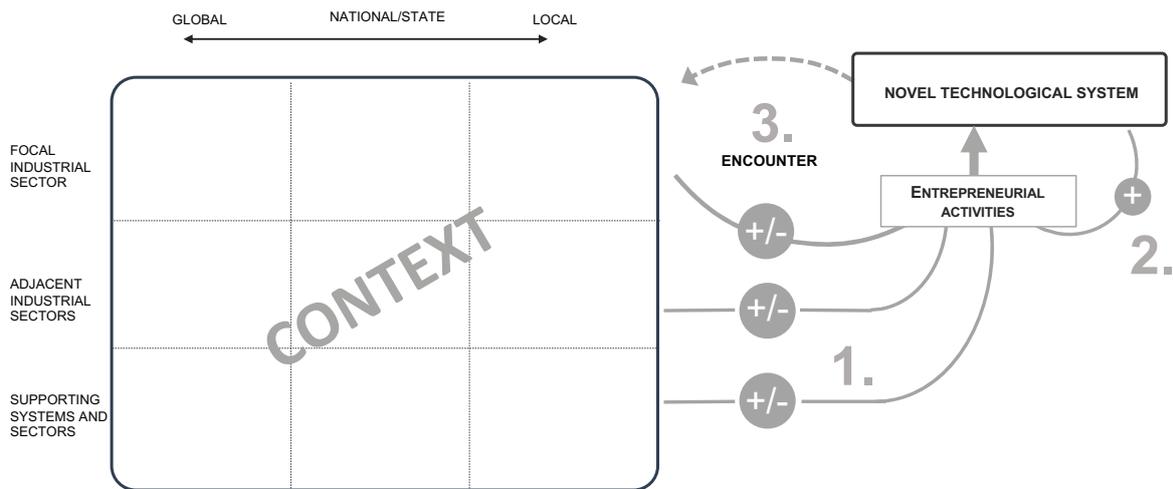
**Figure 7.** Systemic visualisations of technological system build-up: a) the system-building processes are conceptualised as functions (arrow) whose strengths (arrow width) are influenced by internal and contextual factors (based on Bergek et al., 2008b; Hillman and Sandén, 2008); b) in immature systems (early phase), the functions can be interpreted as micro-level entrepreneurial activities, i.e. agency in building the novel system by utilizing supporting contextual factors and (initially weak) internal factors (thin lines), while counteracting blocking contextual factors. The visualisations also include a dotted line depicting the potential influence of the system on some part of the context, which may in turn influence the system (bidirectionality).

### 4.2.3 *The encounter with the established system*

The analysis in Paper II reveals that the conceptual link between the context and entrepreneurial agency in the novel system build-up process is incomplete without a discussion of the encounter with the established system. The importance of dedicated system builders in challenging established systems and overcoming system lock-in (Unruh, 2000) has always been a central theme in the innovation and sustainability transitions literature (Carlsson and Stankiewicz, 1991; Geels, 2014). However, the literature on sociotechnical change has typically limited our understanding of the incumbents as resistant actors trying to prevent transition (Geels et al., 2017; Lauber et al., 2016). Such a conceptualisation is being scrutinised by recent studies demonstrating that incumbent actors can change their activities to take part in supporting new technological solutions (Berggren et al., 2015; Wassermann et al., 2015).

In Paper II, we move away from a view of the encounter as a conflict between resistant incumbents and challenging actors (Wassermann et al., 2015) and suggest that encounters are more complex – that is, encounters tend to have ambiguous effects on the development of new technological systems. We draw on ideas regarding the exercise of power to describe these encounters as *productive* in how they enable action or *repressive* in how they block or hinder it (Ahlborg, 2017; Lukes, 2005). Encounters may be productive in generating strategic responses, causing the emergence of new relations and processes, creating multiple positive and negative outcomes. In contrast, repressive encounters are characterized by eliminated possibilities, stalemates, actor incapacitation, and innovation processes being blocked from continuing. This dichotomy allows us to explore more freely how the encounter comes about and how it changes over time. Because early-stage innovation is more sensitive to its approximate local environment, we argue that the encounter with the incumbents in the focal sector is particularly decisive for early-stage innovation processes.

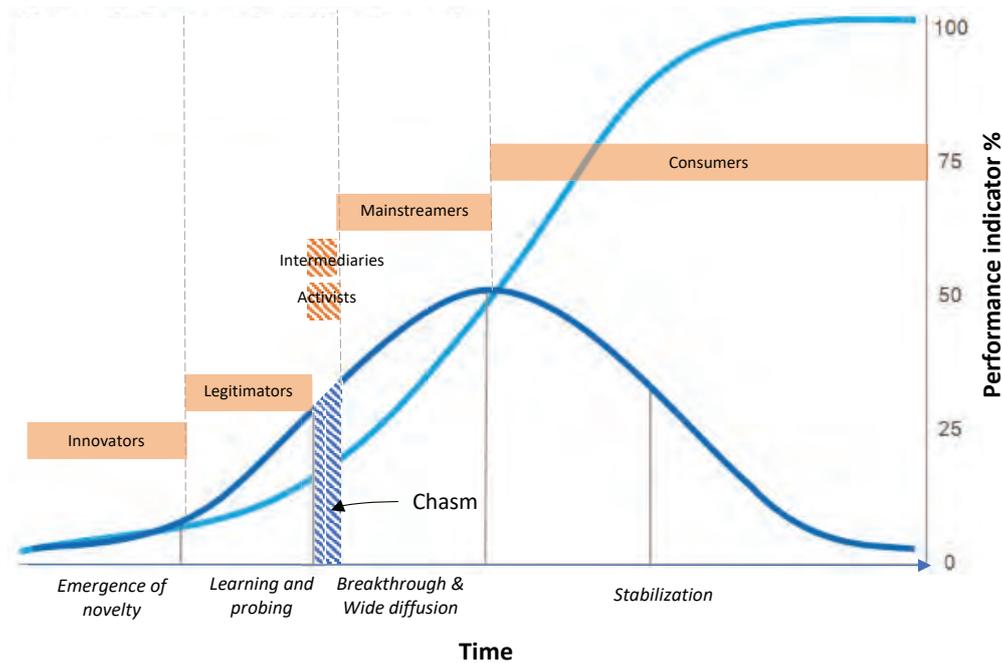
The improved conceptualisations of the context, agency, and the encounter in early-stage innovation are linked in one analytical framework (Figure 8) introduced in Paper II.



**Figure 8.** This analytical framework captures (1) the origins of various contextual factors that influence system build-up (+/-), the positive ones being opportunities used by entrepreneurs to develop the system structure, thus (2) creating an internal positive feedback loop that enhances entrepreneurial capabilities. These interactions shape the encounter (3) between the novel system and the focal sector, as well as how entrepreneurs and incumbents respond to this encounter, with implications for further development.

#### 4.2.4 User roles in innovation

Most innovation and sustainability transition studies on the emergence of renewable energy technologies have emphasised the supply side, i.e. renewable energy production, for which consumer preferences and practices play an arguably small role. However, with the digitalisation of the electricity sector and the growing importance of demand-side flexibility, end-users are more actively participating in shaping the energy transition (Planko et al., 2017; Randelli and Rocchi, 2017). Innovation and transition scholars have started paying more attention to the consumer side, involving users as important system builders throughout the innovation process, from the development of niche market ideas to adopting niche innovations in everyday practices (Randelli and Rocchi, 2017; Schot et al., 2016; Sopjani and al, 2019). Paper III contributes to the literature by synthesising the transition and innovation diffusion literature within a single framework (Figure 9). In this analytical framework, user typologies are plotted along an S-curve, representing user contributions to technological growth and systemic change (Schot et al., 2016), and along a diffusion of innovation bell curve, illustrating the roles of users in influencing their peers in the innovation process (Rogers, 2003). The framework also includes specific roles important in crossing the ‘chasm’ (Moore, 2014) to account for the fact that the technological innovation and diffusion process is not always as straightforward as the S-curve and bell-curve models depict.



**Figure 9.** User roles (graph labels) across four phases of innovation (x-axis labels). This shows the innovation phase in which each user type is most active. This includes the chasm that must be crossed to move from learning and probing to breakthrough and wide diffusion with the assistance of user-intermediaries and activists.

The value of this framework lies in demonstrating that in the early phases of the innovation process, users should not be treated as passive ‘consumers’ of a product. Instead, they can play an important role in co-designing and legitimizing immature technologies, improving their chances of breaking through from niche to mainstream applications (Figure 9). The analytical framework developed in Paper III can help relevant stakeholders know when to create complementary relationships, for example, between users and entrepreneurs. Also, it can help entrepreneurs know how to induce users to support their technological novelty, depending on the innovation phase.

#### 4.3 Drivers and barriers in the development towards future end states

Given the improved conceptualisation of how novel technological systems emerge and expand, and of how system growth is influenced by the context and agency of various actors, Papers II–V provide rich empirical findings about the drivers of and barriers to developing alternative electricity system configurations. A synthesis of the results of Papers II–IV presents findings about the Smart-grid system, whereas Paper V presents findings about the development of the Super-grid system.

The research question to be answered here is *What is driving or hindering developments towards specific alternative electricity system configurations?*

Overall, the results of Papers II–IV suggest that new technological solutions and ideas for interconnecting small-scale RETs in a Smart-grid configuration are often not endemic to the electricity sector, but rather are brought in by incumbents and new firms from other sectors, such as the ICT, finance, and residential building sectors. The role of new entrants lies in borrowing new ideas and institutional support from other sectors, to eliminate their dependence on public support and established value chains to materialise the new system. Because these solutions, illustrated by the case of blockchain-based P2P electricity trading, are seldom compatible with the established electricity system in terms of both the physical grid and market structures, they rarely receive initial support from public policy. Our analysis shows that innovation policies are designed to support the diffusion of distributed RETs (e.g. rooftop solar PV) and grid solutions (e.g. islanded microgrids and batteries)<sup>9</sup>, yet tend to keep the established market structures intact and incumbent actors in charge of steering the innovation process. Consequently, established utilities have the ability to resist innovations that could compromise their dominant position.

Innovative entrepreneurs are thus forced to find new ways to enable the implementation of their solutions, for example, in protective ‘behind-the-meter’ spaces created through collaboration with actors in other sectors. The findings of Papers II and IV highlight the crucial role of protective spaces, not only to shield the novelty from the resistance of dominant actors, but also for accessing key physical infrastructure, establishing new market relations, and trialling new business models.

Paper II demonstrates that ambitious entrepreneurs play a crucial role in navigating uncertain institutional conditions. What is more, entrepreneurs have been found to play a crucial role in finding opportunities outside the proximate local industrial sector and in gaining support from the global level, either to stimulate local support or compensate for the lack of it. Such local–global entrepreneurial activities, for example, seeking collaborations with incumbents

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<sup>9</sup> Small-scale technologies that can use, produce, store electricity or can form a part of the distribution network are collectively referred to as ‘distributed energy resources’ (DER). These can be rooftop solar PV, batteries, virtual market platforms, microgrids, and EVs among others.

elsewhere or mobilising financial support from transnational companies, were driving the local system build-up in both studied P2P electricity trading models. The entrepreneurs, therefore, had a competitive advantage in that they, unlike the local incumbent actors, were not tied to a local physical and institutional infrastructure and had no established role to uphold, making them more flexible and spatially fluent system builders.

In terms of the encounter between new entrants and incumbents, protective spaces with local–global support networks are not always sufficient to achieve a productive encounter with the incumbents, to influence the transformation of the local electricity sector. As our cases demonstrate, in places in which small-scale residential PV and battery systems have caused systemic issues, such as grid defection, duck curves,<sup>10</sup> and negative electricity prices,<sup>11</sup> local incumbents were forced to rethink part of their operational model and engage with radically different entrepreneurial ideas. Somewhat destabilized and unprotected (Karlton and Sandén, 2012), they saw value in the P2P electricity trading innovation despite its potentially disruptive potential.

Another finding is that entrepreneurs failed to include actors at the consumption side in the system-building process. The analysis in Paper III illustrates how the actor consortium leading the P2P electricity trading project treated electricity users as mere passive consumers of a new technological solution. While we found that users, in that case, expressed interest in influencing the project design such that it would better reflect local opportunities and needs, the actor consortium continued to treat users as passive consumers, leading to user disappointment and high drop-out rates. We found that in the case of P2P electricity trading, the project consortium missed a unique opportunity to include users as innovators and legitimators, which could have facilitated learning processes, embedded the innovation locally, and raised expectations directly related to local issues. Paper III concludes that if P2P electricity trading, which depends on the active participation of small-scale prosumers and consumers, is to grow and diffuse, it should not be created *for users*, but rather *with users* in order to avoid unexpected trade-offs for the local community, and loss of user demand.

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<sup>10</sup> This is an electricity demand curve phenomenon first identified by the California Independent System Operator in 2013. The duck curve is created through increasing rooftop solar PV production during daylight hours, minimising the need to produce electricity for the network. When the sun goes down, however, which is also when people return home, the network demand begins to peak. The duck curve leads to operational planning difficulties and reduced grid reliability.

<sup>11</sup> Negative electricity prices occur when the demand for network-provided electricity drops to such an extent that the supplier needs to pay the market to take the electricity away.

Paper V, ‘Building a global Super-grid: A sociotechnical systems perspective’ presents empirical findings about the drivers and barriers encountered when building the Super-grid system.

The findings of Paper V indicate that in terms of the material dimension, the Super-grid has a head start in that its key technological components, i.e. HVDC transmission and large-scale RETs, are relatively mature and integrated into the existing electricity grid and markets. Advances in HVDC technology have increased the possibility of interconnecting existing transmission infrastructures across large geographical areas and of potentially balancing the variable renewable energy production across climate and time zones. As a result, the number of long-distance connections is increasing and experiments with advanced technological configurations are being conducted around the world. Our evidence also shows that the Super-grid has a solid starting point in terms of a strong actor network, rooted in the existing transmission industry, that has large resources, political influence, and the exclusive technical knowledge needed to construct a global Super-grid.

However, Paper V also finds that the established transmission grid infrastructure is subject to strong material and institutional path-dependency that slows Super-grid development. In most of the industrialised world, the state–industry co-dependence in electricity system planning and development hinders the geographical expansion of the Super-grid beyond single state borders. National governments tend to only permit construction of new transmission lines if these bring measurable national-level benefits, without threatening the domestic industry and economy. Without the financial and regulatory security provided by the national government, transmission industry actors advocating for a global grid face too many uncertainties in integrating electricity systems across borders. As a result, Super-grid development is reduced to single countries and relatively small geographical regions, such as the EU and ASEAN. Spatially scattered Super-grids are forming a diversity of technical and market designs that reflect local conditions and needs and might not be easy to harmonise into one globally connected electricity grid. We find that without a global institution with executive power to regulate trade and redistribute costs and benefits, there is no simple solution to this problem.

The conclusion is that the development of the Super-grid system is driven by changes in the technical dimension, with a strong emphasis on improving the efficiency and reliability of

transmission connections, yet the institutional dimensions, such as the market structure and financing mechanisms, rarely come under scrutiny. Unless advocates of a global Super-grid acknowledge the institutional and political realities of technological change, especially the larger geopolitical questions, social consequences, and environmental impacts, they will continue experiencing difficulties in gaining the necessary public support and political commitment they are so dependent on. The paper concludes that, although the idealised configuration of a global-scale Super-grid may work in its technical aspects, the technocratic ideals of ‘optimisation’, ‘efficiency’ and ‘economies of scale’ currently present a major system development barrier, given the political and social risks and trade-offs of the global vision.

## 5 Discussion

From the synthesis of the appended papers and their contributions, this thesis draws implications for the conceptual frameworks and methodologies used, for the original findings of Paper I, as well as for the overall direction of the electricity system transition.

### 5.1 Implications of conceptual positioning

The work presented here builds on perspectives established in the broader innovation and sustainability transitions literature, as presented in Section 2.1. Given that this research has been positioned in this field from the outset, it is much easier to argue for the usefulness of the perspectives, and the core ideas this literature provide, than it is to say anything about other perspectives that could have been used to address the same analytical goal and research questions. I thus intend to reflect on my decision to study the electricity system from a sociotechnical perspective and discuss the limitations and consequences in terms of what I was able to observe and discuss in this thesis.

Though using a sociotechnical systems perspective is often taken for granted in my immediate research community, it should be noted that scholars with different backgrounds might argue that the concept of ‘systems’ should be used in a more critical way, or even omitted completely, especially in research that concerns societal phenomena. Criticism comes from two directions. On the one hand, the systems perspective is argued to be weak because it embraces the co-evolutionary and uncertain nature of systems that limits the ability to formulate generic laws and hypotheses that can be tested and validated. Weak testability is a valid criticism, as it makes systems studies case dependent, with results that can only provide generalised ‘patterns’ but cannot be generalised at scale (von Bertalanffy, 1973). The other line of criticism is that many varieties of systems thinking seek generalisation and ideal patterns in specific cases and share a naïve belief in solving complex societal problems with computational modelling (Lilienfeld, 1975; Rittel and Webber, 1973). The fact that the sociotechnical systems perspective is criticised for being too complex, on the one hand, and not complex enough, on the other, indicates that systems science forms the ‘middle ground’. Less defensively, one could, as Boulding (1956), claim that systems theories are the ‘skeleton’ that holds different knowledge traditions together.

Its position in the middle of other disciplines makes sociotechnical systems research cross-disciplinary in nature. In fact, as Ingelstam (2012) has written, its *raison d'être* is entirely conditional on the successful transfer of a concept from one field of science to another. He argues that systems science needs to be interdisciplinary because the problems it aims to study cannot be analysed within the boundaries of single disciplines. For example, the systems theory of large technical systems (LTS) (Hughes, 1987) that inspired this thesis combines concepts from engineering, history, and sociology (Ingelstam, 2012). Similarly, the MLP and TIS frameworks that serve as conceptual building blocks of this research borrow ideas and concepts from innovation systems theory, evolutionary and industrial economics, institutional theory, and the sociology of innovation.

However, the cross-disciplinary nature of systems research is not without trade-offs. Choosing an alternative perspective could have allowed me to zoom out and analyse more generalisable techno-economic prerequisites, aggregated indexes, or indicators that point towards a certain electricity future. For example, I could have spent more effort investigating global trends in renewable energy capacity growth or statistically assessing investment in grid infrastructure. On the other hand, if I chose to zoom in, I could have explored how specific parts of the system, such as political regime, policy tools, specific actors, or their culture and gender, influence the development towards different electricity system configurations.

## 5.2 The design space of idealised electricity system end states

The key argument that motivates this research is that the transition is open to evolving in many different low-carbon directions. The design space concept contributes to the innovation and sustainability transition literature, facilitating future-oriented studies of emerging transition trajectories by providing definitions of possible end states. This approach complements previous work on transition pathways (Geels and Schot, 2007; Hofman et al., 2004) that takes an interest in the generalisable patterns and mechanisms of the transition process, but without more clearly defining possible end states.

In relation to the analytical goal of this research, the conceptualisation of future system end states in a design space created a useful analytical map that guided the search for real-world cases of novel technologies, for example, blockchain and HVDC transmission technology, that

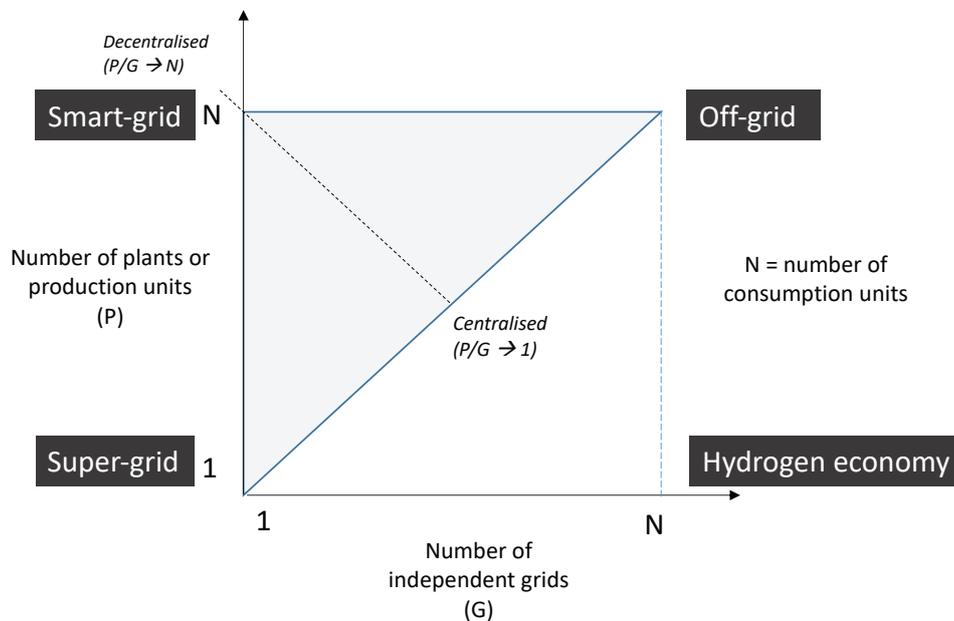
play a key role in supporting a transition towards an idealised version of the future electricity system.

However, the choice to distinguish between alternative future electricity systems based on their technological dimensions, i.e. the production units and grids, can limit our attention to changes in the physical grid, at the cost of the institutional and organisational dimensions. A narrow focus on technological substitutions as inducing complex systemic change (Geels, 2002, 2004) was typical of the early transition literature, but has since been extended to form the concept of ‘deep transitions’ to emphasize that energy transition is not just about replacing carbon-intensive technologies. Instead, deep transitions involve changes in economic logic, social justice, and the distribution of services and resources (Kanger and Schot, 2019). While broader institutional and political issues did emerge as key findings of our case studies, such as the need for global governance of the Super-grid and a decentralised market structure for the Smart-grid configuration, these are not explicitly laid out in the design space.

Accordingly, one could, and arguably should complement the design space with another dimension. Questions of ownership appeared to play an important role in the cases presented in the thesis and could form a dimension. Empirical investigations revealed that large-scale technological components can be owned by small-scale actors or groups of them (e.g. community wind energy) and that the reverse can also be true, that small-scale systems can be centrally owned by a big investor (e.g. utility-owned virtual power plant). The influence of another dimension on the electricity system transition may help in identifying transition dynamics that were not initially visible to us. Other dimensions previously used to differentiate between alternative futures, such as governance structures (Foxon, 2013) and the source of system-building agency (Verbong and Geels, 2010), could also be added to the design space.

The design space could also have been complemented with a fourth corner, an idealised future with one large power plant ( $P = 1$ ) and as many independent grids as customers ( $G = N$ ). Such a configuration resembles the vision of the hydrogen economy, a future in which large-scale renewable electricity production is coupled with hydrogen production and shipped across the world to customers (Figure 10). This vision is different from the Super-grid in that it does not rely on a physical grid connection. The hydrogen economy follows the logic of the mining and extraction industry, with the hydrogen being transported around the world to be used in different applications. Without reliance on grid infrastructure, the hydrogen economy bypasses

the issues related to instant balancing and reliability, while arguably increasing energy losses. An inter-regional HVDC interconnection project between Australia and Indonesia has recently shifted its business model towards hydrogen economy after encountering long-standing challenges in trying to construct a subsea transmission line between two continents.



**Figure 10.** Idealised future end states in all four corners of the design space.

### 5.3 Implications for the TIS framework

The choice of TIS as the main conceptual framework for studying dynamics of system change calls for justification, as it is not commonly applied to the type of technologies studied here (Hallingby, 2016), nor to the experimentation stage of innovation, for which SNM is a more common choice (Köhler et al., 2019). SNM could arguably have been used to study local P2P trading experiments. In fact, it was the initial choice for Paper II, yet the analytical strategy was changed after a few months of trying to ‘fit’ SNM to the empirical cases. The TIS approach was used because it provided a more elaborated framework, enabling a nuanced analysis.

As we argue in Papers II and V, the TIS approach is generic enough to be useful in analysing various types of new technologies, including software, and even business models and service-delivery models enabled by new technological solutions. These studies also show that TIS is suitable for studies of sociotechnical systems of different sizes, geographical scales, and levels of maturity.

Perhaps the most surprising, and for many the most counterintuitive, aspect of using TIS in this thesis concerns the geographical boundaries of the selected cases, none of which is national. While it was an unforeseen outcome of our search for cases to study, rather than intentional, this fact sheds new light on the role of national government agency in innovation. As reported in Paper II, local–global interactions were key in supporting P2P electricity trading experiments, which indicates that national policies are not always of utmost importance in the early stages of innovation. This points to a need to pay more attention to ‘glocal’ systems that grow in local clusters through cross-scale linkages. Nevertheless, the evidence indicates that local incumbents tend to enter a productive encounter with the system builders of a glocal system only after they have experienced challenges caused by the diffusion of small-scale RETs, which was initially a result of national policies.

Paper V shows that another consequence of not setting national-level system boundaries is that governments can be studied as one actor among many, revealing the plural and heterogenous character of national governments. From this perspective, we can make sense of the diverse interests within the nation state and study the international politics and economic relations that affect government priorities and decisions for the energy sector. As a result, the role of national governments in the development of the Super-grid was more complex than initially expected. Applying a global perspective reveals that national governments are faced with domestic and foreign affairs, such as business politics and national security, that are prioritised over the benefits of a perfectly optimised global electricity grid. These findings call for more TIS studies with system boundaries other than national ones in order to continue exploring the variety of factors supporting innovations at different geographical levels.

#### 5.4 Revisiting the three electricity futures

To analyse probable directions of change in electricity systems, it is helpful to set the initial assumptions and findings of the first paper against the results of the case studies. The case studies largely confirmed the initial findings regarding the ongoing build-up of structural components (Table 2) and system overlaps with the incumbent electricity sector (e.g. niche accumulation and hybridisation) but also revealed new and unexpected drivers and barriers for competing configurations.

To begin with, Paper V casts new light on the Super-grid system, a globally interconnected electricity grid of dependent consumers. It confirms that the pathway towards a Super-grid unfolds through hybridisation processes close to the established electricity system and can be considered the ‘natural pathway’ for the electricity system transition in terms of the technological solutions employed, source of agency, and institutional logics. However, while national governments were in Paper I assumed to support the Super-grid build-up, the in-depth analysis in Paper V reveals that states act in ambiguous ways when it comes to grid extension beyond the boundaries of the nation state. Nation states have historically supported electricity system development to bring about nation-level benefits and development, so fears of jeopardising national energy security and increased dependence on other countries are discouraging states from supporting the construction of the global Super-grid. Hence the key institutional process of international harmonisation, described in Paper I, is unlikely to occur without an institutional innovation in the form of new ways to mobilise finance to build cross-border interconnections as well as to coordinate and enforce relations between nation states.

Furthermore, the character and scale of the Super-grid system poses barriers to entry for newcomers, especially small entrepreneurial firms. In contrast to the actors developing the Smart-grid and Off-grid systems, the actor network around the Super-grid is very stable and interacts little with other important actors in the rest of the system, such as distribution system operators, retail companies, local political organisations, civil society, and environmental groups. What Paper I overlooked is that the ambition to build a global Super-grid has developed in isolation from new actors that could challenge the centralised and one-directional logic of transmission infrastructure development and contribute alternatives to the traditional large-scale model of electricity grid development with long lead times. In a rapidly changing electricity sector, the vision of the global Super-grid faces increasing competition from the advocates of small-scale alternative technological configurations.

One such vision is the Smart-grid system, defined in Paper I as a perfectly interconnected system of interdependent prosumers. Analysed through real-world cases of blockchain-enabled P2P electricity trading, the in-depth analysis confirmed that small-scale RETs, storage, ICT, smart metering, and grid technologies play crucial roles in building the technical configuration. However, we also found that integrating storage, advanced metering, and flexible grid technologies can be particularly challenging in the presence of existing, often older technologies. As our cases show, integrating the blockchain platform, a relatively immature

technology, with the existing metering infrastructure leads to technical difficulties, such as data flow inefficiencies and computational latency. Technical standardisation, already identified in Paper I, remains key in constructing a seamlessly interoperable system of distributed energy resources that operates in near real-time intervals.

Contrary to the findings of Paper I, however, case studies show that national governments, distribution system operators (DSOs), and electricity retailers do not always act in favour of the Smart-grid system. Our findings indicate that these actors only support the diffusion and implementation of Smart-grid technologies to the extent that the change in the physical grid does not compromise their dominant market position. Given the narrow focus on the technical dimension in the design space, the findings of Paper I largely missed the fact that new technological solutions that affect the current operation of the distribution grid may also lead to various changes to regulation and market rules, which could have a significant impact on the business models of the established utilities. The in-depth analysis clearly showed not only that blockchain technology is a new technical component that facilitates distributed electricity transactions between small-scale prosumers and consumers, but also that new actors can use blockchain technology to promote a local market model of autonomous prosumer groups that can, in theory, eliminate the need for electricity retailers. Such a shift in market structure would require substantial changes in retail pricing and grid tariff structures, with utilities likely to lose in the process.

A deeper understanding of the institutional dimension of the transition towards an idealised Smart-grid configuration suggests that this scenario may not unfold as the most realistic path, being supported by both existing and novel structures, as initially assumed. Instead, our case studies indicate increasing friction in the process of integrating small-scale energy technologies, a process that is imagined differently by the dominant actors and new entrants. So, whose expectations are attached to demonstration projects will shape whose expectations and interests come to dominate the direction of Smart-grid system development in terms of its institutional structure. The cases studied in this thesis indicate that demonstration projects still mostly reflect the expectations and logics of established actors rather than those of software platform developers or communities of residential prosumers.

A deeper understanding of the institutional dimension of the Smart-grid system also provides a nuanced understanding of feed-in tariffs (FiTs), defined as a key policy instrument in Paper

I. It is safe to say that FiTs are an influential policy instrument that has played an important role in supporting the uptake of small-scale PV panels in both studied cases by lowering the risk of investment and guaranteeing prosumers a certain price for their electricity. This means that in relation to the Smart-grid system as defined in Paper I, FiTs undoubtedly support changes in the technical dimension and create incentives for prosumers to stay connected to the public grid. However, FiTs can have a reverse effect on the efforts to achieve fundamental market change. In both case studies, the risk of losing FiTs discouraged residential prosumers from trialling novel means of value creation for their electricity, which hindered experiments with P2P electricity trading that depend on active prosumer participation. In fact, FiTs were one of the main reasons why prosumers remained with electricity retailers versus shifting to blockchain-based trading platform providers.

Taken together, complementing the two-dimensional design space with institutional dimensions could have enriched the definition of the Smart-grid not only as a decarbonised system but also as one that achieves goals of distributed market structure, prosumer business models, democratisation of electricity provision, and energy justice, making a clearer contribution to the debate on deep transitions (Kanger and Schot, 2019).

While the Off-grid system was not analysed in a separate study, our case studies revealed a previously unexpected type of Off-grid development: behind-the-(utility) meter systems. In contrast to our initial thinking about Off-grid systems, we found that these not only develop physically ‘separate’ from the conventional grid infrastructure in remote locations but can also emerge ‘behind’ the grid, for instance, inside an apartment building or within a university campus. This type of Off-grid system is driven not only by mistrust in established actors, as assumed in Paper I, but also by an effort to overcome incumbents’ resistance to disruptive ideas. As Papers II and IV suggest, behind-the-meter systems are currently the only path to bypass the regulatory obstacles of the established electricity system and enable fruitful experimentation.

Based on our case studies, we can assume that behind-the-meter systems can develop in two directions: a) they can serve as a space for the emergence and growth of the Smart-grid configuration or b) their cumulative growth can gradually make the conventional grid system obsolete, and turn the direction of change towards the Off-grid system. At this stage of

understanding, we believe that the direction depends on the speed with which the established system reacts to change. If the established actors fail to address the challenges of the increasing penetration of distributed energy resources, a growing number of residential and commercial prosumers might decide to move behind the meter, setting in motion the decline of the established system as we know it. However, if the established actors decide to learn from the novelties being developed behind the meter and allow them to expand ‘across the meter’, a future Smart-grid system is more likely.

Finally, it is important to acknowledge that our reflections on the first paper are based on knowledge specific to the selected case studies and idealised visions of the future. Although they are likely to have some general relevance, the results could be improved by studying similar technologies and system configurations in different parts of the world as well as by applying the perspectives of different actors; such as electricity retailers and energy communities. Furthermore, while the results might be generalizable to cases of very-early-stage developments, their implications might change as these systems grow and mature.

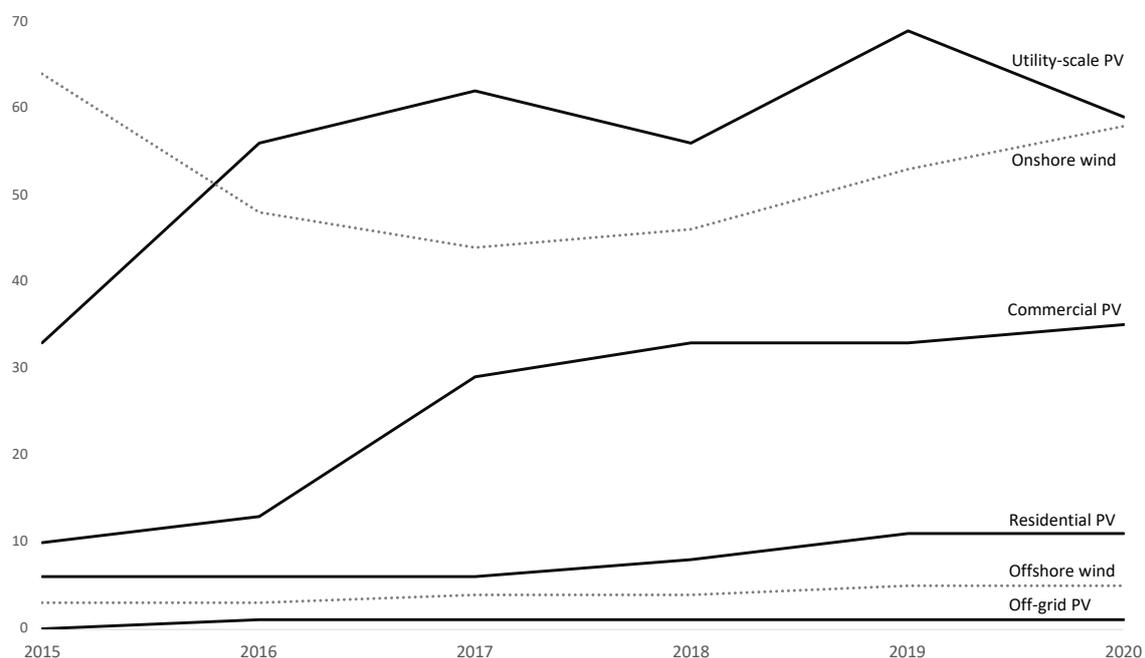
## 5.5 Where are we heading?

Before concluding the discussion of the direction of the electricity system transition from the perspective of the research presented in this thesis, it is important to first acknowledge what global trends and statistics tell us about the current state of the electricity system.

According to the IEA (2019c), the costs of new solar and wind installations have dropped much faster than expected, gradually replacing coal, and in some cases natural gas, as the primary choice for additional electricity capacity. In 2019, the total share of renewable energy technologies, including wind, solar, hydropower, bioenergy, and geothermal, in the global electricity production mix was some 2500 GW, about 35% of total generation capacity. While close to 50% of this capacity is still provided by hydropower, 90% of new capacity installed in 2019 alone came from solar and wind power (IRENA, 2020). While the positive growth trends in renewable energy capacity suggest progress towards decarbonising the electricity system, this gives us little indication of the direction the transition is taking in terms of grid architecture.

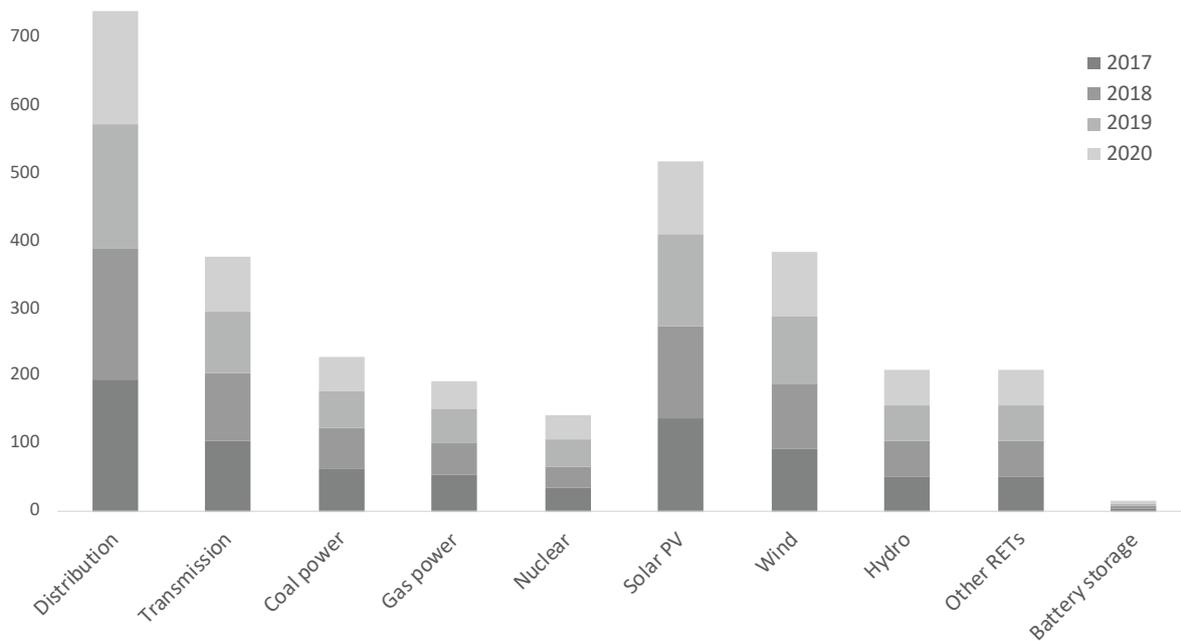
As Figure 11 shows, utility-scale PV and onshore wind have been responsible for the largest part of annually installed capacity since 2015. These figures indicate that centralised electricity

systems are still growing the fastest in terms of GWs, while distributed grid-connected systems come second, and off-grid systems come last.



**Figure 11.** Annual additions of PV and wind production capacity, 2015–2020. Source: (IEA, 2019b).

Similar trends can be observed in terms of investment (Figure 12), with solar PV and wind receiving substantially more investment than new coal, gas, and nuclear power between 2017 and 2019. Investment in distribution networks remains the highest, followed by transmission networks, but network-related investment has been declining steadily since 2017. As an IEA (2020) report explains, spending on digital grids now makes up nearly a fifth of new network investment. In some regions, digitalisation, flexibility, and efficiency measures are removing the need for the new generation and grid capacity, with an increasing portion of investment shifting towards battery storage. Though Figure 12 indicates that battery investment remains far from matching the investment levels of network infrastructure, it should be noted that the investment in batteries goes beyond the electricity sector. It is safe to say that rapid battery development in consumer electrics and vehicles has had a direct influence on the electricity sector development. An explicit coupling is already visible in Tesla’s use of batteries for both electric vehicles and electricity storage.



**Figure 12.** Global investment in the power sector by technology. In billion dollars USD. Source: IEA (2020).

Taken together, recent trends show that the electricity system remains close to the dominant system design in terms of new generation capacity deployed. However, the IEA (2019b) forecasts that distributed solar in homes, commercial buildings, and the industry is set to take off and play a central role in the future growth of renewable energy generation.<sup>12</sup> Distributed PV capacity is expected to double by 2024, an increase equal to that of onshore wind. Such growth in distributed generation could well shift the transition towards the Smart- or Off-grid system configuration (IEA, 2019b).

However, the unmanaged growth of new capacity, primarily distributed PV, behind the utility meter, which is often not an integrated part of market planning and operation, can cause significant issues in terms of the reliability and security of supply. An additional problem caused by the difficulties of accurate system planning is the tendency to overbuild generation and network capacities to handle the intermittency of renewables, leading to rising system costs, reduced revenue for utilities, and thus higher electricity prices for customers. As a result, global trends show us that the transition is reaching a tipping point at which the conventional business model of building more capacity on the supply side is unproductive and needs to be coupled with changes in the transmission, distribution, and retail of electricity.

<sup>12</sup> The IEA (2020) predicts that Covid19 will have affected the growth of distributed PV more than utility-scale PV due to more stable public investment and the withdrawal of private investors.

The value of the in-depth case studies presented here is that they explore what is happening ‘behind the scenes’ and shed light on unique cases that promote solutions to systemic problems. They provide interesting examples of developments ahead of the curve that can be representative of what the rest of the world might look like in a few decades.

This thesis explores cases promoting two contrasting solutions to the challenges posed by renewables. On the one hand, a global high-voltage Super-grid would balance intermittent supply with cross-regional trading to take advantage of supply and demand synergies across climate and time zones. On the other hand, blockchain-based P2P electricity trading, an idealised form of the Smart-grid system, would provide a solution at the distribution level, with demand and supply being matched locally through the dynamic trading of electricity. These cases offer different technological solutions to similar sets of challenges.

For both the Super- and Smart-grid systems, technological solutions already exist, though mostly in the form of conceptual and computational models. The real challenge in both cases is to turn technological novelties into real-world solutions, to trial and improve their performance. Here, our case studies clearly show that the most significant hurdles are political and regulatory. Such a finding is not new or surprising. What is surprising are the particular bottlenecks and strategies that differentiate these cases, indicating their chances of becoming the new dominant configuration.

The research in this thesis suggests that the main point of difference lies in the ability to overcome institutional lock-ins and enable experimentation to de-risk investment and guide the regulatory and market changes necessary to remove the hindrances to all low-carbon solutions. The results indicate that with their comparatively smaller sizes and capital requirements, Smart-grid and Off-grid system alternatives could outpace Super-grid system development. Given the possibility of implementing and trialling new distributed grid architectures behind the meter and in regulatory sandboxes, these solutions could undergo faster trial-and-error cycles, accelerate learning, advance performance, and decrease costs.

As a result, distributed energy resources have a number of benefits in terms of reducing system-level uncertainties:

1. Faster deployment and prototyping without the risk of widespread system consequences
2. Iterative system design that can be regularly tweaked and improved during implementation
3. Lower barriers to entry for new actors
4. Can be built during a single political office term

The case study analysis also revealed a number of macro-level trends that may support the shift towards an increasingly distributed future. Firstly, *extreme weather conditions* are making solutions based on poles and wires less attractive. New York City provides a good example of how awareness of changing weather conditions is shaping local public policy to support locally distributed microgrids over network augmentation.

Another trend concerns the so-called *4<sup>th</sup> industrial revolution*, in which hardware problems are expected to be increasingly solved using a software mindset. With the rapidly falling costs of digitising physical processes into algorithms, bits are accelerating innovation, while atoms are slowing it down (Janeway, 2015). This revolution is already changing many traditionally hardware-based industries. One example is the car industry, in which software solutions may allow car owners to upgrade their car models via software updates instead of buying a completely new car. Software updates are already a reality in the case of mobile phones, and nothing, in theory, prevents similar developments in the electricity sector. The trend towards software solutions will likely favour all low-carbon trajectories. In all future systems, software solutions will enable faster fault identification, while remote control can solve technical issues and simplify repairs. However, if we take the current state of the electricity system as a starting point, software solutions are likely to speed up the pace of Smart-grid and Off-grid system development, as the software allows these configurations to use the current grid in different ways, without the need for network augmentation. Moreover, software technology can break the top-down hierarchy (from the transmission to distribution) of electricity planning and operation, allowing small-scale systems at the distribution level to operate in an ‘islanded mode’ within larger systems. Because software platforms and services are often not dependent on a specific type of hardware, they provide the opportunity to avoid getting locked into a hardware-dependent infrastructure, as in the case of the Super-grid.

A related trend is a shift towards a *prosumer economy*, as first defined by Toffler (1980), signifying a move towards the complete integration of consumption and production. Prosumers produce products for their own consumption, hence the use of the term ‘prosumer’ for individuals and businesses that own renewable energy generation. With the rise of Web 2.0, i.e. open-source user-generated digital content, the term prosumer is being increasingly associated with value co-creation, meaning that prosumers create value not only for themselves but also for the market at large. The web is currently the most important facilitator of prosumption activities, enabling individuals to act as buyers and sellers simultaneously (Ritzer and Jurgenson, 2010). With an increasing number of prosumers in the electricity sector, the traditional logic of passive electricity buyers is being challenged as individuals and companies begin to realise the growing market value of self-produced electricity. Digital platform-enabled prosumption in other sectors such as hospitality (Airbnb) and transportation (Uber) have been the source of inspiration for the blockchain-P2P electricity trading models analysed in this thesis. While this trend clearly turns the transition away from the Super-grid system of passive electricity buyers, there are still some key issues that need to be addressed to achieve a prosumption-based electricity market that could accelerate the growth of small-scale grid network solutions. First, individuals cannot sell their electricity without having access to a regulated market and electricity infrastructure, access that is currently only given to licenced electricity retailers. Second, electricity has historically been provided as a public service rather than a commercial product. An undesired risk of increased prosumption, at least in the short term, could be that traditional utilities lose the ability to cross-subsidise their costs over a customer base to provide a safety net for vulnerable customers who lack the means to self-generate electricity or join a web-based marketplace.

Last, one should not exclude the potential impacts of a changing global geopolitical climate and the global pandemic. While the long-term impact of the pandemic is difficult to predict, its medium-term effects are already visible in terms of the reconsideration of supply chain structure and cross-border investment decisions. These impacts are not exclusively attributable to the pandemic. Instead, they were intensified with the mounting consequences of the recent trade war between the USA and China, which resulted in increasing tariffs and restrictions on foreign direct investment. Firms had already started reconsidering global supply chains before the pandemic, as the costs of the uncertainty associated with the unpredictable decision-making of political leaders have been increasing (Yueh, 2020). The cumulative effects of geopolitical tensions, global lockdowns, and new opportunities such as 3D printing-based manufacturing

may lead to the (re)localisation of supply chains, particularly in the case of services such as electricity that are deemed essential for national security and national economic survival. This trend speaks against the Super-grid vision and potentially provides a window of opportunity to drive development towards a future of Smart-grid and Off-grid systems.

It should be acknowledged, however, that the influence of macro trends cannot serve as a decisive indication of the future direction of the electricity system transition, because of the inherent uncertainty of the interplay between agency, cumulative causation, and the timing of macro-level trends and events. While macro-level trends may play a role in determining the future of the electricity system, the impact of the endogenous path-dependency of the new configuration should not be underestimated. As historical studies show, a novel technology, not necessarily the best one, can come to dominate the market. Commonly cited examples are light-water nuclear power technology (Cowan, 1990) and the QWERTY keyboard (David, 1997), which are teaching us that events early in the innovation process can be crucial in determining cumulative causation through, for example, substantial learning from early experimentation that can lead to irreversible competitive advantage.

Related to this research, at this time we cannot know which alternative system will first gather decisive momentum. What we do know, based on our case studies, is that the Super-grid and Smart-grid systems create momentum in different ways – through the actions of the few versus the actions of the many. The Super-grid system is developed through the decisions of a few actors about a few large-scale investments that have widespread consequences for the rest of the electricity system. The Smart-grid system, on the other hand, develops through millions of small decisions and investments with seemingly minor impacts on the rest of the system. It remains to be seen whether the upscaling of a few large technologies or the accumulation of many small ones will win the race.



## 6 Conclusions

This thesis set out to explore possible and probable pathways leading to a future electricity system powered by renewable energy technologies. This research is positioned in the innovation and sustainability transitions literature and applies a sociotechnical systems perspective as its analytical starting point in order to understand two main aspects of the electricity system transition: the alternative end states, and the dynamics of the transition towards them. The six appended papers provide rich conceptual contributions and empirical findings that together fulfil the aim of this thesis.

An important contribution of this thesis is the ‘design space’ of clearly distinguishable electricity system alternatives that can be categorised as low-carbon. The design space was constructed through an iterative process of shifting between empirical findings and deductive reasoning that identified three idealised electricity future end states, i.e. the Super-grid, Smart-grid, and Off-grid systems. This design space contributes to the literature by facilitating future-oriented studies of emerging transition pathways towards more clearly defined sociotechnical configurations that can be monitored in the form of currently emerging and accumulating structural components. The monitoring exercise presented here revealed that all three alternatives have gained notable momentum over the last 15 years and that the alternative configurations are not exclusive to the electricity sector but are also linked to and borrow components from other sectors, discourses, and societal trends.

The design space of idealised futures guided the case study selection in this thesis. The case studies revealed factors influencing the direction of change towards Smart-grid and Super-grid configurations. The empirical cases also informed and instigated the conceptual development of the TIS and MPL frameworks through elaborating on specific aspects of the novel system build-up. The TIS framework has been enriched with a two-dimensional matrix of contexts that systematises previous insights into the role of context in novel system building. The matrix was linked to the micro-level agency to explain how external factors are mobilised from the context to support novel system development. Both the TIS and MLP frameworks were informed by a more elaborated conceptualisation of the role of entrepreneurs and users in developing and diffusing new technologies. A related contribution has been made by widening the analytical focus of the encounter between new entrants and incumbent actors, from repressive to productive interactions. These contributions could inspire future applications of

the TIS and MLP frameworks, but also suggest new and interesting areas for further conceptual development.

More generally, the research synthesis presented here offers clues as to the direction of change in the electricity sector. The in-depth case studies of unique projects shed light on dynamics and aspects that are not yet visible in present-day statistics. Our analysis indicates that the future will be determined by the interplay of specific kinds of system-building agency, strategies of momentum building, and the timing of macro-level trends and events.

As a follow-up to this thesis, there are several interesting avenues for future research. First, it would be worth complementing the present findings with an in-depth analysis of the Off-grid alternative. Second, further research along the lines of technological complementarities, for instance, between renewable energy technologies and hydrogen, electric vehicles, and data centres, that could steer the electricity system transition in diverse directions would be valuable for a deeper understanding of the electricity system transition. Third, it would be worth further exploring the impacts of the changing ownership of electricity generation assets and grid networks on the traditional institutional structure of the electricity system.

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# Paper I



Contents lists available at [ScienceDirect](https://www.sciencedirect.com)

Futures

journal homepage: [www.elsevier.com/locate/futures](http://www.elsevier.com/locate/futures)

# Three electricity futures: Monitoring the emergence of alternative system architectures



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## ARTICLE INFO

### Keywords:

Electricity system  
System innovation  
Niche accumulation  
Technological innovation systems  
Transition pathways

## ABSTRACT

The electricity system is in transition, but where to? To large-scale global or regional grids or to self-sufficient disconnected prosumers? Although numerous studies have previously dealt with the future of the electricity system, there is a lack of studies that attempt to monitor the development of more complete sets of socio-technical system elements that support alternative futures. This paper addresses this gap by first identifying and characterizing three idealized electricity system futures: ‘the Super-grid’, ‘the Smart-grid’ and ‘the Off-grid’, and then using the characterization to monitor the emergence, accumulation and alignment of socio-technical elements indicating the initial formation of new systems. Besides tracing the ongoing structural build-up at the niche level, we explore how the emerging systems relate to the existing electricity regime, other sectors and discourses. While the final outcome is undecided, the findings indicate that all three of the investigated systems have gained momentum over the last decade, partly relying on growth trends in shared elements such as the rise of renewables and climate change concerns, but also building on different technologies, actor networks, related industries and political and cultural discourses.

## 1. Introduction

At the turn of the century the electricity sector was strikingly similar in different parts of the world, based on a model of centralised and large-scale power generation (IEA, 2016a). This system is now facing problems related to climate change, local air pollution, nuclear safety, energy security and aging grid infrastructure, and, consequently, undergoes a transformation towards larger reliance on smaller scale power plants based on renewable energy (RE) (Frankfurt School-UNEP Centre/BNEF, 2016). The technical potential of solar and wind power exceeds current and projected energy demand (Sandén, Hammar, & Hedenus, 2014), and economic competitiveness of these technologies is being reached in an increasing number of regions around the world. In 2015, the global annual installation of solar and wind surpassed 100 GW despite a significant decline in fossil fuel prices (GWEC, 2017; IEA, 2016b). In addition, rapid innovation in technologies for balancing electricity supply and demand across time and space, such as, high voltage cables, energy storage (incl. electric vehicles) and information and communications technology (ICT), is facilitating a transition to an electricity system solely based on renewables. There are, however, several radically different electricity system architectures, that all could satisfy the criterion of hundred per cent renewables, but these would entail different benefits and drawbacks and affect societal actors in various ways. Hence, there is a value in monitoring the development to better understand what is going on and to gain some foresight. While socio-technical change is highly non-linear and to some degree unpredictable, it is not without logic and the process can be studied.

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<https://doi.org/10.1016/j.futures.2017.12.004>

Received 29 June 2017; Received in revised form 26 October 2017; Accepted 21 December 2017

Available online 27 December 2017

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Previous work on electricity system futures has either focused on techno-economic assessment of different system configurations (Battaglini, Lilliestam, Haas, & Patt, 2009; Blarke & Jenkins, 2013; Funcke & Bauknecht, 2016; Meeuwssen, Myrzik, Verbong, Kling, & Blom, 2008), analysis of existing supporting organizations (Lilliestam & Hanger, 2016), or construction of narrative scenarios (Foxon, 2013; Foxon, Hammond, Pearson, Burgess, & Hargreaves, 2009; Verbong & Geels, 2010). There are also numerous reports on the development of singular components. There is, however, a lack of studies that monitor the development of more complete sets of socio-technical system elements and put these in relation to clearly distinguishable alternative futures and transformation pathways.

Such monitoring can take as starting point a conceptualisation of the electricity system as a socio-technical system in transition (Geels, 2004), where different alternative solutions emerge, compete and coevolve (Sandén & Hillman, 2011). A broad stream of literature on socio-technical systems and technological change describes such path-selection as a process emerging out of accumulation and alignment of heterogeneous structural components, such as actor constellations, technical artefacts and institutions (Bergek, Jacobsson, Carlsson, Lindmark, & Rickne, 2008; Geels, 2004; Hughes, 1987b; Kemp, Schot, & Hoogma, 1998; Rip & Kemp, 1998). Some of these components may be closely linked to, and build upon, the dominant electricity ‘regime’, as well as other established systems and sectors; while others develop in more isolated niches (Raven, 2007).

The aim of this paper is to systematically monitor key structural system components that support different scenarios of future electricity system change. From this we derive four research questions:

- What alternative future electricity system scenarios can be identified?
- What structural components characterise these scenarios?
- Which of these structural components are emerging and accumulating at present?
- How are the alternative scenarios and their emerging components linked to, or decoupled from, the current electricity regime; and to what extent are they borrowing strength from other sectors and trends?

We address the first two questions by deriving three idealised exploratory scenarios (Börjeson, Höjer, Dreborg, Ekvall, & Finnveden, 2006) from a literature review and identifying their overall characteristics and signifying structural components. To address the third question, we use an extensive web-based search to monitor the accumulation of technology, actors and networks, and institutions. Based on these findings, the fourth question is elaborated on in a discussion on socio-technical overlaps (Sandén & Hillman, 2011).

## 2. Theory and method

In the following, we review key concepts from the socio-technical systems literature that provide the theoretical base for exploration of electricity systems in transition, and provide a methodological framework for monitoring emergence of alternative system architectures, including: identification of ideal system types; monitoring accumulation of heterogeneous components that may form building blocks of these systems; and analysing overlaps with other systems. Thereafter, methodological choices on data sources and system boundaries are reported.

### 2.1. Socio-technical systems and transitions

The dominant model for electricity supply, based on large-scale centralised installations and extensive grid infrastructure, has been described as a large technical (or socio-technical) system (LTS) (Hughes, 1987a; Loorbach, Frantzeskaki, & Thissen, 2010; Markard, 2011). An LTS consists of numerous heterogeneous components, including physical artefacts as well as social, economic, institutional and organizational structures (Geels, 2002; Hughes, 1987a; Loorbach et al., 2010; Verbong & Geels, 2010). The number and high degree of alignment between components creates inertia and “lock-in” (Unruh, 2000). However, history teaches that also such locked-in systems can and will be replaced, a phenomenon that has been termed ‘technological transition’ (Geels, 2002). Previous research has identified multiple processes driving such change. Transitions can be triggered by new discoveries that offer new opportunities or by efforts to address major problems within the old system, or, more likely, by both processes in combination (Geels, 2002; Geels & Schot, 2007; Sandén & Jonasson, 2005). The Multi-Level Perspective (MLP) describes transitions from one established socio-technical system to another as unfolding from interaction between processes at three systemic ‘levels’ (Geels, 2004, 2011; Rip & Kemp, 1998): first, the regime level, the essence of the large technological system, where a well-established set of institutions is shared by a large number of actors aligned in efficient value chains utilising mature technologies to deliver a certain good or service; second, the landscape level, where broad societal trends unfold that may put pressure on the regime and thus open up windows of opportunity for novelties; and third, the niche level, where new configurations emerge, grow and gain momentum. Phrased in the language of the MLP model, this paper studies structural build-up at the niche level, which indicates the direction of the ongoing transition, i.e. the development of *alternative socio-technical systems* and their components.

### 2.2. Identifying alternative future systems

To be able to trace the build-up of alternative systems one needs to have an idea of what to look for. In the early days of a transition, however, it is not a trivial task to discern what potential future systems that may eventually emerge. One strategy is to pick alternatives that are frequently discussed, and that some actors consider to be ‘realistic’. However, since what is considered ‘realistic’

is often based on myopic worldviews very much coloured by present day systems, this might lead to a too narrow scope. To broaden the search, scenario methodology can be of help.

Depending on purpose, different types of scenario methodology is applied (Börjeson et al., 2006). One distinction can be made between forecasting and backcasting. Backcasting typically has a normative starting point, a system that someone would like to see materialise in the future. The analysis then identifies scenarios leading to that system. Here, we have no such normative starting point. Instead, the overarching ambition is to take one step towards *forecasting* the development of the electricity system. Forecasting typically builds on trend analysis, possibly also on quantitative modelling of interactions between several trends and time-independent constraints. However, since technological transitions are inherently messy and involve long-term processes where heterogeneous elements interact in a non-linear way, it is not immediately clear which trends and constraints one should look for, how to group them in a meaningful way and how to model interactions. Forecasting in any precise way is impossible.

However, one can draw a map of potential futures to create a ‘design space’ (Stankiewicz, 2000). Like every space, the design space has dimensions, and every conceivable system should be possible to describe in terms of these dimensions. Instead of deciding, a priori, what are realistic futures within this space, the analyst can first look at the extreme positions. The development from the current state towards one of these extreme positions forms an idealised scenario. Such idealised explorative scenarios take as a starting point, neither what is desirable, as in backcasting, nor what is likely, but what is theoretically possible (Börjeson et al., 2006). The key *socio-technical components* of these truly alternative scenarios and endpoint systems can then be the focus of monitoring and trend analysis, which in turn is used to determine which scenarios that are starting to materialise.

### 2.3. Tracing structural build-up by monitoring system components

At one level, the idealised electricity systems can be described by a set of technical artefacts and their relations. However, these need to be accompanied by constellations of actors and institutions that together with the technical components form a socio-technical system. While using slightly different concepts and delineations, various strands of the socio-technical and innovation systems literature seem to agree on a limited number of distinguishable component categories of such systems (Bergek, Jacobsson, Carlsson, et al., 2008; Geels, 2004; Hughes, 1987b; Kemp et al., 1998; Rip & Kemp, 1998; Sandén & Hillman, 2011; Wiczorek & Hekkert, 2012). Here, we structure the empirical data following a categorisation from the technological innovation system (TIS) framework (Bergek, Jacobsson, & Sandén, 2008), an approach that has dealt in detail with the emergence and growth of novel socio-technical systems. Hence, we primarily distinguish between technology, actors and networks, and institutions.

*Technology* here refers to physical artefacts that make use of natural phenomena to produce services (Arthur, 2009), and to descriptions of the same processes, commonly referred to as technical knowledge (Bergek, Jacobsson, & Sandén, 2008; Sandén & Hillman, 2011). *Actors and networks* refers to an organizational dimension populated by people (Sandén & Hillman, 2011), where ‘actors’ refers to individuals or groups of individuals that are hierarchically linked in organizations, and ‘networks’ to more loosely linked groups of actors. ‘Organizations’ includes not only firms but also knowledge institutes, 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, Carlsson, et al., 2008; Bergek, Jacobsson, & Sandén, 2008). The category includes regulative, normative and cognitive institutions (Palthe, 2014; Scott, 2001). Regulative and normative institutions include hard regulations controlled by the juridical systems and norms and attitudes towards what is desirable. The cognitive institutions i.e. beliefs and expectations about what is reasonable, or “true” and taken for granted, are as important. Technologies do not pre-exist by themselves but are created through beliefs and expectations about how the world works and will develop. Beliefs and expectations shape the perceived potential and future materialisation of different technologies (Borup, Brown, Konrad, & Van Lente, 2006; Van Lente, 2012; Van Lente et al., 2013).

Some of the required components need to be developed afresh specifically for the targeted system, while others can be ‘borrowed’ from other systems due to *socio-technical overlaps*.

### 2.4. Socio-technical overlaps, niche accumulation and hybridization

As observed already by Schumpeter (1934), new systems are never independent of old structures and innovation is essentially a process where older and newer elements are combined in novel ways. This means that new electricity systems will make use of technology, actors and institutions available in the old electricity regime and/or borrow such elements from other sectors. In other words, a new system may have a larger or smaller socio-technical overlap with the regime and other industries (Sandén & Hillman, 2011). Novel systems may also share system components with other emerging systems enabling development not only through competition but also through complementarities (Markard & Hoffmann, 2016), leading to parasitic or symbiotic relations (Sandén & Hillman, 2011); the development of one piece of technology, actor constellation or legislation may benefit more than one alternative system.

With regards to the relation between niches and regime, Raven (2007) points at two general ways to create spaces for new systems – niche accumulation and hybridization – that differ in their level of overlap with the regime. *Niche accumulation* is the process where novel systems build up internal momentum, i.e. improve technically and gain economic and political strength, by experimentation and deployment in specific separate niches where the novelty has some kind of performance advantage (Kemp et al., 1998), and where new niches are added as the systems develop. In this case the novel system, or ‘technology’, tends to borrow more from other sectors. A case in point is solar PV that initially was related to and benefitted from the electronics and space industries, and which only lately has made an impact on the energy sector. Another is lithium-ion batteries, that have developed through application in,

first, consumer electronics and, then, electric vehicles, now making them viable for wider application in the electricity system. In the case of *hybridization* the development, instead, starts closer to the dominant regime by forming hybrid technologies (Geels, 2002) or ‘bridging technologies’ (Sandén & Hillman, 2011) that partly build on the old and partly on the new system, which then deviates to more radical forms. The use of the old electricity grid itself in new configurations is an example of hybridisation based on a shared component. Another, more speculative, example is electromobility that could develop into a bridging technology by first relying on and supporting the traditional electricity system and its actors, but also, over time, demanding and facilitating its transformation into something quite different.

The identification of overlaps may provide insights into the speed and strength of different accumulation and alignment processes.

### 2.5. System boundaries

While most things in this world are linked in some way, we need system boundaries to delimit and focus data collection. Here, the unit of analysis is not a single technical component but alternative systems comprising various socio-technical components. We set the socio-technical boundary to include components directly involved in electricity generation, storage and transmission. We acknowledge that reconfiguration of the electricity system will happen in parallel to transformations of other energy supply chains, e.g. biofuels for heating and transportation, but these are outside the scope of our analysis. Since the purpose is to investigate systems based on hundred per cent renewable (not merely climate neutral) energy, development within nuclear energy and carbon capture and storage (CCS) is not monitored, neither is the development within various electricity end use categories (with the exception of electric vehicles that also can function as storage and balancing technology). Since the electricity system cannot be changed overnight, pathways to hundred per cent renewables require phases where nuclear, coal and natural gas power plants play important roles in balancing the system (Göransson, Goop, Odenberger, & Johnsson, 2017; Johnsson, Odenberger, & Göransson, 2014; Qadrdan, Chaudry, Jenkins, Baruah, & Eyre, 2015). The dynamic techno-economic interplay between different power sources in the electricity mix is of relevance for an in-depth analysis of hybridisation in the electricity systems of individual countries or regions. This is, however, outside the scope of the study. The purpose of this paper is to monitor the development of main components of future (endpoint) electricity systems based on 100% renewables, and to discuss a broader set of sociotechnical overlaps with the current electricity system and other sectors.

Furthermore, we set the spatial boundary at the global level. Although many transition studies choose national or regional boundaries, partly for practical reasons, we believe that, in this case, the national scale limits us from capturing key trends. Transitions of this scale in a globalised world economy are partly shaped by supra-national actors such as multi- and transnational organisations (Coenen, Benneworth, & Truffer, 2012; Hansen & Coenen, 2015), and maybe even more so by the aggregated impact of phenomena originating in different countries and spreading across the world, combining in new ways.

While, arguably, many roots of current trends stretch far back in history, for practical reasons, the temporal boundary of data monitoring is set to 2000–2016.

### 2.6. Data

Data were collected from a range of secondary sources. First, we reviewed the existing academic literature to identify three idealised system types that could be positioned at extreme points in a two-dimensional design space. In the second step, we used academic literature to identify key socio-technical components of the alternative systems. The findings from the literature review were coupled with data collected from websites, reports, newspaper articles and online datasets to monitor potential growth trends among these components. The data is limited to sources available in English. While limiting the depth of analysis, our use of only secondary data sources enabled scanning of a very broad empirical field within a limited timeframe.

## 3. Idealised future electricity systems

In this section, we first identify three alternative idealised future electricity system architectures and then trace their evolution in terms of emerging and accumulating system components.

### 3.1. Three scenarios in one design space

Based on existing literature, we found *the level and type of interconnectedness* to be a decisive characteristic in descriptions of different future renewable electricity systems. In principle, one can distinguish between systems of dependent, interdependent and independent electricity consumers (Fig. 1). These idealised network models correspond relatively well to three articulated visions: the ‘Super-grid’, the ‘Smart-grid’ and the ‘Off-grid’.

In their extreme forms, these idealised systems are positioned in three different corners of a *design space* that can be described by two variables, the number of production units (P) and the number of grids (G) in the world, and how they relate to an assumed constant number of consumers (N) (Fig. 2). The Supergrid (A) then represents a step from the current system (X) towards the extreme case where there is only one centralised production unit ( $P = 1$ ) in one global grid ( $G = 1$ ). All consumers are dependent on this one production unit. The extreme version of the Smart-grid configuration (B) also shows maximum global connectedness ( $G = 1$ ), but has as many production units as consumption units ( $P = N$ ). Every consumer is also a producer, i.e. a prosumer, and they are all interdependent. Finally, the endpoint of the extreme Off-grid scenario (C) is a completely disconnected system having as many ‘grids’ as

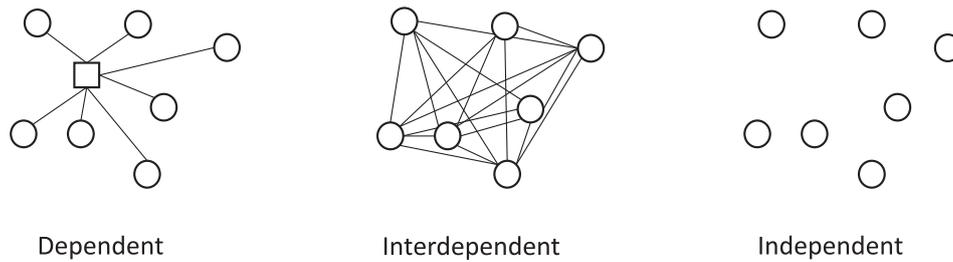


Fig. 1. Different system organizations of electricity consumers and producers representing the ‘Super-grid’, the ‘Smart-grid’ and the ‘Off-grid’ scenarios.

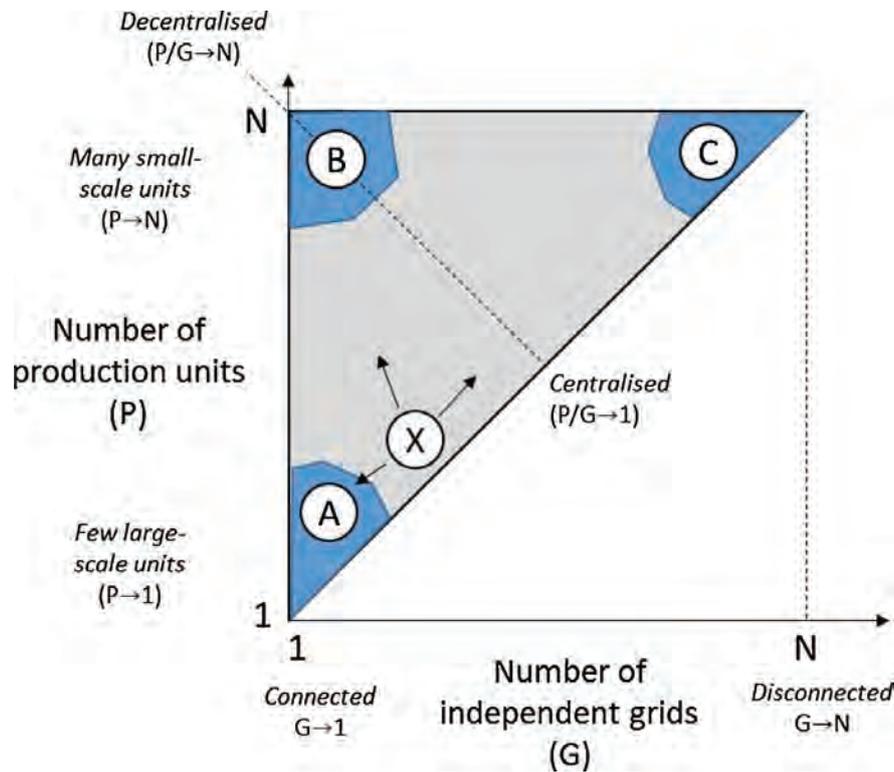


Fig. 2. Three scenarios in one design space. The number of independent grids ( $G$ ) ( $x$ -axis), and the number of electricity production units ( $P$ ) ( $y$ -axis), can vary between 1 and the number of consumption units ( $N$ ). The current electricity system ( $X$ ) may develop towards a ‘Super-grid’ ( $A$ ), a ‘Smart-grid’ ( $B$ ) or an ‘Off-grid’ system ( $C$ ).

production and consumption units ( $G = P = N$ ). Every consumer is independent. One can then note that the Super-grid and the Off-grid scenarios have one attribute in common: centrality, i.e. each grid is hierarchically organised with one production unit per grid ( $P/G = 1$ ), allowing for top-down control in each grid. The extreme Smart-grid on the other hand is the ‘ideal market’ with extremely decentralised production ( $P/G = N$ ), no hierarchy and no top-down control.

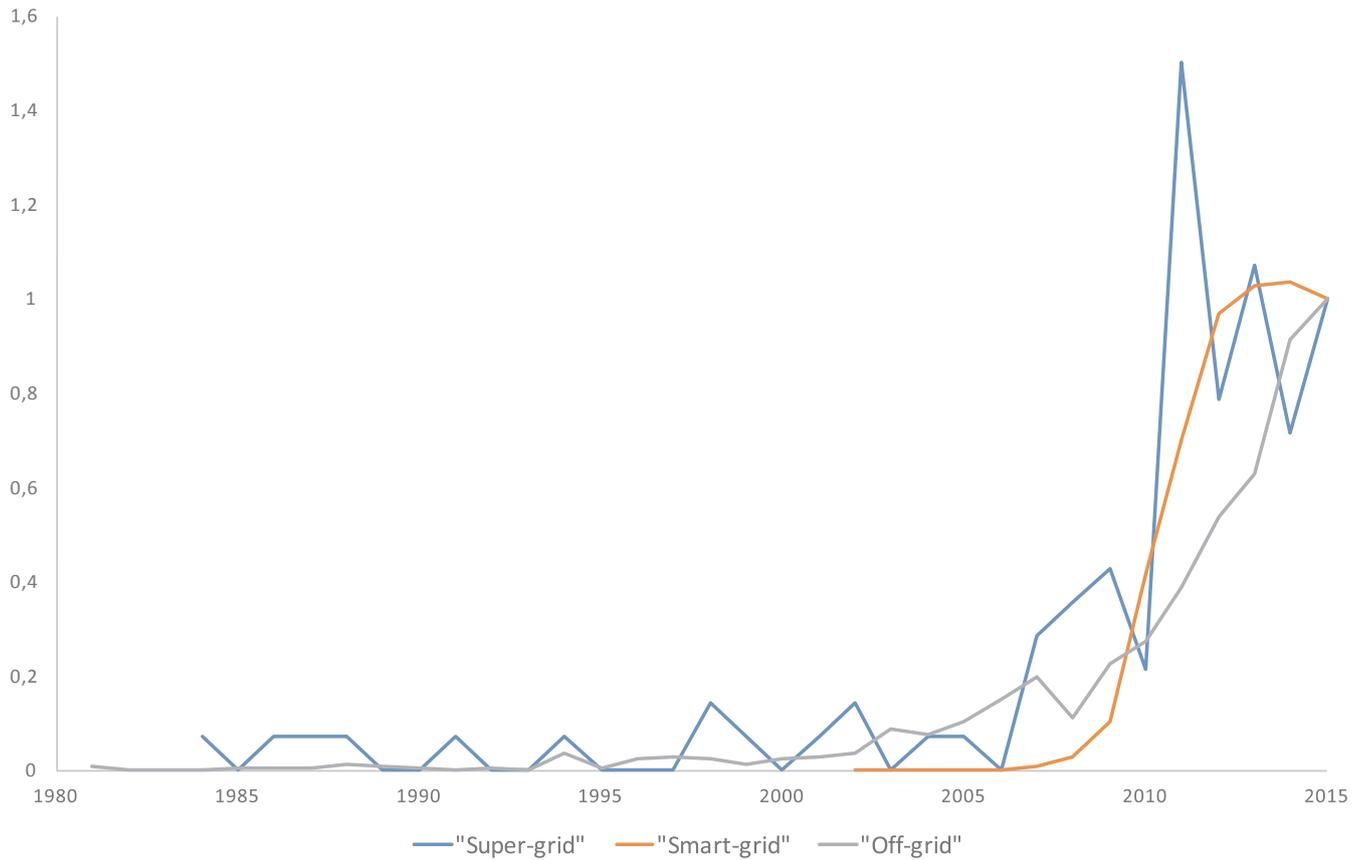
If we assume that the number of production units does not exceed the number of consumption units, any system configuration can be positioned within the design space illustrated by the grey triangle in Fig. 2.

To bring clarity to the analysis we select idealised systems that are positioned quite close to the extreme corners as a starting point, instead of striving to identify some arbitrary ‘realistic’ scenarios (that are bound to be strongly coloured by present day dominant discourses). This also makes it easier to discuss various hybrid and middle-ground system configurations at a later stage. In the following, we refer to our idealised scenarios (and the visionary concept or idea) with capital letter, e.g. the Super-grid. The literature is inconsistent in spelling, so we use organizational and project names as they appear in the literature, e.g. the “European Supergrid”.

As illustrated in Fig. 3, a bibliometric analysis indicates a rapidly growing interest, in relative terms, in all three scenarios. The next step is to monitor the emergence of key socio-technical components that enable, or are required for, realization of the three alternatives. An overview of main socio-technical components of the three scenarios, detailed in the following sections, are provided in Table 1.

### 3.2. The Super-grid scenario

One articulated vision is a system characterised by highly centralised renewable electricity production and large-scale transmission over long distances, spanning across continents or even the entire globe (Battaglini et al., 2009; Funcke & Bauknecht, 2016).



**Fig. 3.** Relative growth of interest in three emerging systems. Number of academic articles in the database Scopus that explicitly refer the three system architectures: Super-grid, Smart-grid and Off-grid. All numbers are scaled to the publication rate in 2015. See also Fig. 6 for absolute numbers. Search terms: ‘Super-grid’, ‘Smart-grid’, ‘Off-grid’.

Source: [scopus.com](http://scopus.com)

**Table 1**  
Socio-technical components of the three idealised scenarios.

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

The rationale behind such a ‘Super-grid’ is to make efficient use of unevenly distributed renewable energy resources, connect them to load centres, and handle large-scale penetration of variable energy sources, while avoiding the need for storage or demand flexibility (Blarke & Jenkins, 2013; Liu, 2015). It requires close cooperation between central governments and an exclusive number of manufacturers, utilities and transmission system operators (TSOs) (Foxon, 2013). The Super-grid scenario resembles the ‘greening of the centralised production’ scenario, proposed by Verbong and Geels (2010), as the incumbent actors of the dominant electricity sector are assumed to keep their positions, while electricity consumers remain a passive part of the system.

### 3.2.1. Technology

The envisioned electricity system of the Super-grid is based on large power plants, typically power parks at the multi GW scale of on-shore wind in desolated areas, off-shore wind at sea, and solar photovoltaics (PV) and concentrated solar thermal power (CSP) around the equator, combined with large-scale installations of tidal and wave power, biomass and geothermal energy where available (Battaglini et al., 2009; Foxon, 2013; Meeuwssen et al., 2008). Generation is connected to load centres with long distance extra high (EHV) and high voltage cables (HV).

Technology seems not to be a show-stopper for turning the global Super-grid into reality (MacLeod et al., 2015). In fact, most of the technical components required are relatively mature and some already exist as parts of the current electricity system. In addition, knowledge production in key technologies has accelerated over the last decade, as illustrated in Fig. 4. HVDC technology is of particular interest since it enables very long-distance transmission on land and ocean floors. According to MacLeod et al. (2015), 2013 saw a breakthrough in HVDC technology, with the introduction of the voltage source converter (VSC) that allows for 50% higher voltage level and the HVDC circuit breaker that is crucial for reliable operation of an interconnected HVDC infrastructure.

While a Super-grid can reduce the need for storage, as excess of power at one place can be transferred to other places, the grid also enables hydropower stations to be used as centralised storage. Such storage potential already exists in about 40 countries (Williams, 2016), possibly best exemplified with the endeavour to turn Norway’s hydropower plants into Europe’s battery (Fairley, 2014).

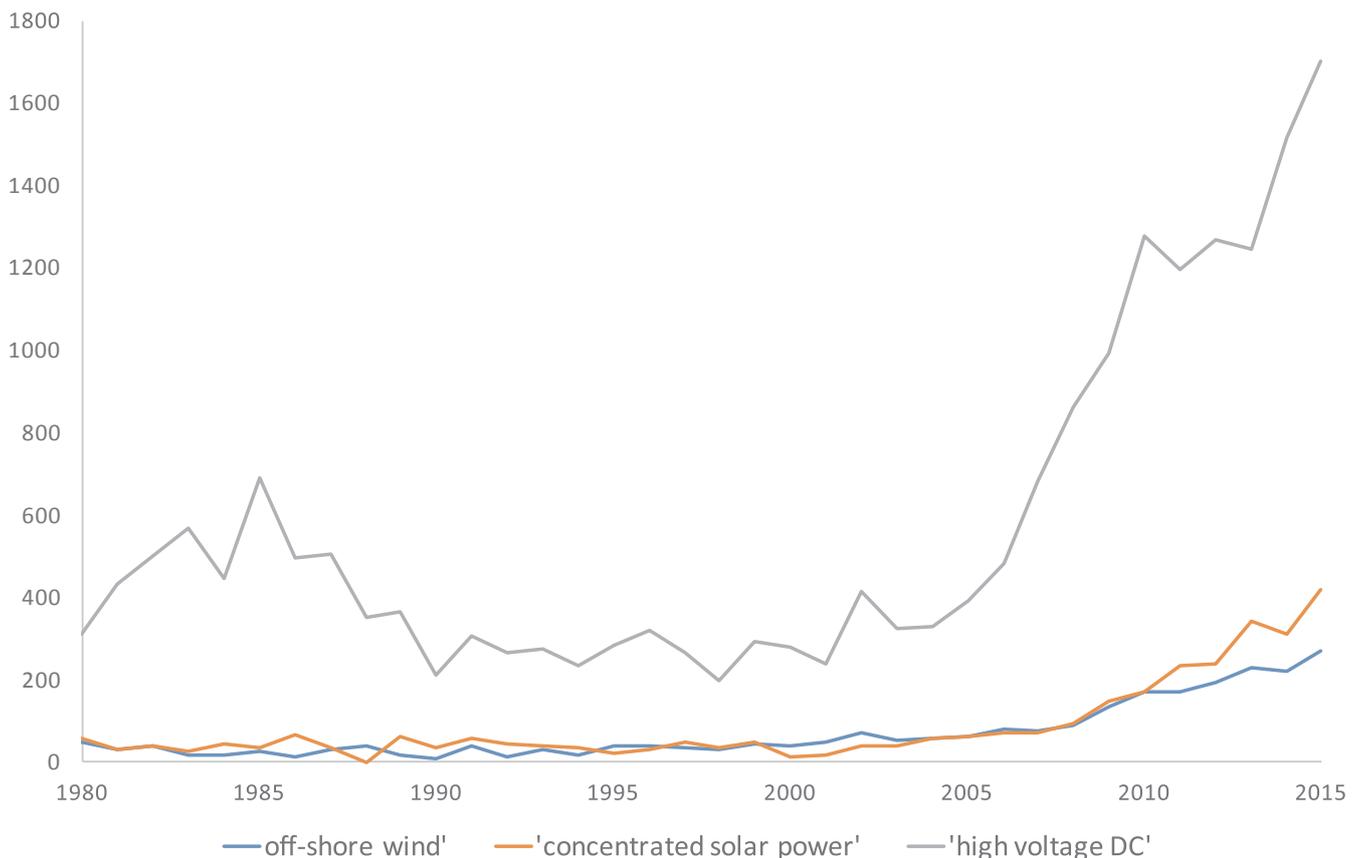


Fig. 4. Knowledge creation related to three characteristic technical components of the Super-grid system (values are deflated by scaling annual values to total annual number of publications in the database). Search terms: ‘off-shore wind’, ‘concentrated solar power’, ‘high voltage DC’.

Source: [scopus.com](http://scopus.com)

### 3.2.2. Actors and networks

A Super-grid interconnecting all the corners of the world today only exists as an ambitious idea. The planning and implementation of cross-national grids has, so far, been based on ‘the government logic’ with a strong political character, according to which national government actors together with a few large private stakeholders coordinate expansion to achieve energy policy goals (Chatzivasileiadis, Ernst, & Andersson, 2013; Verbong & Geels, 2010). The construction of Super-grid infrastructure is currently in the hands of a few leading incumbent power system companies such as the ABB, Siemens and GE Grid Solutions.

A significant number of actors and networks advocating the Super-grid can be found in EU and surrounding regions. In 2008, the European Commission called for the construction of regional transmission grids that could eventually be linked into a pan-European Super-grid and supply Europe with renewable power generated from the Mediterranean region to the North Sea<sup>1</sup> (Gellings, 2015). The European Network of Transmission System Operators (TSOs) for Electricity (ENTSO-E), an association of 42 TSOs, from 35 countries, has been given the responsibility to develop a roadmap towards a pan-European power system by 2050, known as e-Highway2050. Since 2012, the industry association Friends of the Supergrid (FOSG) has published annual reports on the roadmap (FOSG, 2016). FOSG represents the entire supply chain required for construction of a Super-grid, comprising of TSOs, experts from cable manufacturers, project developers, consultants and logistics companies (MacLeod et al., 2015).

Dominant actors promoting the Super-grid in the wider European region is the Desertec Foundation and the Desertec Industrial Initiative (Dii), both founded in 2009. Desertec Foundation was formed as a non-profit network of scientists, politicians and economists from around the Mediterranean region with a plan to use HVDC to power Europe by Saharan large-scale CSP. Dii was established as an ‘international’ consortium of companies with the target of converting the Desertec concept into a profitable business project (Hamouchene, 2015). Dii brings together firms of mainly German origin such as E.ON, Munich Re, Siemens and Deutsche Bank, but cooperates also with Middle East and North African countries, for instance within the Medgrid project (SETIS, 2014).

Inspired by the Desertec concept, an Asian version known as the Gobitec Initiative was proposed in September 2009 by academics in Northeast Asia. The Gobitec Initiative triggered an interest in constructing an Asian Super Grid, which would connect grids of China, Japan, Korea, Mongolia and possibly also Russia (more speculatively also Taiwan, Thailand, the Philippines, and India) and transmit wind and solar electricity from remote areas to load centres. The Asian Super Grid was proposed by Son Masayoshi, CEO of Japan’s Softbank, in 2012 after the Fukushima disaster. Later the same year, the first agreement was announced with a Mongolian company, Newcom, on developing a giant wind farm in the Gobi desert that would be connected to the Super-grid (Mathews, 2012). In 2016, the world’s largest electricity utility company, the Chinese State Grid, officially joined (Colthorpe, 2016; Minter, 2016). China has recently become the world leader in the development and deployment of HVDC technologies, which shows in the significant growth of kilometres of HVDC in Asia over the last fifteen years (Fig. 5). The Chairman of the Chinese State Grid, Liu Zhenya, publicly called himself a supporter of the Super-grid as it will “create a community of common destiny for all mankind with blue skies and green land”, and the Chinese president Xi Jinping proposed an initiative on establishing a Global Energy Interconnection (GEI) to meet global power demand and green alternatives (GEIDCO, 2017; Minter, 2016).

In contrast, in the USA a historical heritage of balkanised grid infrastructure with multiple tiny grids and ineffective regulatory structure has hindered upgrades of the U.S. transmission network and the construction of a North American Super-grid (Kraemer, 2009). The only big project in this direction is known as ‘Tres Amigas’, proposed in 2009 with the aim of connecting three separate grids: the Eastern Interconnection, the Western Interconnection, and the Texas Interconnection (Kraemer, 2009). In 2015, however, the billion-dollar plan to connect the three grids had failed to meet its milestones after losing a key partner (St.John, 2015). In other parts of the world, such as South America, Australia and Oceania, or Sub-Saharan Africa, few or no actors promote projects aiming at building a Super-grid.

### 3.2.3. Institutions

The real challenges for turning the global Super-grid into reality are not technical but political and social. According to Gregor Czich, a German Super-grid advocate, if a regulatory framework for the intercontinental grid were established today, our current technical abilities would allow us to build the Super-grid within twenty years (Dauncey, 2009). However, large-scale infrastructural projects across national boundaries is hindered by a low level of institutional alignment (Shuta et al., 2014). A necessary first step towards the required coordination is a shared vision of, and belief in, the Super-grid as the electricity system of the future. Vision statements and roadmaps as well as expectations forming around pilot projects are thus representing the first (cognitive) institutional building blocks of the Super-grid in Europe and Asia (Borup et al., 2006; Van Lente, 2012).

In Europe, FOSG articulates the expectation of the Super-grid as the only means to achieve a 90% decarbonised electricity system in Europe by 2050, as well as an enabler of secure, reliable and cost-effective electricity (FOSG, 2014). Although no legal frameworks or regulations are in place at this point, efforts are made, especially within the EU, to encourage collaboration and harmonization between various projects.

The vision of the Asian Super Grid is backed up by high expectations that it will bring job creation, poverty alleviation and reduction of carbon dioxide emissions (Shuta et al., 2014). To meet these expectations, the Asian Super Grid Initiative proposed the Energy Charter Treaty (ECT), a legal framework for long-term cooperation between countries that are producing, consuming and transmitting energy across the grid. ECT is an inclusive multilateral agreement that provides a comprehensive set of rules covering the entire energy chain from production and generation to the terms under which electricity can be traded and transmitted across

<sup>1</sup> Projects funded by the European Union: Better Project, E-Highway2050, GridTech Project, Market4RES, MEDOW, NSCOGI, The North Sea transnational grid, The North Sea Grid (FOSG, 2016; Gellings, 2015)

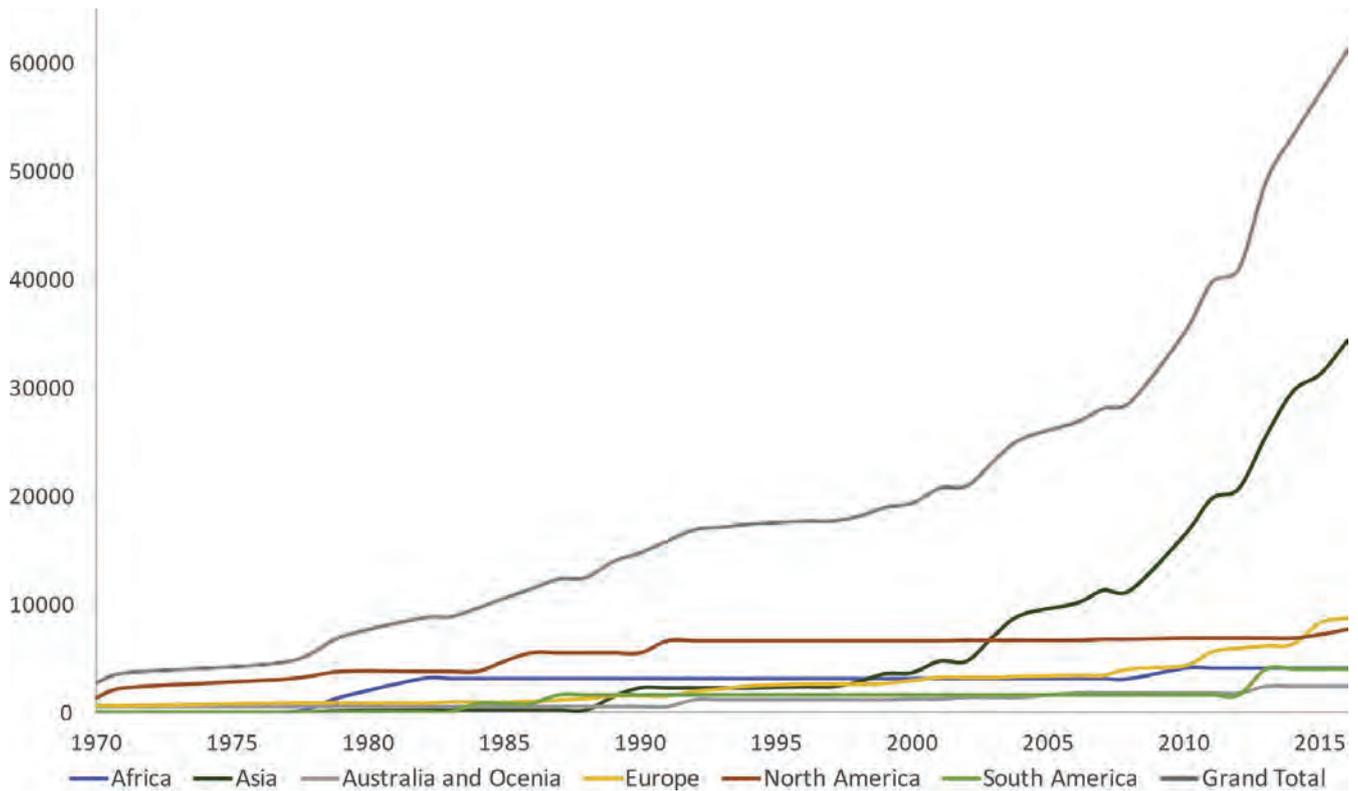


Fig. 5. Number of kilometres of HVDC worldwide (cumulative numbers). ([https://en.wikipedia.org/wiki/List\\_of\\_HVDC\\_projects](https://en.wikipedia.org/wiki/List_of_HVDC_projects)).  
Source: [wikipedia.org](http://wikipedia.org)

different national jurisdictions and markets. So far, 52 countries plus the EU and the European Atomic Energy Community have signed the treaty, which serves as a uniting framework for political and legal aspects related to the Asian Super Grid Initiative (Shuta et al., 2014).

Besides these visions and early attempts of grid regulation, we also find that market support of renewables has shifted from investment support and feed-in tariffs (FiTs) towards call for tenders for utility-scale renewable energy projects, which tends to support the development of centralised renewable electricity production. In the case of solar power, the shift from feed-in tariffs to tenders began in 2015 and is expected to continue over the next couple of years (PVPS, 2016).

### 3.3. The Smart-grid scenario

Another option for the future is a system based on decentralised interconnected electricity production, which we here refer to as the Smart-grid. Although the concept of the Smart-grid can be interpreted in different ways, we understand it as an interconnected bidirectional electric and communication network of ‘prosumers’. Such a system is enabled by the small-scale modular character of many renewable energy technologies (Battaglini et al., 2009). Furthermore, ICT plays a major role in increasing efficiency, reliability and security of the Smart-grid (Blarke & Jenkins, 2013; Hertzog, 2010). Such ‘smart’ technologies enable a system with a flat hierarchy in which everyone has the chance to actively participate in a highly competitive electricity market (Foxon, 2013).

#### 3.3.1. Technical components

From a technical perspective and in comparison with today’s system, the average size of production units and the voltage level decreases and the electricity is delivered over shorter distances (Foxon, 2013). Importantly, a Smart-grid system is comprised of not only electricity networks and renewable electricity generation technology but also of interfaces using various innovative communication, metering and storage technologies. Many of these technologies are already considered mature in both their development and application, while others require further development and demonstration (OECD/IEA, 2011). Fig. 6 shows that the scholarly interest in the concept of the Smart-grid has been notably higher than in the other two system configurations over the last ten years. Looking at some of the individual technical components in a Smart-grid, we can also observe increased research activities (Fig. 7). Technical components typically contributing to a Smart-grid are listed in Table 2.

A key component is the flexible AC transmission system (FACTS), i.e. flexible power electronics that reduce energy losses by enabling real time reconfiguration of power flows. FACTS allows system managers to send more power through the cable, for example at times of peak hours when solar panels generate higher volumes of electricity than usual (Fairley, 2010). ICT in general enables real-time power control and two-way exchange of information between stakeholders (OECD/IEA, 2011). The two-directional flow of information is enabled by Advanced Metering Infrastructure (AMI) technologies, which provide prosumers and local utilities with

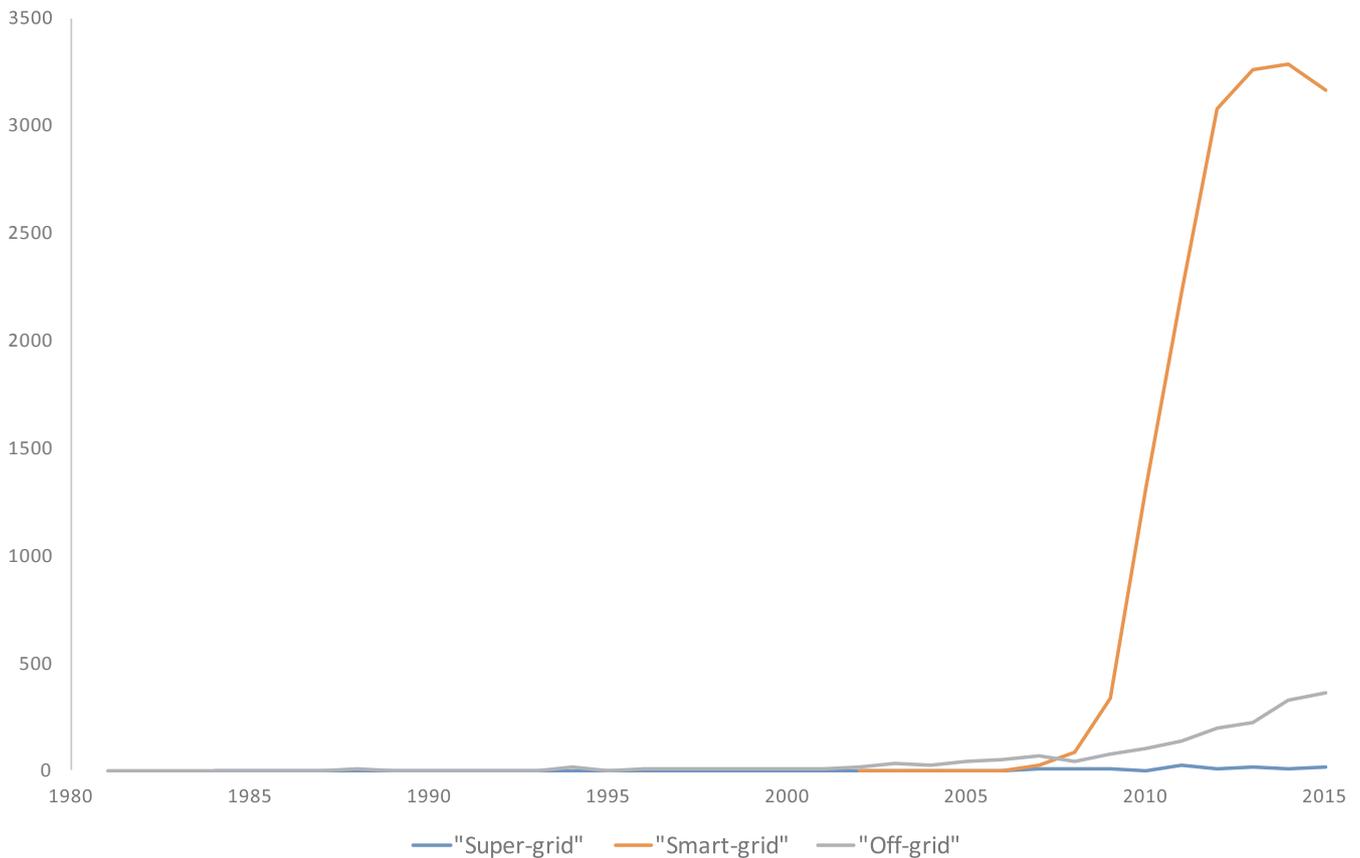


Fig. 6. Number of articles, in absolute terms, related to the three scenarios (compare relative numbers in Fig. 3).

Source: [scopus.com](http://scopus.com)

time resolved data on prices and electricity production and consumption (OECD/IEA, 2011). Also other, currently less well-developed, artefacts could solve issues of control in the future smart grid; battery technologies and technologies for distribution grid management and customer-side management are increasingly affordable and accessible (OECD/IEA, 2011). In addition, electric vehicles play an increasingly important role as a flexible balancing technology via the vehicle-to-grid (V2G) concept, in which EV and the grid exchange electricity. Existing research has shown that most vehicles are parked almost 95% of the time. These vehicles could be connected to the grid and deliver stored energy required in case of need to balance local electricity supply. In fact, many assume that since available stationary storage technologies are still expensive, EV batteries can act as dynamic storage devices and support the integration of variable RE technologies into the grid (Mwasilu, Justo, Kim, Do, & Jung, 2014)

One advanced vision of the Smart-grid could be termed the “internet of electricity” (Mazza, 2002), where anyone would be able to upload and download electrical energy packages at any time (Meeuwssen et al., 2008), also known as Peer-to-Peer electricity trading (Murkin, Chitchyan, & Byrne, 2016; Zhang, Wu, Cheng, Zhou, & Long, 2016). The blockchain technology, applied for instance in the financial sector through cryptocurrencies such as Bitcoin, is increasingly promoted to be the future solution for Peer-to-Peer trading and the ‘internet of things’ (Dickson, 2016). Blockchain seems to offer an alternative to the dominant monopolised supply and distribution of electricity based on administrative systems. Blockchain is a database that automatically records and keeps track of individual actions within a system and stores the results in a secure online folder available to anyone anywhere. In a future system based on prosumers, such technology could enable a quicker and more decentralised transaction system (Hirtenstein & Zha, 2016).

### 3.3.2. Actors and networks

A global network of actors promoting the Smart-grid is the International Smart Grid Action Network (ISGAN) established in 2010 by the Clean Energy Ministerial (CEM), a regular convention of energy and environment ministers from 23 countries and the EU. The USA initiated ISGAN at the Copenhagen climate convention in 2009. It is a knowledge network that serves as a platform for multilateral intergovernmental collaboration and aims to drive the development and deployment of Smart-grid technologies and systems. ISGAN collaborates with various Smart-grid organizations (IEA-ISGAN.org, 2016). One of these is the Global Smart Grid Federation (GSGF) also established in 2010 as a global stakeholder organization comprising public and private organizations involved in Smart-grid development from 15 countries and the EU. Among members of the GSGF we can find the European distribution system operators (EDSO), Smartgrid Ireland, France and Norway, the Israeli, Japanese and Korean Smart Grid Associations, India Smart Grid Forum and Smart Grid Mexico ([globalsmartgridfederation.org](http://globalsmartgridfederation.org), 2016).

The European Commission launched six Europe-wide demonstration projects in 2011, Grid4 EU, that brought together European DSOs; utilities such as Vattenfall, Enel and ERDF; manufacturers such as ABB, Cisco and Siemens; and research institutes. An example

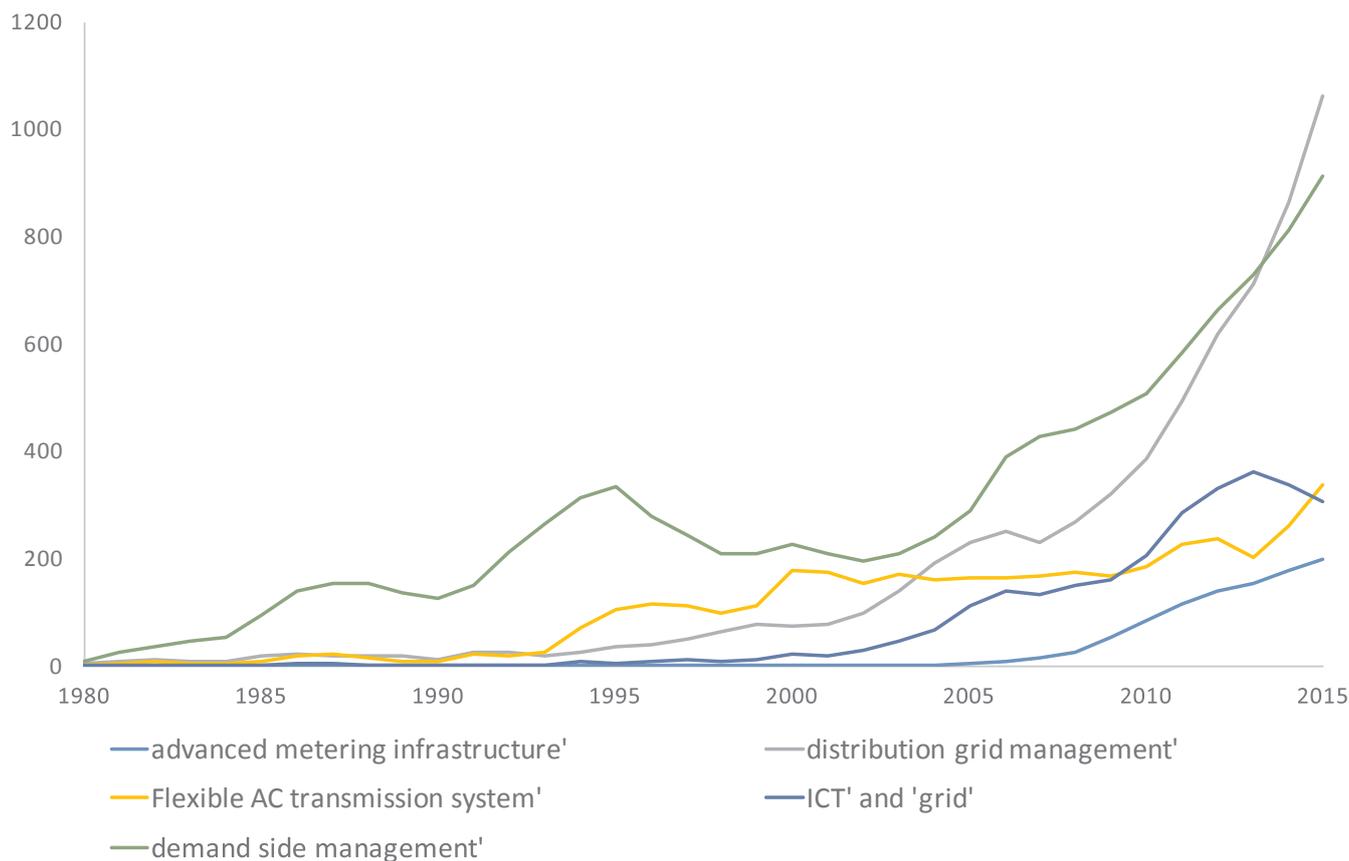


Fig. 7. Knowledge creation related to smart-grid technical components (deflated values). Search terms: ‘advanced metering infrastructure’, ‘distribution grid management’, ‘Flexible AC transmission system’, ‘ICT’ and ‘grid’, ‘demand-side management’.  
Source: [scopus.com](http://scopus.com)

Table 2  
A selection of smart-grid technical components. Adapted from [OECD/IEA \(2011, 2015\)](#).

Technology area	Technical components	Maturity level
Grid infrastructure	Flexible AC transmission systems FACTS	Mature
ICT integration	Communication equipment Routers, relays, switches, gateway, computers (servers) Customer information system Enterprise resource planning software	Mature
Advanced metering infrastructure (AMI)	Smart meters In-home displays Servers, relays Meter data management systems	Mature
Variable and distributed generation integration	Geographic information and management systems Communication and control technology for generation and storage technology	Developing
Distribution grid management	Remotely controlled distributed generation and storage Transformer sensors, wire and cable sensors Automated re-closers, switches and capacitors Distribution, outage and workforce management systems Geographic information systems	Developing
Customer-side systems	Vehicle-to-grid storage and balancing systems Smart appliances, routers, building automation systems Thermal accumulators, smart thermostat Energy management systems and dashboards Energy applications for smart phone and tablets Blockchain electricity transaction platforms	Developing

is the Nice Smart Solar District at the French Riviera, where voluntary prosumers from residential buildings and commercial local industries had the opportunity to actively manage their electricity consumption ([Accenture Consulting, 2015](#)). In total 459 Smart-grid projects from the 28 member states of the EU have been launched between 2002 and 2014. These include all the projects that aim to make the grid intelligent by implementing new technologies and ICT capabilities. [Fig. 8](#) shows the notable increase in the number of new Smart-grid projects between 2003 and 2013 ([European Commission, 2014](#)).

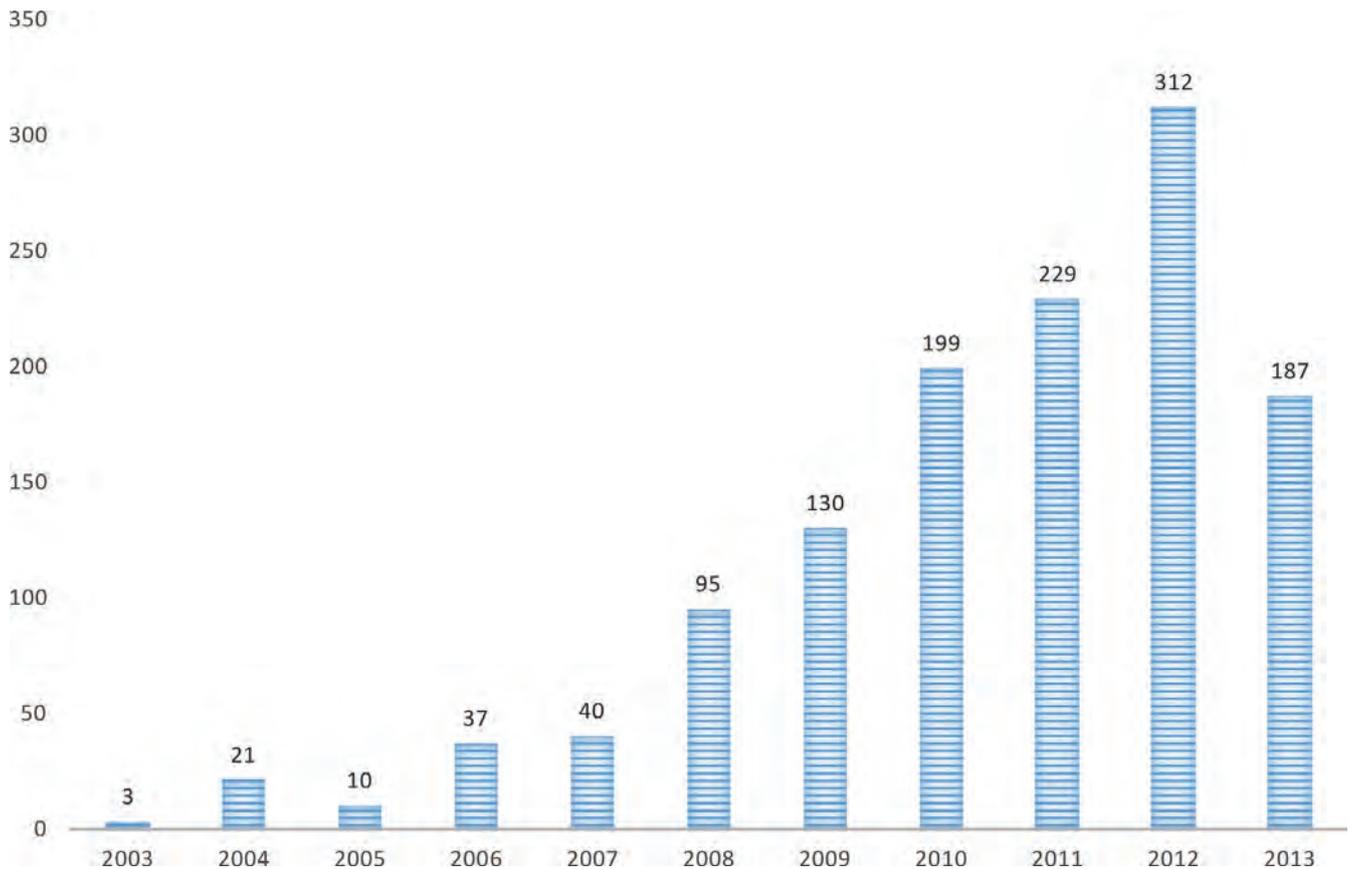


Fig. 8. Annual launch of new Smart-grid projects between 2003 and 2013 in the European Union. Source: <http://ses.jrc.ec.europa.eu/smart-grids-observatory>.

Furthermore, the Asia-Pacific Economic Cooperation (APEC) launched the Energy Smart Communities Initiative (ESCI) in 2010, proposed by the presidents of US and Japan. ESCI incorporates a knowledge sharing platform that represents a space for collecting and sharing best practices for creating Smart-grid communities ([Esci-ksp.org](http://Esci-ksp.org), 2016). After the Fukushima nuclear disaster in 2011, Japan is particularly dedicated to promoting Smart-grids to increase energy efficiency and renewable power generation. The New Energy and Industrial Technology Development Organization (NEDO) has funded several demonstration projects. In 2010, NEDO brought together nine Japanese companies to launch a Japanese-US Smart-Grid demonstration project in Albuquerque, New Mexico. This project is perceived as a good example of the growing international cooperation promoting the Smart-grid (Stuart, 2012). In 2016, NEDO coordinated domestic Smart-grid and international projects in India, Indonesia, China, multiple European countries and the USA.

In North America, dedicated supporting legislation in 2011 resulted in record spending on Smart-grid projects in the USA and Canada. In 2012, the major projects funded by the US Department of Energy included 99 Smart-grid investment grants, 32 Smart-grid demonstration projects and nine renewable and distributed system integration projects (Fulli & Bossart, 2012; [Smartgrid.gov](http://Smartgrid.gov), 2016).

Many of the Smart-grid technologies are being developed and supplied by incumbent power system companies, such as ABB and GE producing FACTS, but also incumbents from other sectors such as Siemens testing AMI technologies, Cisco supplying ICT solutions, and Nissan working together with power company Enel to develop ways to use EVs as storage and balancing technologies for Smart-grids (Lambert, 2016). In addition, a growing number of start-up companies are entering the market and receiving increasing capital funding. They offer innovative solutions for Smart-grids, battery technologies and energy efficiency (Hill, 2016). Thus, a more diverse and competitive market is being created around Smart-grid systems compared to the Super-grid.

### 3.3.3. Institutions

The global community is still in the early stages of creating standards for the technical artefacts and their interoperability in a Smart-grid system. However, despite the lack of universal standards, countries all over the world actively continue Smart-grid related planning and implementation. Given that a Smart-grid system can be built around multiple regional and highly connected systems, the development of standards does not necessarily have to be globally aligned. Rather, alignment needs to take place along the supply-chain, involving various governmental actors, utilities, private vendors and other stakeholders. Their cooperation is crucial for the development of necessary standards (Lundin, 2015). Such collaboration was enabled after the establishment of ISGAN and GSGF in 2010, as platforms that facilitate international discussion related to Smart-grid standardization and development (SAIC, 2011).

In 2016, Smart-grid systems existed in the form of demonstration projects. Expectations attached to these initiatives is what drives the further development of Smart-grids. Although the vision of the smart-grid differs among various actors and networks (Fulli &

Bossart, 2012; SAIC, 2011), the general expectation is to build a grid that can integrate and better utilise distributed small-scale renewables (IEA-ISGAN.org, 2016) and empower the consumer side (ANEC/BEUC, 2010).

3.4. The Off-grid scenario

Instead of increased connectedness as in the Smart-grid, the electricity system transition could lead to large-scale grid defection (Zinaman et al., 2015). ‘Leaving the grid’ and ‘living off-grid’ have recently become feasible options, mainly due to falling prices of solar cells and batteries.

Hitherto, off-grid systems have mainly been viewed as a solution for poor countries, where people still live without access to well-functioning electricity grids. While off-grid systems are not new and not just a vision, they have been perceived as short-term solutions. However, this understanding is shifting and off-grid solutions are more and more seen as a way to leapfrog the conventional centralised mode and avoid carbon intensive electricity production. Off-grid solutions are increasingly accepted as an essential part of future energy solutions that could provide global access to electricity (Ahlborg & Sjöstedt, 2015; Doig, 1999). More recently, increased attention has been given to the phenomenon of going off-grid also in industrialised countries (Bronski et al., 2014; Khalilpour & Vassallo, 2015).

3.4.1. Technical components

Off-grid systems are not connected to large-scale utility grid infrastructure. Instead, they consist of stand-alone systems of power generation and distribution that supply electricity to local communities via a mini or micro-grid, to a single house, or even to individual appliances. Key enabling technologies for off-grid systems are small-scale renewables, such as PV, wind or micro-hydropower plants coupled with a storage technology (Zinaman et al., 2015). Off-grid systems based on small-scale hydropower and diesel generators have a very long history, but the recent cost reduction and availability of solar PV and batteries has given off-grid systems a renaissance. The rapid development of these key enabling technologies is also reflected in scholarly knowledge production (Fig. 9).

At the household level, the use of Solar Home Systems (SHS) in developing economies is not new but increasingly affordable, and SHS are nowadays seen as a leapfrogging technology for communities without access to the national utility grid. Also, SHS are used in

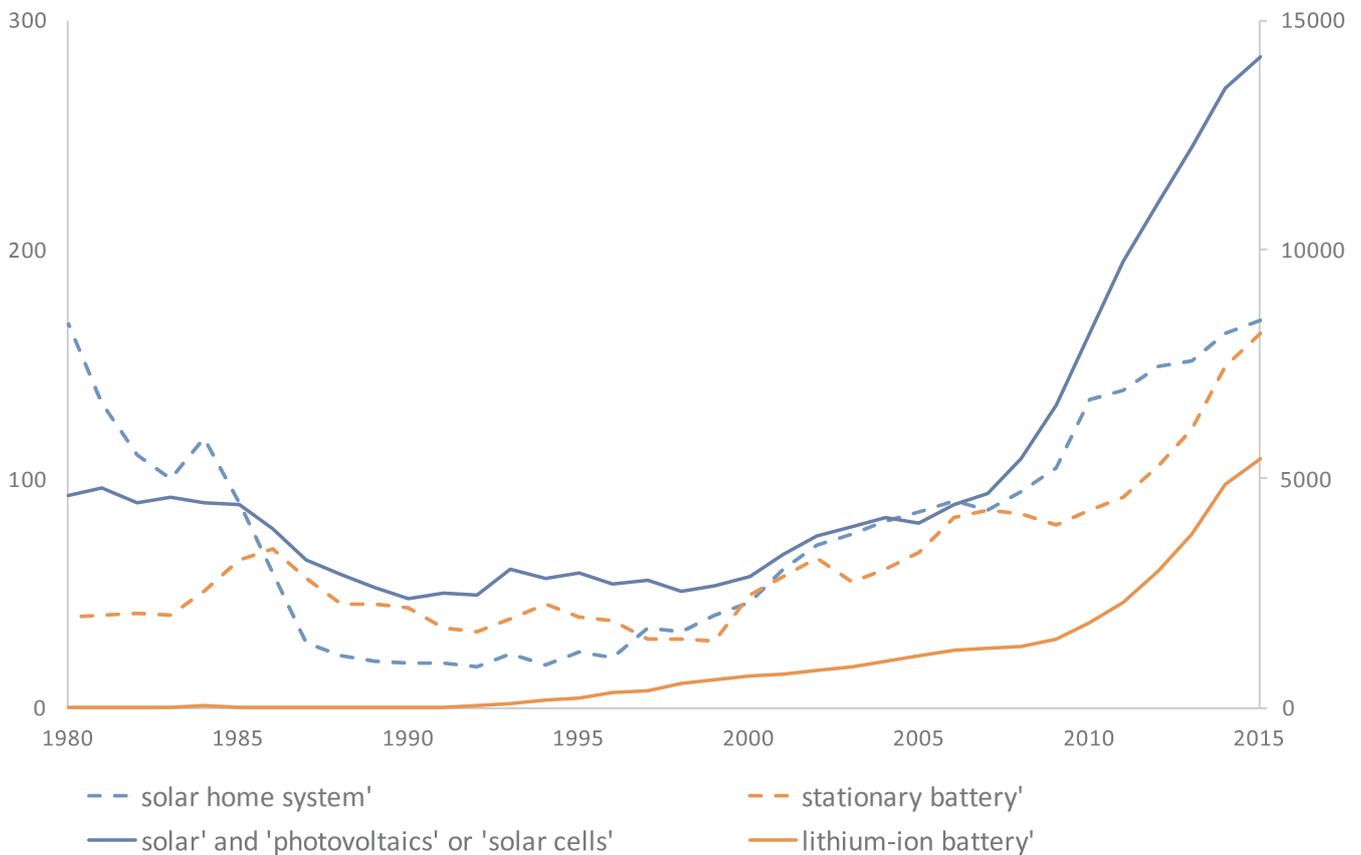


Fig. 9. Knowledge creation related to Off-grid technical components (deflated values with three years floating average). The dashed lines represent values for the primary axis, while values on the secondary axis are represented with the solid line. Search terms: ‘solar home system’, ‘stationary battery’, ‘(solar’ and ‘photovoltaics’) or ‘solar cells’”, lithium-ion battery.

Source: scopus.com

urban areas as backup or alternatives to unreliable grids. Between 2009 and 2014, the price of SHS fell by 64% (Bloomberg New Energy Finance, GOGLA, & Lighting Global, 2016).

Over the last decade, Solar Pico Systems (SPS) have emerged as a new technology for powering appliances and lighting devices. SPSs often come as a set consisting of solar panels, a battery, a charging station, and an LED lamp. The price dropped by 75% between 2012 and 2016 and is expected to halve again between 2016 and 2020 (Bloomberg New Energy Finance et al., 2016). SPS technologies are now contributing significantly to the expansion of the off-grid market in the Global South (Bloomberg New Energy Finance et al., 2016; Lysen, 2013).

Also in industrialised countries, the idea of taking “the energy future into your own hands”, that is, becoming energy independent at the household level, is increasingly popular (Elsasser, 2015; Sonnen, 2016). Innovative integration of PV in walls and windows of buildings, in textiles and all kinds of materials, open for new ways of designing electricity systems. Cost reduction, design thinking and branding make solar home batteries more attractive (Elsasser, 2015). In 2015, the American EV manufacturer Tesla introduced the PowerWall, a lithium-ion home battery that is designed to be paired with rooftop solar panels and enable consumers to ‘go net zero’ (Tesla, 2016). The PowerWall is a part of a new generation of batteries with the ambition of not only being automatized, compact and easy to install but also of becoming an interior wall-decoration.<sup>2</sup>

### 3.4.2. Actors and networks

Actors promoting the Off-grid electricity scenario vary in size, motive, geographical origin and organizational model. There is a clustering of actors in the Global South, where off-grid solutions are seen as a way to electrify remote and poor communities. Currently, the off-grid market is partly commercial and partly driven by donor financing and development aid. It includes private entrepreneurs, social entrepreneurs, charity organizations, international developing agencies and governmental agencies. Charity-based initiatives exist in parallel with business and distribution models targeting different customer segments in urban and rural areas.

At the global level, off-grid solutions are promoted by Sustainable Energy for All (SE4All), which was established in 2011 as an initiative under the United Nations. SE4All works to achieve universal access to clean and efficient energy sources for all humans and acknowledges that off-grid electricity systems are not a provisional solution, but rather an economically viable route to sustainable energy for all (SE4ALL, 2016).

Lighting Global was initiated by the World Bank to support the off-grid solar market targeting those without access to grid electricity. It brings together the World Bank, the Global Off-Grid Lightning Association (GOGLA), manufacturers, distributors and other development partners to develop the off-grid electricity market (Lightingglobal.org, 2016). GOGLA is an independent and non-profit industry organization with the overall mission to scale-up the off-grid electricity solutions sector (Bloomberg New Energy Finance et al., 2016; GOGLA, 2016).

In 2016, more than 100 private companies were providing SHS and SPS and approximately 20 companies offered “pay-as-you-go” financing mechanisms instead of payments in cash. Investment in the off-grid market increased 15-fold between 2012 and 2016. According to Bloomberg New Energy Finance (BNEF), the number of electrified off-grid households will grow from 25 million in 2016 to 99 million in 2020 (Bloomberg New Energy Finance et al., 2016; Zaripova, 2016a).

In places where the electricity grid infrastructure is fully developed, actors promoting Off-grid systems as a vision are often individuals or communities of individuals who aim to become independent from the centralised electricity system, avoid costly electricity bills, or simply take the sustainability transition into their own hands. Here we also find the emerging concept of “energy democracy” with its focus on social justice, sustainable development and grassroots mobilization (Angel, 2016; The Center for Social Inclusion, 2013). Importantly, internet and social media makes it easier to form grassroots initiatives that encourage others to join ‘the off-grid movement’. The ‘off-gridders’ usually communicate via websites that enable people from all over the world to share experiences in going off-grid. Off-grid.net, an online portal that encourages and supports people interested in building off-grid systems, is accessed by 75 000 visitors every month (in 2017), mainly from the USA and Great Britain. This webpage serves as a knowledge sharing platform and a news portal related to off-grid life-style. A special networking opportunity is the ‘Landbuddy’ section that serves for finding ‘buddies’ to go off-grid with (Off-grid.net, 2016).

In relation to off-grid solutions, some important innovative companies might influence the electricity system transition. For instance, the recently merged innovative energy businesses SolarCity and Tesla, create a vertically integrated energy company offering a single system for off-grid living. Together, they envision a future of a “one-stop solar plus storage experience” offering one installation, one service contract and one phone application (Hanley, 2016).

Many ‘off-gridders’ live in the US, especially in those states where the electricity costs are very high and solar energy is abundant, such as Hawaii, Arizona, Nevada and California. Even though only 1% of US consumers lived off-grid in 2014, going off-grid is no longer seen as a rebellious step but rather as a decision of a savvy homeowner (Chediak, 2014). In Australia, a combination of high electricity prices and a high risk of electricity outages due to natural disasters creates favourable conditions for off-grid system (Parkinson, 2015; Zaripova, 2016b). In fact, Australia has the highest penetration of residential rooftop PV in the world and presents an attractive market for many companies specializing in battery technologies, such as Tesla, Bosh, Redflow, Samsung, LG and Sonnen. Since off-grid systems became a viable option, many local utilities and electricity suppliers offer a PV plus battery system combined with grid access in order to keep the customers connected to the grid (Parkinson, 2015).

<sup>2</sup> The creative burst related to local electricity production does not stop at solar and battery technologies. An example of a novel wind power technology is the ‘Vortex Mini’ for domestic power generation, which has no blades, gears or bearings and looks just like a slim cylinder that oscillates or vibrates (Vortex, 2016).

### 3.4.3. Institutions

Besides increased performance and reduced cost of key enabling technologies, there are also examples of regulations that encourage individuals to leave the grid. The cost barrier for going off-grid can be reduced by subsidy schemes for PV plus battery systems, such as in Germany since 2013 and Japan since 2014 (Colthorpe, 2014; Enkhardt, 2016). In the first half of 2016, the Green party in Australia also proposed such subsidies (Gifford, 2016b). However, if the PV plus battery subsidy schemes are combined with reasonable FiTs (and if the seasonal variation of solar influx is larger), as they are in Germany or Japan, then it is more beneficial for the consumer to stay connected. This is, however, not the case in Australia or Hawaii where FiTs are very low and fees for houses with installed solar panels are high, making the off-grid systems increasingly cost-effective (Gifford, 2016a). As the Australian environmental minister Greent Hunt (in Parkinson, 2015) said: “it’s up to individuals”. Some consumers may leave the grid because of economic and regulatory issues, while others leave the grid in order to declare their independence or to directly contribute to the carbon-free electricity system (Off-grid.net, 2016; Parkinson, 2015).

In the countries of the Global South, off-grid solutions are often the only option; yet, these are usually not supported by formal regulatory frameworks. Formal institutions are therefore being substituted with innovative practices that are emerging in relation to all aspects of electricity provision. Through these practices, many actors attempt to enter the growing market for off-grid systems by adjusting to the context of poverty, no access to financial services from commercial banks, ineffective payment structures, gender inequality or criminality. To exemplify, micro-loans are often provided by microfinancing institutions to support diffusion of renewable technologies in poor areas; users are enabled to pay for services via ‘pay-as-you-go’ business models with help of ICTs; local communities are trained to ensure technical service and maintenance with a special attention to women; and technologies are designed to avoid theft. Such practices are often borrowed from other sectors, such as micro-financing, ICT solutions, water and sanitation (Adib, Gagelmann, Koschatzky, Preiser, & Walter, 2001; Sanyal, 2017).

## 4. Socio-technical overlaps

We have identified three different stylised alternative systems and traced the emergence and accumulation of a range of socio-technical components supporting these systems and how they take form at the niche level. We now turn to the question of how these components relate to the incumbent electricity regime, other sectors and discourses.

We can conclude that the Super-grid system configuration develops close to the existing electricity system, and can be characterised as hybridization processes. The global and continental Super-grid is enabled by incremental innovation in power transmission and supported mostly by regime actors such as national governments, research institutes and dominant firms that possess the capabilities to coordinate such megaprojects. At this point in time, visions, roadmaps and pilot projects seem to be particularly important to hold the main actors together and enable the top-down harmonization required for the centralised, border-crossing and capital-intensive transition to the global Super-grid. The vision alludes to ideals of control and efficiency (Lilliestam & Hanger, 2016) and link up to trends of economies of scale and globalism (Liu, 2015).

The Smart-grid seems to be emerging out of a combination of hybridization and niche accumulation. The Smart-grid system deviates from the dominant centralised system by creating a decentralised system configuration enabled by small-scale renewables and innovative communication, metering and storage technologies. Some technical components of the Smart-grid, such as ICT and batteries, which have primarily been developed in other sectors, have found niche market opportunities in Smart-grid development. Transaction technologies such as blockchain are borrowed from the banking sector. The parallel development of electromobility may both create demand for and enable Smart-grid solutions, e.g. via vehicle-to-grid systems. New entrants are increasingly contributing to the market for Smart-grid components and systems, and a range of public and private house owners and industries are becoming involved as prosumers directly contributing to Smart-grid experiments. Arguably, the Smart-grid scenario borrows legitimacy from other systems that build on networks of prosumers, most importantly the Internet, and from ideas such as the ‘sharing economy’, or the ideal market. However, governmental actors still hold a strong position in propelling the Smart-grid development by forming special organizations and financing demonstration projects. These projects most often involve incumbent actors such as existing DSOs, utilities and large power system companies, which are assigned to plan and carry out the project in collaboration with research centres and universities. Furthermore, in a transition period the relation to traditional power plants is complex, possibly allowing for some symbiosis with flexible gas power plants while being less compatible with coal and nuclear (see e.g. Göransson et al., 2017).

The Off-grid scenario is clearly an example of niche accumulation. It deviates from the regime by creating a highly disconnected and decentralised electricity system without the conventional utility grid infrastructure and electricity market. It is enabled by the rapid development of energy storage technology and small-scale renewables such as solar PV that, historically, have benefitted from a growing demand for electricity in remote areas and in mobile applications, in turn driven by progress in the aerospace, ICT and automotive industries. Currently, off-grid systems find growing markets in developing economies, where large-scale grid infrastructure is unreliable or non-existing. Since the current institutional frameworks offer very limited regulation of off-grid systems, practices are borrowed from other more established sectors such as ICT or banking. This has contributed to faster diffusion and easier maintenance in countries of the Global South. Over time, the perception of and vision for Off-grid systems has changed from it being considered a temporary fix until the conventional grid arrives, to a long-term solution with increasing economic and political strength and recognition. Moreover, the decreasing costs of solar and battery technologies make the Off-grid system scenario an increasingly feasible option even in countries with a fully developed electricity grid. Here, several innovative companies have found a growing market opportunity for stand-alone systems enabling off-grid living. The Off-grid vision in industrialised countries link up to quite different political and social discourses and ideals, including not only environmental responsibility but also social justice, individual independence and design-driven consumerism.

## 5. Conclusions

This paper represents an attempt to monitor the socio-technical transition in electricity systems around the world by mapping accumulation and alignment of structural components that indicate an initial formation of new alternative systems. The results make evident that there is indeed an ongoing transformation process, while its direction is not yet decided. We identify three distinct idealised transition endpoints: ‘the Super-grid’, ‘the Smart-grid’ and ‘the Off-grid’ systems. We find that all three alternatives have built momentum since the turn of the century through development of technology, mobilisation of actors, formation of networks and institutional work, as well as by linking up to the existing regime, the development in other industries and to various societal discourses and ideals. While the proponents of each scenario tend to articulate their vision as the most likely and beneficial future, we find it to be too early to announce ‘a winner’, i.e. a future dominant configuration, or even to clearly state in which direction in the design space we are heading. Some findings suggest that the future path will be closely aligned with the current electricity system and result in a ‘greening of the existing system’, while other findings suggest that the currently dominating system will be radically reconstructed.

A next step towards a deeper understanding of the ongoing transition processes would include a closer study of each system and the causal links between structural components to identify drivers and barriers enabling or hindering the breakthrough of each alternative system configuration.

## Acknowledgements

This research is funded by the Swedish Energy Agency as a part of the ‘New networks of power: on the emergence, diffusion and impact of alternative electricity system architectures’ project. We are grateful to two anonymous reviewers for constructive comments.

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# Paper II





# Entrepreneurial use of context for technological system creation and expansion: The case of blockchain-based peer-to-peer electricity trading

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## ARTICLE INFO

### Keywords:

Resistance to innovation  
Innovation context  
Entrepreneurship  
Energy transition  
Peer-to-peer electricity trading  
Blockchain

## ABSTRACT

This paper engages with the question of why certain radical innovations succeed while others fail or stagnate when encountering established actors and sector logics. We develop an analytical framework that extends the technological innovation systems (TIS) functional approach to explicitly account for contextual factors and entrepreneurial activities. We contribute to two ongoing debates: the conceptualization of context in TIS and the micro-foundation of TIS. First, a two-dimensional matrix is constructed to locate influential factors in the spatial (geographical) and sociotechnical (sectoral) contexts. Second, for early stages of the innovation process, we identify entrepreneurial activities as the locus of the system-building functions, i.e. the activities that use contextual and system-internal factors to develop the novel technological system. We use the TIS approach to analyze the innovation system build-up of peer-to-peer (P2P) electricity trading on a blockchain platform, materializing in two local projects, one in Australia and another in the USA. We find that how and why the new configuration succeeded in productively encountering electricity sector incumbents can be explained by the extent to which entrepreneurs could use opportunities in various contexts across spatial and sectoral boundaries.

## 1. Introduction

Growing environmental, social, and economic sustainability challenges are putting pressure on established sectors around the world to innovate and transition to more sustainable modes of production and consumption. In most sectors, sustainability transitions require major changes of dominant system designs (Markard et al., 2012). Such radical innovation poses great difficulties for incumbent firms, which therefore may seek to block new alternatives or steer change in less radical directions to reinforce their dominance (Geels, 2014; Henderson and Clark, 1990).

Overcoming incumbent resistance in order to achieve fundamental system transformation has been a central theme in the innovation and sustainability transition literature (Dahmén, 1989; Foxon and Pearson, 2008; Foxon, 2014; Geels, 2014). This line of research stresses that innovations and transitions are always sociotechnical in nature and occur as processes in which 'the social' and 'the technical' influence each other (Hughes, 1987; Van den Bergh et al., 2011).

By applying a sociotechnical systems perspective, this study considers why certain radical innovations succeed while others fail or stagnate when encountering established actors and sector logics. More precisely, we use the technological innovation system (TIS) approach as

an analytical tool to describe and explain the emergence and growth of novelties or the lack thereof (Bergek et al., 2008; Hekkert et al., 2007). This article contributes by improving the understanding of the role wider contexts play in enabling radical system innovation. While it is well established that context matters for successful innovation (Bergek et al., 2015; Coenen et al., 2012; Coenen and López, 2010; Hansen and Coenen, 2015; Truffer et al., 2015), the innovation system literature has differing assumptions regarding what context is and what aspects of it matter the most.

We argue that to overcome the resistance of established actors, radical innovation requires substantial agency on the part of new challengers. Previous TIS literature has emphasized the role of entrepreneurs (Alkemade et al., 2011; Farla et al., 2012; Markard and Truffer, 2008; Musiolik et al., 2018; Planko et al., 2017) as system builders who can skilfully use opportunities and structures from different contexts to create momentum for their innovations under conditions of extreme uncertainty (Saravathy, 2007). This is arguably more pronounced at the early stages of the novel configuration build-up, when actors are few, institutions and technical infrastructures favor incumbents, and the novel configuration has little momentum.

For our empirical investigation of encounters between entrepreneurs and incumbents, we select the ongoing innovation process

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in the electricity sector. The existing capital-intensive electric grid and associated regulatory frameworks generate substantial inertia and obstruct fundamental changes (Bolton and Foxon, 2015; Frantzeskaki and Loorbach, 2010; Markard, 2011). However, the ongoing growth of distributed renewable energy technologies is disrupting the dominant system built around centralized nuclear, hydropower, and fossil fuel-based generation (Markard, 2018), opening it to radically different system architectures and new innovations (Foxon, 2013; Gui and MacGill, 2018; Hojčková et al., 2018; Verbong and Geels, 2010).

One example of such an innovation is peer-to-peer (P2P) electricity trading via blockchain, a distributed software technology that redefines the roles of, or even removes the need for, utilities and energy retailers in the electricity market, by creating a programmable digital utility managed by consumers and prosumers.<sup>1</sup> It has the potential to disrupt the centralized institutional arrangement in the electricity sector by creating a distributed electricity trading network, often referred to as energy democracy (Angel, 2016; Burke et al., 2017; Fairchild, 2017).

This study has both conceptual and empirical aims. Conceptually, we aim to improve the TIS functional approach to enable a more nuanced description of how actors' entrepreneurial activities use and are influenced by various factors when building a new system and overcoming resistance from incumbent actors. In particular, we aim to develop and test a categorization of system contexts that may help describe the origin of a broad range of supporting and blocking factors. Our empirical aim is to better understand how this process influences the success of blockchain-based P2P electricity trading and its encounter with the incumbent sector.

To achieve our aims, we review how the context has been conceptualized in the innovation system literature and propose a two-dimensional matrix that systematizes previous insights. We also link the TIS context to the agency of entrepreneurs as innovators and system builders. Consequently, we provide a framework for analysing how entrepreneurs can utilize various contexts across scales and socio-technical sectors, how this contributes to the build-up of a new technological system, and how, in turn, this affects the encounter with the established sector. We illustrate the framework in a comparative case study of two local demonstration projects of blockchain-based P2P electricity trading.

## 2. Theoretical foundations

### 2.1. Technological innovations systems and early system build-up

The TIS framework, or model, is a tool for analysing the emergence and growth of new technologies, products, and related industries (Bergek et al., 2008a; Hekkert and Negro, 2009). Studies applying the TIS framework have predominantly focused on sustainability-oriented innovations, making TIS a prominent framework in the growing field of innovation and sustainability transition research (Markard et al., 2012). The popularity of the TIS functional approach is attributable to its usefulness in identifying 'blocking factors', or 'system weaknesses', thereby guiding policy intervention to support particular technologies.

Although the framework has mainly been used to study the emergence and growth of systems producing and using tangible products such as windmills or PV panels, we propose that it is generic enough to be useful in analysing any sociotechnical innovation phenomena, including new products, business models, and service-delivery models enabled by digitalization and new communication technology (see also Hallingby, 2016). This also applies to studies of systems of different sizes and levels of maturity. While many studies focus on semi-mature emerging industries in which many firms, artefacts, and technology-specific institutions already exist, nothing in the framework precludes

<sup>1</sup> 'Prosumers' are actors who both produce and consume electricity, such as a homeowner whose house has a solar roof.

the same theoretical categories from being applied to study the emergence and expansion of very immature and small systems early in their structural formation (see Andersson et al., 2018; Hellsmark et al., 2016).

The TIS framework highlights collective ('systemic') processes of forming, aligning, and expanding the heterogeneous structural components required for a successful novel 'technological system' (comprising actors, networks, institutions, knowledge, financial resources, and physical artefacts) (Bergek et al., 2008b; Hillman and Sandén, 2008).<sup>2</sup> These processes, termed 'functions', carry different weights and matter in different ways during a technology lifecycle; accordingly, Table 1 summarizes the key functions as we understand them to matter at the early stage of system build-up, based on the various formulations presented in the literature.<sup>3</sup>

The strength of each function depends partly on the internal state of the growing technological system itself (i.e. internal factors such as the number and size of actors, level of knowledge, and technology-specific institutions) and partly on supporting and blocking factors in its environment (Bergek et al., 2008b; Hillman and Sandén, 2008; Sandén and Hillman, 2011) (Fig. 2a).<sup>4</sup> As the system grows, internal factors become increasingly important. With the entrance of new actors, the development of physical artefacts, networks, and knowledge, and the alignment of institutions, internal factors become linked in loops of positive feedback, setting off a process of 'cumulative causation' (Hekkert et al., 2007; Hillman et al., 2008). Over time, the new system gains momentum (Hughes, 1987). This also implies that the new system exerts increasing influence on its environment as it grows – that is, the interplay between system and context becomes more bidirectional. Immature systems, however, are heavily dependent on contextual factors, as the internal structure is not yet well developed and provides only weak support.<sup>5</sup>

Apparently, the external environment, or context, is crucial for the early development and overall prospects of a novel system. However, scholars have recently argued that, in the TIS framework, the context is under-theorized (Andersson et al., 2018; Bergek et al., 2015; Coenen et al., 2012; Hansen and Coenen, 2015; Truffer et al., 2015). To better understand why certain innovations develop successfully in some contexts but not in others, and how the context not only helps or hinders novel technological systems but also shapes them, we need a more elaborate conceptualization of the system context.

<sup>2</sup> The literature provides many examples of a growing system being called a 'TIS'. In our view, using the same term for the model of change (which can be viewed as a higher-order 'system' that creates change) and the object undergoing change creates conceptual confusion. Here, we follow Hughes (1987) and Hillman and Sandén (2008) and call the growing system a 'technological system', reserving the term 'technological innovation system' for the model describing and explaining the growth process.

<sup>3</sup> We follow Hekkert and Negro (2009) and do not include the function 'creation of positive externalities', which we view not as an independent function but rather as an aspect of other functions; for example, knowledge and markets may be shared or used exclusively by individual actors (through secrets, patents, contracts, and monopolies).

<sup>4</sup> In some texts, the term 'resources' is used instead of 'factors' (Andersson et al., 2018; Musiolik et al., 2012; Musiolik et al., 2018). Here, we prefer the more general term 'factor' to allow also for the negative impacts of blocking factors. In addition, while most supporting factors can be viewed as resources in a broad sense, a narrower interpretation of 'resources' would likely exclude supporting factors such as beneficial regulations and positive attitudes.

<sup>5</sup> As proposed by Bergek et al. (2008b), in TIS models, it is in principle possible to work with layers of system boundaries, creating a hierarchy ranging from very internal to very external factors, relative to certain actors or technologies. Musiolik et al. (2012), for example, differentiate between organizational, network, and system resources. Due to the small size and low complexity of the systems studied here, we abstain from a refined internal stratification; however, a major aim of the paper is to identify layers of external structure, or contexts (Section 2.2).

**Table 1**

Functions of the TIS (left) with corresponding descriptions (right); abbreviations will be used in Section 5 (Bergek et al., 2008a; Hekkert et al., 2011; Hekkert and Negro, 2009; Perez Vico, 2014).

Function		Description
Guidance of search	G	The process of attracting and motivating new actors to enter the system, completing value chains.
Network formation (social capital development <sup>a</sup> )	N	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.
Knowledge development and diffusion	K	The process of importing and creating new knowledge and diffusing it across actor groups.
Entrepreneurial experimentation	E	The process of experimenting and combining knowledge and other resources to create something new that can be sold on a market; experimentation creates and tests variety, thus reducing uncertainty.
Legitimation	L	The process of creating formal and informal institutions to overcome resistance to change, making an innovation accepted and perceived as a relevant and appropriate new technology.
Market formation	M	At the stages of experimentation and early build-up, this captures the demand formation that often occurs by creating niche markets with a competitive advantage for specific applications of the focal technology.
Resource mobilization <sup>b</sup>	R	The process of accessing necessary resources in the form of technical (i.e. hardware and software), natural, financial, and human resources.

<sup>a</sup> This function was added by Perez Vico (2014) and Andersson et al. (2017), who called it social capital development. We chose the name ‘network formation’, which we find more appropriate as the focus is on creating networks of relationships instead of social capital as an asset.

<sup>b</sup> Unlike elsewhere in the literature, here we add technical resources to account for resources such as complete technical modules from somewhere else (i.e. other industrial sectors), for example, ‘plug and play’ software.

## 2.2. Conceptualizing the context: spatial and sociotechnical dimensions

As TIS scholars often pay empirical attention to how contextual factors influence the processes they study, the literature provides rich accounts of context-influenced processes. However, it is much less clear how the ‘context’ is understood conceptually, what is considered important, and how and why some factors matter more. There is also a need to reflect on how systems are framed analytically and how the setting of system boundaries sheds light on some actors, activities, and events while obscuring others (Bergek et al., 2015). When reviewing the innovation system literature, we find that existing frameworks differ in their assumptions, with the resulting analytical biases often incurring criticism.

In regional (RIS) and national (NIS) innovation system studies (Cooke et al., 1997; Lundvall, 1988), the territorial context is crucial, with analytical priority given to the regional or national geographical scales and organizational levels. The TIS framework was developed partly in response to RIS and NIS, focusing on technology-specific factors rather than factors specific to given geographical areas. Although early formulations of TIS emphasized the importance of factors and causalities crossing spatial boundaries, this became less explicit in subsequent formulations, and TIS case studies often adopted the national scale as the system boundary. This has led to recent efforts to revisit the issue of geographical boundary setting.

The strongest criticism of analytical bias originates in the ‘geography of TIS’ literature. Here scholars emphasize the variety of geographical contexts and illustrate how places can be more or less conducive to sustainability-oriented innovation. They argue that system build-up depends on processes and interactions at different spatial scales and organizational levels, ranging from local to global (Coenen et al., 2012). In their view, geographical locations contribute to the success of innovation processes by providing local supporting factors such as natural resources, favourable policies and visions, industrial specialization, knowledge and networks, supportive informal institutions, and markets (Binz et al., 2012; Hansen and Coenen, 2015). They argue that nationally focused TIS studies may also overlook how the global level works as an important source of knowledge and production skills (Lee et al., 2018) and how multi-scalar actor networks and institutional contexts support or hinder development (Binz and Truffer, 2017). Furthermore, an emerging body of work suggests making the TIS approach more relevant also in non-Western contexts and developing economies, where established sectors are less monolithic and society-wide institutions less stable (Edsand, 2017; Van Welie et al., 2018).

Parallel to territorially focused innovation system studies, sectoral innovation system (SIS) scholars argue that the industrial sector context

(e.g. the electricity sector) is what matters most for innovation processes (Malerba, 2002; Stephan et al., 2017). Hanson (2018) and Raven (2007) noted the importance of interactions with incumbent actors in focal and adjacent industrial sectors, and with sector-specific institutions and logics. Others have stressed the interaction dynamics between a novel focal technological system and other related novel or mature technological systems (Haley, 2014; Hanson, 2018; Hillman et al., 2008; Mäkitie et al., 2018; Markard and Hoffmann, 2016; Sandén and Hillman, 2011; Wirth and Markard, 2011). Here, we refer to sector-specific structures in the categories of ‘focal industrial sector’ and ‘adjacent industrial sectors’, which in turn comprise a range of more narrowly defined technological systems (see Fig. 1).<sup>6</sup>

Yet other innovation scholars have stressed the key role of society-wide sectors providing specific system-level assets (see e.g. Van de Ven, 1993). In the TIS literature, Karltorp (2014) discussed the educational and financial sectors as specialized ‘resource sectors’ providing skilled labor and financial capital for innovation systems (Karltorp, 2014; Karltorp et al., 2017), while Bergek et al. (2015) elaborated on how the political system can adjust regulatory institutions to support novel technologies. Other sectors can be added to this list, for example, the media sector, influencing legitimizing and delegitimizing processes (i.e. normative institutions), and the research sector, providing formal knowledge. Besides these societal sectors, it has also been noted that basic physical resources (e.g. energy and materials) and services and disservices are provided by natural systems (Markard and Hoffmann, 2016; Sandén and Jonasson, 2005; Wirth and Markard, 2011).<sup>7</sup> Here, we call these systems that, from the TIS viewpoint, support or weaken specific functions ‘supporting sectors and systems’ (see Fig. 1). Note that they do not necessarily only support the development of the novel configuration but may also host blocking factors.

Bergek et al. (2015) made a first attempt to combine many of the

<sup>6</sup> An industrial sector, in our terminology, is a broadly defined technological system. All technological systems contain more narrowly defined technological systems. For example, the electricity sector (or system) contains technological systems built around technologies such as wind, nuclear, and natural gas power, as well as batteries, HVDC cables, and smart meters, but also those centered on different grid infrastructures such as microgrids and super grids, and associated business models such as P2P electricity trading and virtual power plants.

<sup>7</sup> Obviously, one can make a case for not including natural systems in a dimension labelled ‘sociotechnical’. However, as systems are made of matter and information, providing certain kinds of resources, services, and threats, these natural systems are similar in kind to sociotechnical systems, for example, compared with segments of the spatial dimension. While future research may want to expand this dimension into a socio–techno–ecological space, the proposed simplification is sufficient for our aims.

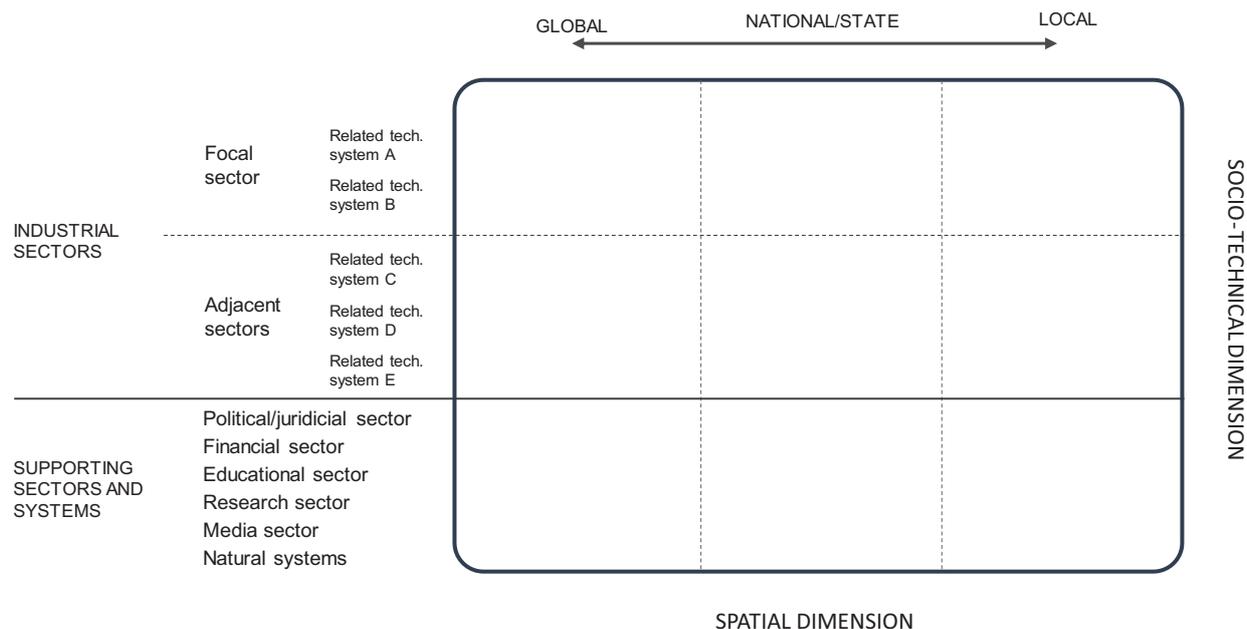


Fig. 1. A two-dimensional matrix describing the context of the focal technological system. Contextual factors supporting or blocking the focal technological system may be located in any part of the matrix, for example, in the local focal industrial sector or in the global financial sector.

contextual factors emphasized as important for system build-up into a more comprehensive framework. Here, we intend to take this one step further. Based on the above literature review, we identify two main ways in which the wider innovation system literature conceptualizes context. First, there is the *spatial dimension of the context*, in which contextual factors reside at a certain level along a spatial scale, resulting in differentiation between factors from the local to global, with many possible relevant levels in between; for simplicity, these are visualized in Fig. 1 as local,<sup>8</sup> national, and global. Second, factors can be positioned along a *sociotechnical dimension of the context*, resulting in differentiation between industrial sectors and supporting sectors and systems. Industrial sectors are subdivided into a focal industrial sector and adjacent industrial sectors. These can be further subdivided into more narrowly defined technological systems to enable visualization of the influence of specific related technological systems. Similarly, supporting sectors and systems can be subdivided into more specific categories (e.g. political/judicial, financial, educational, research, media, and natural systems). The two-dimensional matrix presented in Fig. 1 highlights that spatial factors crosscut the sociotechnical dimensions of the context. For example, the housing sector and political/judicial systems also have a spatial dimension, as they can range from local to global. To us, this matrix permits analytical and empirical richness, encouraging explorative framings rather than *a priori* assumptions about which contextual factors matter for the growth of new technological systems. A strength of using TIS, versus the other innovation system frameworks discussed above, is that it does not come with an inherent bias towards a (single) specific spatial scale, nor does it assume that sectoral dynamics matter more than spatial ones. Instead, it is flexible enough to allow for empirical exploration of how and why contextual factors matter along this two-dimensional categorization.

While this matrix describes the sources of contextual influence, TIS scholars have also discussed the sign and directionality of the interaction between context and focal system. We have already noticed that influence may be supporting (positive sign) or blocking (negative sign).

<sup>8</sup> These classical levels and the idea of the 'local' are simplifications that sometimes result in analytical blindness unless critically examined. For a case study illustrating overlapping and messy jurisdictions and social relations shaping electricity provision, see (Nucho, 2016).

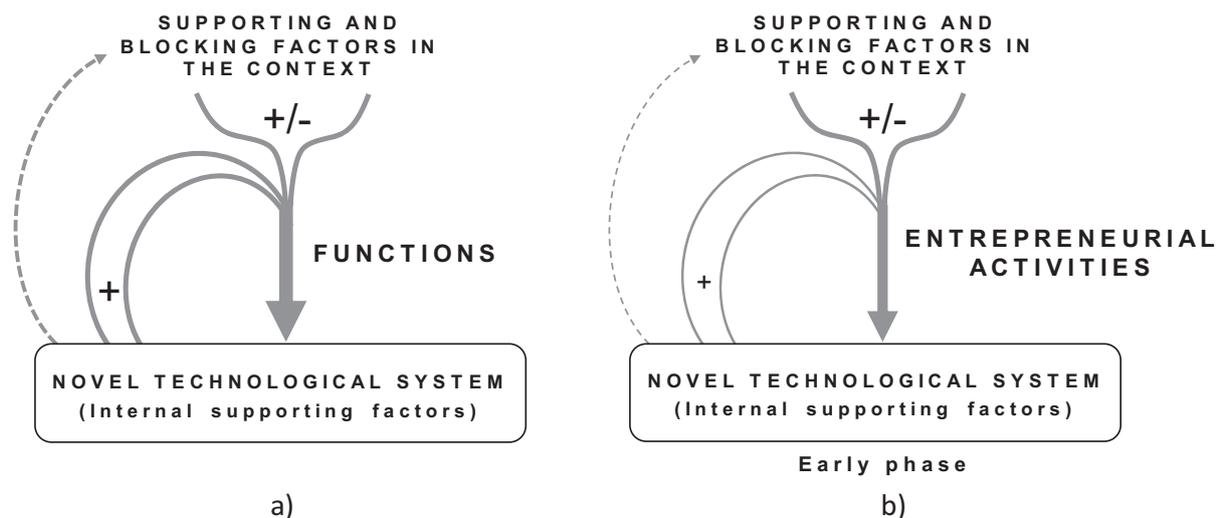
In addition, Bergek et al. (2015) distinguished between 'external links' and 'structural couplings', differing in degrees of reciprocity.<sup>9</sup> Contextual factors could potentially be placed on a scale ranging from external links, affecting the system in a one-directional way, to fully bidirectional couplings, where the context is also influenced by the focal system. The TIS framework, however, is primarily intended to describe the development of a focal technological system, not the development of the rest of the world. The level of bidirectionality is thus of interest only to the degree that it affects the development trajectory of the focal system.

One specific form of bidirectionality is when interaction between the system and a contextual sector results in the inclusion of new elements in the focal system, leading to system growth. However, since any real-world entity is part of many different systems, a new element, such as a firm, may still be part of a context, controlling resources that are not yet mobilized for the novel system. The boundary between any sociotechnical system and its closest context will therefore be somewhat fuzzy and dependent on analytical choices.

### 2.3. Micro-level understanding of the system build-up: the role of entrepreneurs

We now turn to the criticism that TIS lacks a micro-level foundation and pays too little attention to actors' agency and the role of entrepreneurs (Alkemade et al., 2011; Farla et al., 2012; Markard and Truffer, 2008; Musiolik et al., 2018; Planko et al., 2017). The TIS framework proposes that the emergence and development of a novel technological system depends on internal (technology-specific) and external (contextual) factors (e.g. actors, networks, institutions, knowledge, and physical artefacts). This build-up process is conceptualized by a set of abstract functions (Fig. 2a; Table 1). However,

<sup>9</sup> A similar way to think about contextual interaction in TIS was developed by (Markard and Hoffmann, 2016), who defined unilateral and bilateral complementarities with structures outside a systems analytical boundary. Sandén and Hillman (2011) provided a framework accounting for positive/negative interaction as well as the degree of symmetrical/asymmetrical dependence, including not only competitive and symbiotic relations, but also neutral, parasitic, and ammenalistic ones.



**Fig. 2.** Systemic visualizations of technological system build-up: a) The system-building processes are conceptualized as functions (arrow), whose strengths (arrow width) are influenced by internal and contextual factors (based on [Bergek et al., 2008b](#); [Hillman and Sandén, 2008](#)); b) in immature systems (early phase), the functions can be interpreted as micro-level entrepreneurial activities, i.e. agency in building the novel system by utilizing supporting contextual factors and (initially weak) internal factors (thin lines), while counteracting blocking contextual factors. Each visualization also includes a dotted line depicting the potential influence of the system on some part of the context, which may in turn influence the system (bidirectionality).

when we look more closely at the micro-level of innovation processes, for example, in local demonstration projects, we discover the importance of individual actors who can utilize available resources and initiate collective action to promote system development. These actors are often entrepreneurs<sup>10</sup> who play crucial roles as inventors with strong incentives to support their emerging technologies' market introduction.

The role of entrepreneurs in TIS approaches has so far been reflected in the 'entrepreneurial experimentation' ([Bergek et al., 2008a](#)) or 'entrepreneurial activities' functions ([Hekkert et al., 2011](#)). While semantically similar, there seems to be a clear difference between these concepts. [Bergek et al. \(2008a\)](#) viewed 'entrepreneurial experimentation' as a system-level phenomenon simultaneously generating variety and reducing uncertainty. In contrast, [Hekkert et al. \(2007\)](#) highlighted micro-level activities, with the role of the entrepreneur being 'to turn the potential of new knowledge, networks, and markets into concrete actions to generate – and take advantage of – new business opportunities' through experimentation in different applications (see also [Alkemade et al., 2011](#); [Hekkert et al., 2007](#), p. 421). Although such a definition seemingly favours a focus on agency, the presence of this function is usually measured quantitatively by counting the number of involved entrepreneurs (firms) ([Bergek et al., 2008a](#); [Hekkert et al., 2007](#)). While the number of entrepreneurs can be an important indicator when analysing larger national and global systems over longer periods, this is not the case for micro-level analyses of local technology demonstrations. Here, [Alkemade et al. \(2011\)](#) highlighted that entrepreneurs are enacting substantial agency through their strategic actions in the early phases of innovation build-up, when only a few actors are involved.

In line with their view, our interest in the roles and activities of entrepreneurs<sup>11</sup> does not concern their search for profit but rather their activities as (i) 'innovators' ([Schumpeter, 1934](#)) introducing new

practices differing significantly from those in established sectors (i.e. radical rather than incremental innovation), and (ii) 'system builders' ([Hellsmark, 2010](#); [Hughes, 1987](#); [Musiolik et al., 2018](#)) striving to build novel systems. Hence, we abstain from viewing entrepreneurial activities as merely one of the innovation system functions; instead, we argue that entrepreneurial activities embody all functions as they use supporting internal and external factors in building the system while being hindered by blocking factors ([Fig. 2b](#)). We study the emergence of technological systems through the entrepreneur's efforts to combine system-internal resources with means and opportunities across spatial and sociotechnical contexts, as well as their efforts to counteract negative contextual influences (i.e. blocking factors), considering how these efforts help make the new system potentially strong enough to challenge established systems ([Bergek et al., 2015](#); [Hansen and Coenen, 2015](#)).

#### 2.4. Productive and repressive encounters with the established sector

The importance of the entrepreneurial role in innovation systems was already emphasized in the 1980s by the industrial economist [Dahmén \(1989\)](#), who considered entrepreneurial activities central to creating a 'development block' that encounters the wider system, i.e. the incumbent industrial sector. This concept influenced the first definitions of technological systems (as a forerunner of TIS) developed by [Carlsson and Stankiewicz \(1991\)](#). The system innovation and transition literature has traditionally described incumbents as resistant actors, trying to prevent transition ([Geels et al., 2017](#); [Lauer and Jacobsson, 2016](#)), joining innovation efforts merely for fear of 'missing the boat' ([Van Lente, 2012](#)). However, the relation between incumbents and innovators may be more ambiguous and can also change character over time ([Berggren et al., 2015](#)). The encounter with the incumbent sector may lead to the disruptive innovation being suppressed or tamed into an incremental innovation, leaving the incumbent system intact ([Henderson and Clark, 1990](#)). However, in other cases, the encounter with incumbents may lead to system change, especially when the innovation affects substantial parts of 'their' production-consumption chain. Taking an example of transition in the electricity sector, changes in electricity generation technologies do not necessarily challenge the incumbent architectural logics. However, when these are combined with changes in other parts of the electricity system, such as grid infrastructure, storage, and market dynamics, they may have a more

<sup>10</sup> The recent transition and innovation literature has paid increasing attention, not just to entrepreneurs, but also to the key role of *systemic intermediaries* as important individuals able to align other actors to affect the transition ([Gliedt et al., 2018](#); [Kivimaa, 2014](#); [Lukkarinen et al., 2018](#)). While we acknowledge the importance of intermediaries in the innovation process, our interest goes beyond actor-to-actor interaction.

<sup>11</sup> Our use of the term 'entrepreneur' is inclusive, emphasizing all actors who actively innovate, promote, and engage in system-building activities.

destabilizing effect on the established sector (Markard, 2018). In this changing environment, both the innovators and incumbents must navigate a complex and multifaceted terrain, which may permit unexpected alliances and collaborations and increasingly bidirectional influence.

Here, we move away from a view of the encounter as a conflict between resistant incumbents and challenging actors (Wassermann et al., 2015) and suggest that encounters are indeed more complex – that is, encounters tend to have ambiguous effects on the development of new technological systems. We draw on an idea regarding the exercise of power to describe these encounters as *productive* in how they enable action or *repressive* in how they block or hinder it (Ahlborg, 2017; Lukes, 2005). Encounters may be productive in generating strategic responses, causing the emergence of new relations and processes, creating multiple positive and negative outcomes. In contrast, repressive encounters are characterized by eliminated possibilities, stalemates, actor incapacitation, and innovation processes being blocked from continuing.

While encounters between innovators and incumbents certainly occur outside the local geographical and sectoral boundaries as well as in different sectors and supporting systems, we argue that the encounter with the local incumbents in the focal sector is particularly decisive for early-stage innovation processes developing locally. We argue that to better understand these encounters, we must pay attention to the agency of entrepreneurs, who can use various contextual factors to stimulate novel system build-up, accumulate enough momentum, and overcome obstacles in order to establish productive interaction with the local incumbent sector.

### 3. Case study description

#### 3.1. Blockchain-based P2P electricity trading systems

As electricity production from variable small-scale renewable sources on the consumer side is increasing, it is becoming evident that the existing electricity market design must adapt. Maintaining a design that fails to include prosumers as direct market participants could increase investment costs, lower system efficiency, and increase electricity prices, gradually leading to a death spiral for traditional utilities (Say et al., 2018; Sousa et al., 2019). However, no clear solution for integrating prosumers in the electricity market structure has yet been established (Ahl et al., 2019).

Blockchain technology has recently been promoted as a potential game-changer enabling P2P electricity trading within autonomous markets of prosumers and consumers. Blockchain is a digital infrastructure that allows a network of decentralized actors to reach consensus around a shared data state (e.g. transaction data) without a central coordinator or the involvement of an intermediary. Applied to the energy sector, the blockchain platform could allow consumers and prosumers to buy and sell self-generated electricity and other services, such as flexibility or demand response, in an open P2P electricity market (Parag and Sovacool, 2016; Sousa et al., 2019). While in the existing market design, prosumers are obliged to either self-consume their electricity or sell it to a licensed electricity retailer, in a P2P market, the conventional retailer is replaced by a software platform and the ownership and control can be shared in a distributed network of prosumers and consumers (Ahl et al., 2019; Sousa et al., 2019; Zhang et al., 2018). However, as of 2019, P2P electricity trading across the regulated grid infrastructure is not allowed in most industrialized countries without the involvement of licenced electricity retailers and grid operators, whose business models depend on their central role in electricity retail and in ensuring reliable and secure electricity supply (Parag and Sovacool, 2016). When encountering the electricity sector, it remains unclear whether and how blockchain-enabled P2P trading can overcome all regulatory, technical, and cultural barriers (Lavrijsen and Carrillo Parra, 2017).

During case selection in late 2016, blockchain-based P2P trading systems were being trialed in just a few demonstration projects around the world, of which we selected the Brooklyn Microgrid (BMG) in New York City (NYC), USA, and the White Gum Valley (WGV) project in Fremantle, Western Australia (WA).

#### 3.1.1. The White Gum Valley project

The White Gum Valley project is a housing development located in Fremantle, WA. Since early 2016, the WGV project has been a demonstration site for blockchain-based P2P electricity trading. The design of the P2P trading is based on research conducted at Curtin University in Perth, which also provided partial financing for the P2P trading out of governmental funding (Interview 3). The City of Fremantle provided institutional support for innovation in the WGV area. Housing developers LandCorp, AccessHousing, and Yolk Development Group integrated P2P trading into new apartment buildings in WGV. These buildings (for 150 residents) were built with integrated PV plus battery systems, installed by Solar Balance, a microgrid expert company. After construction, the ownership and operation of the PV and battery systems were transferred to the strata title companies<sup>12</sup> acting as the ‘citizen utilities’.<sup>13</sup> Power Ledger, a locally based start-up, provides a blockchain-based trading platform that enables citizen utilities to share renewable electricity P2P within apartment buildings, behind the meter<sup>14</sup> (Interview 1). By regulation, the distribution system, across the meter, between the buildings in WGV is operated and managed by Western Power, the public grid operator, and Synergy, the public electricity provider and retailer (Accesshousing.org.au, 2016; Diss, 2015).

#### 3.1.2. The Brooklyn Microgrid (BMG)

The Brooklyn Microgrid is located in residential areas of Park Slope and Gowanus in Brooklyn, NYC. The project was established at the beginning of 2016 by Lo3Energy, a start-up that intended to build a community microgrid with blockchain-based P2P electricity trading. Lo3Energy started the project in collaboration with Siemens, a multinational energy manufacturing company that provided technological and financial support to develop the infrastructure for the microgrid. Via community outreach, Lo3Energy recruited local residents in Park Slope and Gowanus, i.e. approximately 80 prosumers and 500 consumers, as future P2P trading participants (Interview 16). By regulation, the distribution grid in Park Slope and Gowanus is operated and managed by Con Edison, the public utility that also provides most of the electricity retail in Brooklyn (ConEdison, 2018; Lo3Energy, 2017).

## 4. Methodology

### 4.1. Research design

This study is designed as a comparative case study (Flyvbjerg, 2006; Yin, 2009) based on a qualitative research design. Comparative analysis is undertaken to find ‘puzzles’ that can be difficult or even impossible to identify without making comparisons (Pennings et al., 2006). The two cases have a suitable mix of similarities and differences: they started the same year and both use blockchain technology to enable P2P trading,

<sup>12</sup> Strata title is a combination of individual ownership of part of a property (e.g. an apartment) and shared ownership of the rest of the ‘common property’ (e.g. foyers, driveways, and gardens) through a legal entity called a strata company (<https://www.strata.community/understandingstrata/what-is-strata>).

<sup>13</sup> A citizen utility is a consumer, producer, and electricity system manager in one. It is the foundation of the blockchain-based P2P system developed by Power Ledger.

<sup>14</sup> Keeping electricity ‘behind the meter’ refers to individually generated or stored electricity kept at a residential or commercial property without entering the utility metering system.

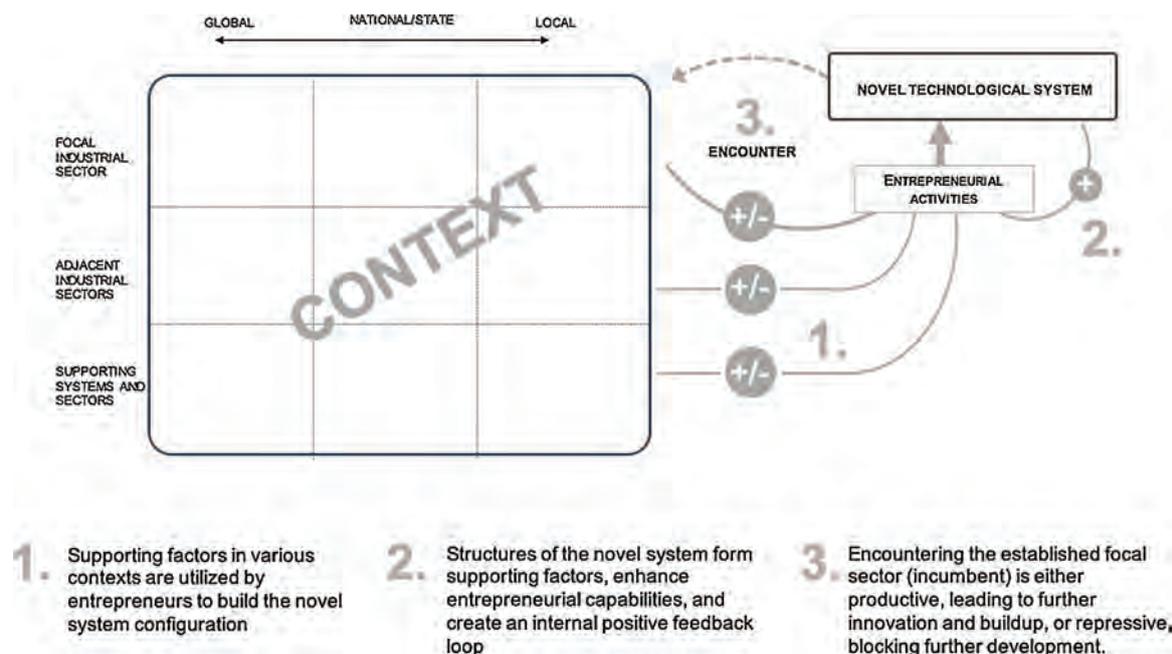


Fig. 3. This analytical framework captures (1) the origin of various contextual factors that influence system build-up (+/-), the positive ones being opportunities used by entrepreneurs to develop the system structure, thus (2) creating an internal positive feedback loop that further enhances entrepreneurial capabilities. These interactions shape (3) the encounter between the novel system and the focal sector, as well as how entrepreneurs and incumbents respond to this encounter, with implications for further development. Based on Figs. 1 and 2.

yet they differ in their local geographical, physical settings and in the institutional environment in which they developed.

TIS studies may be retrospective and descriptive, trying to explain the sociotechnical dynamics behind a certain historical development path and outcome, or they may be prospective and prescriptive, aiming to identify current weaknesses in a specific system hindering it from reaching a future system goal. This retrospective study uses the TIS framework as an analytical scheme to guide and create coherence in data collection, analysis, and interpretation. Interview guides were designed to identify structural components, functions, the roles of different contexts, and entrepreneurial agency. The analytical framework, presented in Fig. 3, builds on the TIS literature, but was refined based on empirical and conceptual insights emerging from the analysis. In section five, we present the findings using a narrative approach (Clandinin and Connelly, 2000). In the narratives, we make explicit the connection to the analytical framework using parentheses to indicate what TIS function is supported or blocked by a factor located in a specified part of the two-dimensional context matrix. For example, research at the local university (supporting sectors and systems) contributes to P2P trading through the function of knowledge development, indicated as (+K; local; supporting). National regulations for electricity infrastructure that hinder the legitimacy of P2P trading across the grid are indicated as (-L; national; focal), with 'focal' denoting the focal industrial sector, i.e. the electricity sector.

#### 4.2. Analytical system boundaries

The focal technology is a new electricity trading model, i.e. P2P trading via blockchain. This study sets the system boundaries of the focal technological system around those structural elements that are part of the production-consumption system developing around the focal technology. While we are interested in studying the system build-up around the blockchain technology, the details of its technical performance and suitability for P2P electricity trading are beyond the scope of this study and are addressed elsewhere (Ahl et al., 2019; Sousa et al., 2019).

The 'context' of interest is kept analytically open *a priori*. We are

describing a process rather than a snapshot in time, meaning that new system elements will be included within these boundaries over time. In very early phases, when the technology exists only as an entrepreneur's ambition (or a start-up), very few structural elements are 'inside' the system boundaries. The entrepreneur thus seeks external elements (e.g. specific firms and policy targets) in various sectors and supporting systems, and attempts to internalize them in the new technological system through innovation system processes (e.g. market formation and legitimation). As the new system accumulates structure and strength, it becomes less dependent on specific agency as the internal positive feedback loop allows for systemic 'collective' processes. Retrospectively, we make judgements regarding when an initially external element can be considered internal.

Spatially, our empirical investigation sets the starting point at the geographical location of our P2P development projects, i.e. in White Gum Valley, Fremantle and Brooklyn, NYC. From here, we explore contextual factors from other spatial levels ranging from local to global, as contributing to the local P2P system build-up. Examples of local factors are the housing sector sustainability targets and housing developers (adjacent sector), and examples of global factors are the emergence of blockchain technology (adjacent sector) and the attention of global media (supporting system). We denote trials of P2P electricity trading elsewhere in the world as 'global' relative to our empirical starting point, although these could be viewed as 'local' from their own perspective.

From a temporal perspective, this study captures the novel system build-up from its inception in 2016 until 2018.

#### 4.3. Analytical framework

Fig. 3 visualizes our analytical framework for studying the influence of micro-level entrepreneurial activities on the enactment of key TIS processes to translate the contextual factors into a novel technological system that can in turn shape the productive or repressive encounter with the focal industrial sector.

In terms of generic value, the findings of the comparative case analysis provide nuanced and concrete knowledge from which we may

**Table 2**  
Performed interviews.

Number	Position	Affiliation	Date	Number	Position	Affiliation	Date
1	PhD graduate at Curtin University, Co-founder of Power Ledger	WQV	February 2018	15	Business Manager at Lo3Energy	BMG	March 2017-November 2017
2	Professor at Curtin University of Technology	WQV	February 2018	16	Brooklyn Microgrid Community Outreach	BMG	December 2017
3	PhD candidate at Curtin University	WQV	January 2018	17	Policy Director at the Office of the Brooklyn Borough President	BMG	December 2017
4	Project Manager at LandCorp	WQV	February 2018	18	Analysts at Department of Distributed Resource Integration, Con Edison	BMG	December 2017
5	Architect at York Development Group	WQV	February 2018	19	5th Avenue Committee, Gowanus Brooklyn	BMG	December 2017
6	Access Housing Project Manager	WQV	February 2018	20	Director at CHIPS shelter, Gowanus Brooklyn, BMG participant	BMG	December 2017
7	Mayor of Fremantle	WQV	February 2018	21	Director at Architectural Grille, BMG participant	BMG	December 2017
8	Chairman of Solar Balance	WQV	February 2018	22	Resident, BMG participant	BMG	December 2017
9	Power Ledger CEO	WQV	February 2018	23	Resident, BMG participant	BMG	December 2017
10	Power Ledger CTO	WQV	February 2018	24	Resident, BMG participant	BMG	December 2017
11	Power Ledger Co-founder	WQV	February 2018	25	Resident, BMG participant	BMG	December 2017
12	Business Development Manager at Western Power	WQV	February 2018	26	Resident, BMG participant	BMG	December 2017
13	New Energy Delivery Manager at Synergy	WQV	February 2018	27	Resident, BMG participant	BMG	December 2017
14	AEMO-Principal and Market Development Analyst	expert	February 2018	28	Resident, BMG participant	BMG	December 2017

learn much about the importance of contextual factors, especially given that the two cases are similar in many respects but differ in the two main aspects we are interested in: the strategic actions of entrepreneurs and the context in which they experiment. The explanatory focus and in-depth analysis provide a basis for developing theory, and we identify theoretical propositions and questions for further study (Flyvbjerg, 2006).

4.4. Data collection

The analysis is informed by data from interviews, participatory observations, and desktop research. Semi-structured interviews were chosen as a primary data source to ensure good control over the data relevance and quality, which is not always possible with secondary data sources (Karlsson et al., 2011). From February 2017 to February 2018, 28 semi-structured interviews were conducted, 14 for each case, with various participants directly involved in the P2P electricity trading demonstration projects, including representatives of small entrepreneurial companies, researchers, electricity system operators and retailers, and local residents (see Table 2). The selection and number of interviews were limited by the researchers' time in the field and ability to access key informants involved in the studied projects. For example, more residents were interviewed in Brooklyn because of the size of this actor group and their degree of influence on the project. Their input was therefore important but only accessible via direct interviews. Most interviews were conducted face to face during a field visit. Open-ended questions were posed, to explore interviewees' perspectives on the innovation process. All interviews, generally one hour long, were recorded, transcribed, and analysed in a first round by the first author, using the Visual Understanding Environment software as a coding tool to categorize data thematically based on our theoretical categories (e.g. structural components, functions, contextual factors, entrepreneurial activities, motivations, capabilities, and encounters with incumbents). In a second round, the authors jointly analysed and discussed the interpretation of the findings. The interviews were triangulated with other data sources, such as field observations and secondary case-related documents, in an effort to improve the validity of our primary data source.

5. The early-phase development of P2P electricity trading models

In this section, the case analysis is presented as chronological narratives supported by the analytical framework (Fig. 3), allowing us to interpret the system build-up process from the perspective of entrepreneurs using contextual factors to build the novel system structure and improve their own capabilities, improving their position vis-à-vis incumbents in the focal sector. A detailed summary of the build-up processes in each case is found in Tables A and B in the Appendix.

5.1. The White Gum Valley project

The electricity sector in Western Australia has been undergoing rapid changes, with the rooftop PV and battery market becoming increasingly successful, driving innovation in microgrid technologies and related prosumer-focused business models (+G; local; focal). The increase in rooftop PV installations was largely supported by the high utility-provided electricity prices and availability of solar irradiation throughout most of the year. However, this market has evolved almost exclusively within the single-household residential sector (Interview 2; Interview 3). The system build-up of P2P electricity trading in WGV started with the ambition to support the diffusion of rooftop PV and battery installations in the high-density residential sector (+G; local; adjacent). In 2016, Professor Peter Newman and PhD student Jemma Green of Curtin University developed the concept of 'citizen utilities' that create commercial incentives for PV and battery adoption in apartment buildings (Green and Newman, 2017) by enabling P2P

electricity *sharing* among tenants and apartment owners (+K; local; supporting). Under this model, the PV and battery systems become the common property of the strata company, which assumes the 'citizen utility' role within the building. Residents pay their electricity bills to the citizen utility, which is in charge of electricity management and redistribution. This utility charges a small fee for its services, but its revenue is returned to the residents in the form of PV and battery system maintenance, for example (Interview 1; Interview 2; Interview 3; Interview 4). The model thus reduces dependence on the public utility and enables residents to earn revenue from their self-generated electricity. While beneficial for residential consumers, the model threatens the monopoly of local incumbent utility companies, which lose revenue with increasing grid defection (Say et al., 2018).

The model does not disrupt the housing sector, which it can help attain ambitious energy efficiency targets (Interview 4; Interview 7). Aware of this opportunity, Green identified a suitable housing development in WGV led by LandCorp, a public housing developer. WGV, a high-density housing<sup>15</sup> project with ambitious energy and water efficiency targets, was a suitable testbed for innovation. WGV is located in Fremantle, a city that prides itself on being a sustainability leader and provided a suitable environment for sustainability-oriented innovation, such as P2P electricity sharing (+L; local; adjacent; supporting) (Interview 4; Interview 5). Here, Curtin researchers successfully formed a collaboration with LandCorp developers and the city council of Fremantle, with clear support from the Mayor (+G; +N; local; adjacent; supporting). LandCorp saw potential in the 'citizen utility' concept and decided to experiment with the P2P sharing model in one of its developments – the 'Gen Y' multi-residential building (+E; local; adjacent). The Gen Y building provided necessary physical resources and a market for the P2P model (+R; +M; local; adjacent) in the form of PV and battery systems embedded in a distribution network owned and operated by the strata company (+M; local; adjacent).

For the trial, the local microgrid expert company Solar Balance was invited to join the WGV actor network (+G; +N; local; focal) to improve the integration of the PV and battery systems with the P2P model in the apartment building (+K; local; focal). With their expertise, the WGV network obtained funding from the Australian Renewable Energy Agency (ARENA) to invest in additional PV and battery systems, the most expensive part of the physical infrastructure (+R; national; focal). With reduced financial constraints, the PV and battery systems together with the P2P sharing model were integrated and trialed in another two buildings in WGV (+R; +E; local; adjacent) (Interview 5; Interview 8). The strata companies in these buildings provided new markets for the P2P model (+M; local; adjacent) (Interview 5; Interview 6).

Theoretically, this means that the early system build-up was locally grounded in a discourse on sustainability and the growing PV and battery market, but entrepreneurs could also find supporting factors in adjacent industrial sectors and supporting systems. In the initial phase, researchers were instrumental in facilitating the system build-up process by partnering with other actors to turn the governance model from a research concept into a real-world experiment. This illustrates how activities of a key entrepreneur can create momentum for the early-phase system build-up, without having to encounter the incumbent electricity sector (i.e. the focal industrial sector).

A need to look outside the local housing and electricity sectors emerged when Curtin researchers and Solar Balance identified problems in fairly pricing self-generated electricity within residential buildings (Interview 8). Around the same time, Perth-based company Ledger Assets was actively seeking investors and market niches for their

blockchain-based trading platform. Ledger Assets saw potential for the blockchain platform to resolve the pricing issues in WGV, by providing a distributed ledger for electricity transactions (Interview 9). Ledger Assets joined the WGV project partners (+G; +N; local; adjacent) and the P2P sharing experiment was improved with the blockchain technology, providing the backbone for the digital P2P trading platform (+K; +R; global; adjacent) implemented in the WGV housing developments (+E; local; adjacent). In analytical terms, by finding a blockchain solution in the global IT sector, provided through a local software company with global expertise, the P2P innovation build-up started expanding beyond the local context of the housing sector.

Assisted by Ledger Assets, Curtin researchers approached local energy sector specialists, Future Effects, to explore electricity sector-wide opportunities for the blockchain-based P2P model (+G; +N; +K; +L; local; focal). Together, they created the start-up Power Ledger. The creation of the new company increased the ambitions to develop a local niche solution for P2P electricity *sharing* into a global P2P electricity *trading* solution with applications beyond apartment buildings (Interview 9; Interview 11). At this point, the new system structure had built internal momentum, but its shift of focus and new, more radical vision brought new challenges.

In 2017, the use of blockchain technology in electricity trading was still immature and required further experimentation. Power Ledger started seeking financial resources to improve the P2P trading platform and demonstrate it locally as well as globally. As a blockchain company, Power Ledger used a novel type of fundraising, initial coin offering (ICO),<sup>16</sup> to fund its innovation. Power Ledger's ICO was very successful and raised AUD 34 million from investors around the world to develop its P2P trading digital platform (Higgins, 2017). With its success in gaining global investment (+R; global; supporting), Power Ledger attracted significant interest from the global community of blockchain enthusiasts as well as media attention (+L; global; supporting) (Interview 1). Global publicity attracted the attention of electricity utilities in other countries, offering Power Ledger opportunities to expand P2P trading trials abroad (+G; global; focal). Electricity utilities in Thailand, Japan, and the USA integrated Power Ledger's P2P trading platform in their electricity systems (+R; +E; global; focal), improving knowledge development (+K; global; focal), as well as the legitimacy of Power Ledger's technology (+L; global; focal) (Interview 11).

Up to this point, a new system structure for P2P electricity trading in the WGV had been built without having to directly interact with the local electricity sector. The encounter was delayed thanks to the nurturing space provided by the WGV housing development, which allowed P2P trading to achieve the initial system build-up. Consequently, no significant blocking factors were experienced while the P2P electricity trading was kept 'behind the meter', beyond the reach of the local focal incumbents. However, when Power Ledger proposed P2P electricity trading as a solution across the city of Fremantle in early 2018, interactions with the incumbent electricity sector became more frequent and some friction emerged.

At the time, the local electricity sector did not provide favourable regulatory conditions and incentives for P2P electricity trading across the regulated electricity grid (-L; local; focal). On this grid, exclusively operated and managed by the incumbents, Western Power and Synergy, small-scale electricity producers, such as residential prosumers and strata companies, could not act as 'citizen utilities', but were instead obliged to trade via the incumbents. In addition, the grid tariffs were too high to make P2P trading economically more viable than trading with utilities, blocking demand from small residential prosumers in Fremantle (-M; local; focal) (Interview 3).<sup>17</sup> Consequently, it was

<sup>15</sup> The WA housing sector has historically been dominated by low-density residential developments, making Perth one of the most geographically extended cities on earth. The WA government has set density targets, to build more apartment buildings to eliminate further urban sprawl (Matan and Newman, 2012; Newman and Kenworthy, 2007).

<sup>16</sup> ICOs are similar to IPOs and have recently been used extensively by cryptocurrency ventures to raise funds from individual investors and enthusiasts. ICOs bypass the otherwise highly regulated process that is a criterion for raising capital from banks or venture capital investors.

practically impossible to trial P2P electricity trading across the regulated grid infrastructure without incumbent involvement (–E; –R; local; focal).

Despite significant barriers imposed by the local regulations, the legitimacy of the P2P trading, both locally in WGV and globally, encouraged the local incumbents to join the WGV project. They did not join out of mere curiosity but also in an effort to find a solution to their own local challenges (+G; +N; local; focal). Increasing penetration of rooftop PV production in residential buildings and ‘behind the meter’ electricity consumption had been substantially affecting the revenue streams of both incumbents. They viewed P2P trading as a potential opportunity to re-engage with disconnecting customers, increase utilization of the utility grid infrastructure, and improve demand flexibility (Interview 12; Interview 13). The entry of incumbents further legitimized the P2P innovation (+L; local; focal). Theoretically, we see an example of how the successful build-up of a novel system can attract the attention of local incumbents that, facing serious challenges to their business model, choose to engage in a productive encounter with disruptive system builders.

The novel system had gained significant momentum at this point, but further development necessitated financial and institutional changes. Joined by the local utilities, the existing actor network mobilized additional financial resources from the federal government (+R; national; supporting) to trial and expand P2P trading across the city of Fremantle and establish the Smart Cities and Suburbs project (+R; +E; local; focal) (Interview 7). This motivated the incumbents to use their institutional power to create flexibility in existing regulations and revisit the electricity pricing structure to enable P2P electricity trading across the regulated grid in Fremantle (+L; +R; local; focal). In addition, the new project strengthened the local actor network, which formed a consortium of partners who signed a binding contract, institutionalizing actors’ responsibilities in the new P2P trial (+N; +L; national, supporting) (Interview 9; Interview 10; Interview 11).

## 5.2. The Brooklyn Microgrid project

The BMG system build-up was from the outset a global innovation effort. It was initiated by Lo3Energy, a small start-up company that since 2012 has promoted the innovative transactive energy model<sup>18</sup> to enable self-sufficient community-driven microgrids (+G; global; focal). Lo3Energy aimed to improve transactive energy model ideas by complementing them with blockchain technology (+R; global; adjacent), which had the potential to tackle what they saw as the biggest technical barrier for local microgrids – i.e. tracking a large number of transactions and near real-time settlement in a distributed grid network and allowing for P2P trading (Interview 15; Interview 16). Lo3Energy developed a blockchain-based electricity meter for community microgrids, and in 2016 received technical support and capital investment from Siemens (+R; +K; global; focal).

While not originally from NYC, Lo3Energy identified Brooklyn as a suitable environment for the first blockchain-based P2P microgrid trial. Their decision was influenced by NY State’s Reforming the Energy Vision (REV) plan to re-build NY’s aging electricity infrastructure into a clean, resilient, and affordable energy system for all (NYSERDA, 2017). REV was established after NY State was severely impacted by Hurricane Sandy in 2014 and experienced widespread blackouts. Building

<sup>17</sup> The network charges in WA are high due to socializing the costs of previous investment in bolstering grid infrastructure and long-distance transmission. These charges do not reflect the increasingly local and distributed character of the grid.

<sup>18</sup> Transactive energy markets are essentially smart distributed grids combined with the Internet of Things, a software platform for monitoring, analysing, and managing a large number of smart devices instead of market actors. Advocates believe that the production and utilization of electric energy will in the future become indistinguishable from the Internet of Things (Collier, 2015).

community microgrids became one of the most important components of the REV strategy, and microgrid development projects started flourishing across NY State (Wood, 2016).

Via REV, the NY State government provided public funding to the companies providing the best solutions. From Lo3Energy’s perspective, the REV strategy in NY State conferred legitimacy on their innovative technology (+L; local; supporting) as well as potentially providing public funding. Within Brooklyn, Lo3Energy targeted the residential areas of Park Slope and Gowanus due to their reputation for strong community and sustainability values as well as their high penetration of residential PV systems, indicating strong market potential (+M; local; focal). Analytically, we see deliberate action by entrepreneurs seeking a market for their innovation, finding opportunities in the seemingly favorable industrial and institutional context of NYC.

Actor network formation in the BMG project began with Lo3Energy convincing residential electricity prosumers and consumers to participate in BMG. These participants became the main source of legitimacy and demand for blockchain-enabled P2P trading (+G; +L; local; focal). The startup focused specifically on residents, businesses, and community organizations affected by blackouts after Hurricane Sandy and thus presumably critical of the incumbent electricity sector (Interview 15; Interview 16). Many were persuaded to install blockchain-based electricity meters and thus provide Lo3Energy access to their production and consumption data, a key resource for P2P trading experimentation (+R; +E; local; focal). Lo3Energy also used the opportunity to involve two of the residents, one with and one without PV systems, to film a demonstration video of the first P2P transaction in April 2016 (Interview 22; Interview 23). The video spread rapidly across the Internet, attracting considerable attention internationally from blockchain enthusiasts, increasing the legitimacy of the BMG project (+L; global; supporting) (Interview 22). In theoretical terms, the entrepreneur sought to build an actor network involving future customers, and used media and global interest in blockchain to enhance its legitimacy.

Despite the seemingly favourable environment in NYC for P2P electricity trading via blockchain, the entrepreneurs soon faced barriers that developed into a repressive encounter with the incumbent electricity sector. Lo3Energy did not manage to form a strong local actor network with PV system providers or housing developers that could provide support during the initial system build-up and encounter with the local incumbent sector. In fact, negotiations with local actors such as the electricity utility, community board, and local government were unproductive, resulting in little to no interest in joining and supporting the BMG project (–G; –L; local; focal). Many residential customers, despite being interested in the benefits of P2P trading, considered the incumbent utility, Con Edison, more trustworthy than small energy service companies and start-ups such as Lo3Energy (Interview 17; Interview 23). In addition, residential customers were also obliged and financially incentivized to continue trading with Con Edison through the net-metering scheme<sup>19</sup> versus trading electricity with their neighbours (–L, local; focal) (Interview 22; Interview 23; Interview 24). Consequently, consumer demand remained weak as local residents were not convinced of the P2P trading-related benefits (–M; local; focal).

The BMG project eventually failed to access financial resources provided by the REV fund, mostly because the funding for community microgrids was only available for Con Edison-led project proposals (–R; local; focal), giving local incumbents a chief position and control over the innovation process. Con Edison had freedom to select which entrepreneurs to engage with and financially support, and Lo3Energy was

<sup>19</sup> This is a financial mechanism that pays prosumers retail price to feed their solar energy into the utility grid. Net-metering offers prosumers an attractive way to reduce their electricity bills, so prosumers are strongly incentivized to feed electricity back into the utility grid.

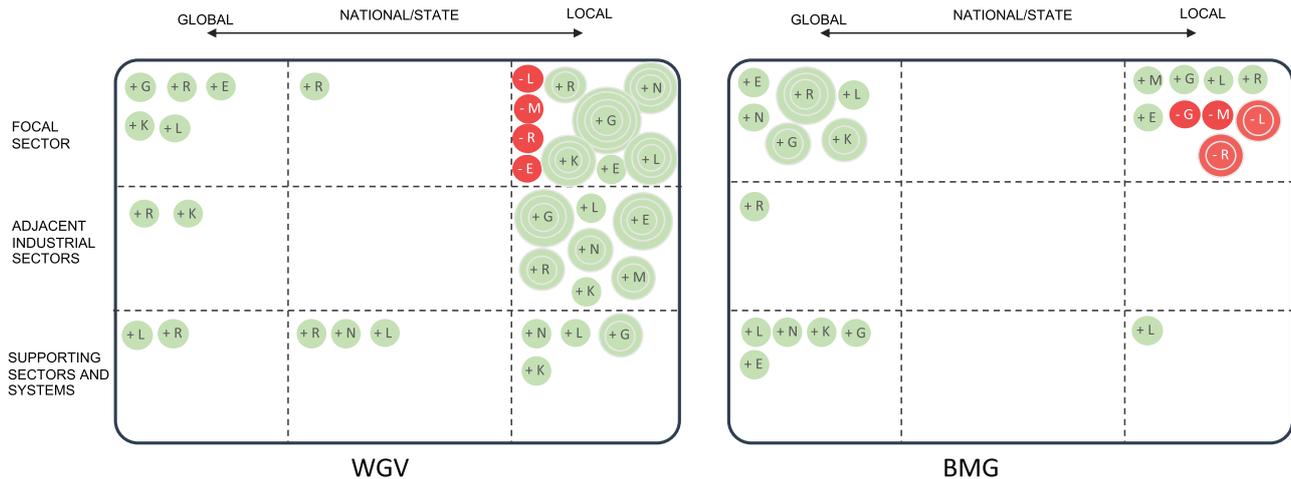


Fig. 4. The contextual origins (Fig. 1) of supporting and blocking factors are presented in terms of the entrepreneurial activities (i.e. functions) they influence (abbreviations explained in Table 1). Contextual factors successfully used by the entrepreneurs are represented by '+', while those blocking entrepreneurial agency are represented by '-'. If multiple factors influence the same function and originate in the same part of the context, the circle around the function is enlarged.

not among them (Interview 17; Interview 18; Interview 19). Consequently, the entrepreneurs failed to operationalize P2P trading across the Con Edison-owned grid infrastructure in Brooklyn (-R; -E; local; focal) (Interview 16). Unlike in the WGV case, the local incumbent sector was not under pressure to engage in the project and saw little potential in the innovative technology (Interview 18). After the initial set-back, Lo3Energy decided to open negotiations with the energy market regulators in NY State, with the strongest institutional power, to push for experimental 'sandboxes' and regulatory exemptions. In the meantime, the BMG project was put on hold, blocking further local system build-up (Interview 16).

In the face of the repressive encounter with the local incumbents in NYC, Lo3Energy used the positive global media attention to continue the system build-up in other institutional environments. By early 2018, Lo3Energy had initiated collaborations with Karlsruhe Research Institute in Germany and with utilities and energy communities worldwide (+G; +N; +K; global; focal; supporting). These new collaborations resulted in the creation and exchange of new knowledge about P2P trading, for example, via a joint research paper about the BMG project (see Mengelkamp et al., 2018). Together with new partners, Lo3Energy initiated trials in residential, commercial, and university microgrids in Germany, the USA, Australia, Japan, and the UK (+E; +R; global; focal; supporting) (Interview 15; Interview 16). They also attracted financial support and expertise from major private companies such as Bremer Energy Ventures and Centrica (+R; +K; global; focal). Forming international actor networks and acquiring financial capital and technical expertise further increased the global legitimacy of the BMG project (+L; global; focal). Experimenting in other locations helped maintain the momentum of Lo3Energy's P2P electricity trading platform, despite Lo3Energy's failure to achieve its initial ambitions in NYC (Interview 15; Interview 16).

## 6. Discussion

### 6.1. Key insights from the case comparison

In line with previous literature, our findings confirm that local industrial and supporting systems matter, especially in guiding the search and attracting disruptive entrepreneurial activities (Coenen et al., 2012; Cooke et al., 1997; Hansen and Coenen, 2015; Lundvall, 1988; Malerba,

2002; Stephan et al., 2017). This was true of both WGV, which was created in the local context of a growing PV and battery market in Western Australia, and of BMG, which was attracted by the opportunities potentially afforded by the REV strategy in NY State. However, as the BMG case showed, a seemingly conducive institutional environment can in fact favor incumbents and incremental innovation at the expense of radical innovation.

Furthermore, our findings support the arguments of 'TIS geographers', as we find that achieving productive encounters with incumbents requires converting contextual factors from multiple spatial scales into a new system structure to stimulate local support or compensate for a lack of it (see Fig. 4) (Binz and Truffer, 2017; Binz et al., 2014; Coenen et al., 2012). We contribute to this argument by providing evidence that 'multiscalar' innovation activities in the early innovation phase require substantial entrepreneurial agency, citing the examples of Power Ledger in WGV and Lo3Energy in BMG (Alkemada et al., 2011; Planko et al., 2017).

In fact, our cases confirm that entrepreneurial capabilities to navigate uncertain conditions are key to successful early-stage build-up (Jansma et al., 2018; Planko et al., 2017). We found that those entrepreneurs who recognize the importance of engaging with incumbents in adjacent industrial sectors can protect and nurture their immature technologies (Farla et al., 2012; Hanson, 2018; Markard and Truffer, 2008; Musiolik et al., 2018; Raven, 2007), confirming established ideas in the literature regarding niche market management (Kemp et al., 1998; Raven et al., 2010; Smith and Raven, 2012). As Fig. 4. shows, the entrepreneurs in WGV benefitted from a protected niche market in the local housing sector that provided them with actor support, physical infrastructure, financial resources, and legitimacy before they encountered local electricity utilities. In contrast, the entrepreneurs from the BMG challenged the local electricity incumbents from the outset, by trying to convince Brooklyn residents to leave the old electricity system and join the new P2P-based microgrid, yet stood little chance against Con Edison.

Based on these two cases, we also found that entrepreneurs have a competitive advantage in that they, unlike incumbents, are not tied to a local infrastructure and have no local role to uphold, and are therefore more flexible and spatially fluent system builders (Jansma et al., 2018). The BMG case indicates that even though the encounter with incumbents in one place is repressive, the entrepreneurs can still continue the

system build-up by seeking productive encounters with incumbents elsewhere. Using contextual factors outside the proximate local context allowed Lo3Energy to maintain the momentum of their technology by creating a supporting network, gaining financial resources, and implementing their technology in other countries. Power Ledger in the WGV case also used a range of non-local factors. This finding could provide new insights into why, when, and how entrepreneurs can overcome fierce resistance and generate momentum for disruptive innovations (Alkemade et al., 2011; Hekkert et al., 2007).

However, the position of local incumbents was also found to be a key factor. The productive encounter in WGV was possible not only due to the successful entrepreneurial use of contextual factors, but also because the utilities in WA were in a destabilized position (Karlton and Sandén, 2012), shaken by growing load defection, and had to rethink their business model. It remains to be explored whether there is a general pattern to the combination of contextual supporting factors, entrepreneurial activities, and type of threat to incumbents that can encourage radical innovation.

A surprising insight is the absence of national-level factors in our two cases, with the main dynamic in both cases being the local–global interaction (see Fig. 4). We have not seen this pattern as clearly in previous TIS literature, which tends to interpret the national level as an important driver of innovation. We propose that further investigation is necessary to reveal whether this is a unique pattern, a pattern characteristic of very early system build-up, or a common pattern overlooked due to prior analytical bias favouring the national level. There may be a need for improved theorizing of the polycentric structure of an emerging ‘glocal’ technological system that grows in local clusters with increasingly important cross-scale linkages to similar clusters elsewhere, combining the local ‘geographically immobile’ and global ‘ubiquitous’ supporting structures (Asheim and Isaksen, 2002).

## 6.2. Contributions to the TIS approach

This study confirms that TIS is useful for analysing early-stage innovation processes when the novel system has a weak internal structure and is almost fully dependent on micro-level agency to gain support from external factors. Moreover, we demonstrate the usefulness of the TIS approach in analysing the emergence and growth of software-based focal technologies. We suggest that using TIS as a lens for analysing a more varied set of technologies, beyond physical artefacts such as wind turbines and PV panels, can be beneficial for gaining new transition-related insights. This is of particular importance in the era of digitalization, when software and Internet-based technologies are radically transforming the sociotechnical fabric of established industries.

We contribute to the TIS approach by developing and testing a two-dimensional matrix of contexts, and by linking it to the role of agency within a single analytical framework (Fig. 3). Our framework improves the TIS approach by connecting the previously separate concepts of context and agency through conceptualizing the TIS functions as activities of system builders, i.e. entrepreneurs, who transform a rich set of contextual factors into a new system structure (Alkemade et al., 2011; Bergek et al., 2015; Binz and Truffer, 2017; Coenen et al., 2012; Planko et al., 2017). While the analytical framework in this study improved our understanding of how entrepreneurs can use contextual factors to start building a system and achieve productive encounters with incumbents, we argue that the proposed way of structuring context has generic value, and may also be applied to studies of more mature technological systems.

## 6.3. Implications for the blockchain-based P2P trading model

A key empirical discovery from both cases is that while blockchain-

based P2P electricity trading is intended to disrupt the centralized character of the electricity sector, its realization still relies on accessing physical grid infrastructure typically owned and managed by incumbents. To avoid premature repressive encounters with incumbents that wish to maintain their centralized position, experimentation could begin behind the utility meter, for example, in apartment buildings, university campuses, and remote microgrids, where the electricity grid is privately owned and operated by non-utility actors. Through a growing global patchwork of behind-the-meter experiments, P2P electricity trading may gradually gain momentum that can no longer be ignored or resisted by the incumbent utilities.

However, to expand P2P electricity trading across the regulated grid, entrepreneurs may still have to collaborate with established utilities. That is also the reason why many experiments are currently designed as ‘peer-to-utility-to-peer’. It seems unlikely that all communities of prosumers and consumers will be willing to create P2P marketplaces bottom-up, since individuals are generally not allowed or able to take on the responsibility and complexities that P2P electricity trading would entail, without the safety net of the electricity retailers and grid operators, who in many countries provide high-quality public services. Productive encounters between incumbents and entrepreneurs are therefore central to the future of P2P electricity trading. Nevertheless, one should expect that incumbents will try to ‘hybridize’ disruptive trading models to maintain their position, potentially hindering radical architectural innovation (Henderson and Clark, 1990).

Our study, albeit limited to two cases, suggests that to explore the potential of distributed software technologies, policy frameworks should provide institutional flexibility and reduce incumbent control over the innovation process, in order to challenge the myopic thinking about the future electricity system configuration and how to realize it. Inviting disruptive innovation is important in order to address transition-related unknowns and trade-offs, such as the possibility of empowering end-users while ensuring public service provision, security of supply, price stability, and paying for the existing grid infrastructure.

## 7. Conclusions

This study addresses the generic question of how a radical innovation that fundamentally challenges an established industry can overcome the resistance of incumbent actors. Addressing this question requires an analysis that considers influential factors across multiple scales as well as the role of entrepreneurial activities. This study presents a framework that extends the TIS functional approach with a two-dimensional matrix of contextual structures and an explicit conceptualization of entrepreneurial activities.

The framework is applied to a comparative case study of two blockchain-based P2P electricity trading experiments that challenged the established centralized architecture of the electricity sector. The case study suggests that if the position of the incumbents remains secure, as leaders of the sustainability transition, innovation processes are likely to remain slow and incremental. However, disruptive innovation can still succeed with the help of dedicated entrepreneurs who use opportunities in various contexts across spatial scales, ranging from the local to the global, and across sociotechnical sectors, going beyond the focal electricity sector. This study is limited to retrospectively studying two cases of local P2P demonstration projects over a two-year period and it cannot predict future developments. Further studies of other demonstration projects elsewhere in the world can confirm whether the patterns observed here during the initial build-up are unique or are repeated elsewhere.

**CRedit authorship contribution statement**

**Kristina Hojckova:** Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing, Visualization. **Helene Ahlborg:** Conceptualization, Data curation, Writing - original draft, Writing - review & editing, Visualization, Supervision. **Gregory M. Morrison:** Resources, Supervision. **Björn Sandén:** Funding acquisition, Conceptualization, Writing - original draft, Writing - review & editing, Visualization, Supervision.

**Declaration of Competing Interest**

The authors whose names are listed immediately below certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment,

consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

**Acknowledgments**

This research was funded by the Swedish Energy Agency as part of the project, 'New networks of power: on the emergence, diffusion and impact of alternative electricity system architectures', and by the Kamprad Family Foundation. We would like to express special thanks to our reviewers for their constructive feedback that challenged our thinking and helped us improve the theoretical coherence and the quality of this paper.

**Appendix**

Table A

**Table A**

The White Gum Valley case summary of entrepreneurial activities making use of contextual and internal factors to build a new system structure. Table is organised chronologically.

Entrepreneurial activity making use of contextual (and internal factors), or blocked activity	Origin of contextual factor influencing a function (+/-)	New (or blocked) system structure
EARLY BUILD-UP Identification of opportunities for microgrids and prosumer-based business models stemming from growing residential solar PV + battery market, but lack of installations in high-density residential buildings	(+G; +K; local; focal; adjacent; supporting)	<b>New actor:</b>  Researcher group at Curtin University, WA <b>New knowledge:</b> 'Citizen utility': P2P electricity sharing model <b>New institution:</b>
The WGV in Fremantle, WA development identified as a place for P2P technology due to sustainability targets in the WA housing sector and in the city of Fremantle	(+L; local; adjacent; supporting)	<b>New actors and network:</b>  Positive expectations about the potential of P2P sharing in WGV housing development
Negotiations with actors from local housing development company and the city government	(+G, +N; local; adjacent; supporting)	<b>New physical artefacts:</b>  -WGV partners: Curtin researchers collaborate with a public housing development company and Fremantle city council
Housing demonstration - the 'Gen Y' multi-residential building in WGV selected as a first demonstration site	(+E; +R; +M; local; adjacent)	<b>New market:</b>  P2P sharing integrated in the embedded solar distribution network of 'Gen Y' 'Gen Y' strata company become the first 'citizen utility', making use of P2P sharing
Local microgrid expert company was invited to join and provide the technical expertise	(+G, +N; +K; local; focal)	<b>New actor, reinforced network and new knowledge:</b>  WGV partners joined by a microgrid expert with microgrid specific knowledge
WGV partners obtained funding from the Australian Renewable Energy Agency (ARENA) to invest in the PV and battery systems in two more buildings in WGV	(+R; national; focal)	<b>New financial resources and physical artefacts:</b>  P2P sharing model was integrated and experimented with in two additional housing developments in WGV
Two local housing companies provide new customers	(+M; local; adjacent)	<b>Enlarged market:</b>  Two new housing companies applies the technology of P2P sharing
Blockchain company invited to solve the accounting issues in the WGV project	(+G; +N; local; adjacent)	<b>New actors and reinforced network:</b>  Blockchain company joins WGV partners
	(+K; +R; global; adjacent) (+E; local; adjacent)	<b>New knowledge and physical artefact:</b>  Programming expertise and blockchain technology is combined into a P2P trading digital platform trialed in the WGV housing developments

(continued on next page)

Table A (continued)

Entrepreneurial activity making use of contextual (and internal factors), or blocked activity	Origin of contextual factor influencing a function (+/-)	New (or blocked) system structure
Incumbent energy sector consultants approached to explore electricity sector-wide opportunities	(+ G; + N; local; focal) (+ K; + L; local; focal)	<b>Reinforced network and new actor created:</b>  Curtin researchers, blockchain company and consultants create a P2P start-up Power Ledger <b>New knowledge and institutions:</b> Incumbent sector expertise and the ambition to take P2P electricity <i>sharing</i> to a global P2P electricity <i>trading</i> solution moving beyond embedded microgrids in high-density buildings <b>New financial resources:</b>
Power Ledger uses blockchain-based fundraising - Initial Coin Offering (ICO)	(+ R; global; supporting)	Capital for Power Ledger to improve the P2P trading digital platform <b>New institutions:</b>
Via ICO, P2P trading from WGV attracts significant global interest from the community of blockchain enthusiasts as well as substantial media attention	(+ L; global; supporting)	Positive expectations about the potential of P2P trading in disrupting the electricity sector
<small>SPATIAL BROADENING</small> Via ICO and global media, electricity utilities from other countries are interested in collaborating with Power Ledger	(+ G; global; focal)	<b>Reinforced network:</b>  With electricity utilities from other countries, the actor network grows beyond WGV <b>New physical artefacts and knowledge:</b>
Foreign electricity utilities integrate Power Ledgers P2P trading platform and trial it in electricity systems outside WGV	(+ R; + E; + K; global; focal) (+ L; global; focal)	Power Ledger access electricity grids, solar and battery systems in other countries, more experimentation and improved knowledge on P2P trading <b>Reinforced institutions:</b> Global collaborations reinforce the legitimacy of Power Ledgers P2P trading platform
<small>ENCOUNTER</small> Rights to trade electricity across the public grid are exclusive to public electricity utilities in WA	(-L; local; focal)	<b>Lack of aligned institutions:</b>  Electricity market regulations in WA do not allow for P2P trading across the public electricity grid <b>Lack of markets:</b> Potential customers do not wish to leave current contracts for the P2P trading model <b>No access to physical artefacts:</b> Lack of access to physical infrastructure restricting experimentation across the regulated grid <b>Reinforced network:</b>
P2P trading is economically infeasible due to high grid tariffs	(-M; local; focal)	
Public utilities in WA own and manage the public grid infrastructure	(-E; -R; local; focal)	
Electricity utilities in WA joined the WGV project in the effort to find a potential solution to the electricity sector challenges in WA	(+ G; + N; local; focal) (+ L; local; focal)	WGV partners joined by local utilities seeking for a solution to sector challenges <b>Reinforced institutions:</b> The entry of incumbents increases legitimacy of P2P trading and expectations for trading across the grid <b>Reinforced financial resources and physical artefacts:</b>
WGV partners mobilized additional financial resources from the federal government	(+ R; national; supporting) (+ R; + E; local; focal)	- Funding for the <i>Smart Cities and Suburbs project</i> was raised to trial and expand P2P trading across the regulated grid in Fremantle <b>New institutions:</b>
WA utilities used their institutional power to reshape the existing regulations to enabled P2P trading in Fremantle	(+ L; + R; local; focal)	Regulatory exception allowing P2P trading across the regulated electricity grid in Fremantle <b>New physical artefacts:</b> Funding and access to the grid enable trial of P2P trading across the regulated grid <b>Reinforced network and institutions:</b>
WGV partners institutionalizes the existing actor network, partly as a result of the nationally funded project	(+ N; + L; national; supporting)	Partners establish a 'Consortium' and sign a binding contract about P2P- related experiments in Fremantle

Table B

Table B

The Brooklyn Microgrid case summary of entrepreneurial activities making use of contextual and internal factors to build a new system structure. Table is organised chronologically.

Entrepreneurial activity making use of contextual (and internal factors), or blocked activity	Origin of contextual factor influencing a function (+/-)	New (or blocked) system structure
<b>EARLY BUILD-UP</b>		
Identification of opportunity to create community-driven microgrids with transactive energy market models	(+ G; global; focal)	<b>New actor:</b>  Creation of start-up LO3Energy
Lo3Energy combine transactive energy models with blockchain technology	(+ R; global; adjacent)	<b>New physical artefact:</b> Lo3Energy develops a blockchain-based electricity meter for P2P trading in microgrids
Lo3Energy receives capital investment and technical support from Siemens	(+ R; + K; global; focal)	<b>New financial resources and knowledge:</b> Investment and technical expertise raise Lo3Energy's capability to improve the smart meter
Lo3Energy make use of the REV strategy which provides institutional (and financial) support for community microgrids	(+ L; local; supporting)	<b>New institution:</b>  Higher expectations for P2P trading technology in NY state
Residential areas in Brooklyn identified as a place for the P2P technology due to local community, sustainability values and high share of solar PV installations	(+ M; local; focal)	<b>Potential market:</b>  Community and sustainability values and high shares of PV installations supports the case for P2P trading in Brooklyn
Lo3Energy approaches residential customers asking them to become BMG participants, to legitimize and create demand for blockchain enabled P2P trading	(+ G; + L; local; focal)	<b>New network and reinforced institutions:</b>  Residents and businesses in Brooklyn sign up as participants of the BMG and share the positive expectations for P2P trading
By recruiting residents, Lo3Energy can access their PV rooftop systems and metering data	(+ R; + E; local; focal)	<b>New physical artefacts:</b>  Access to residential PV systems to enable experimentation with P2P electricity trading
Marketing of the first P2P transaction between Brooklyn residents in global media	(+ L; global; supporting)	<b>Reinforced institutions:</b>  Video attracts attention from a global community of blockchain enthusiasts and media, increasing expectations.
<b>ENCOUNTER</b>		
Unproductive negotiations with local electricity utility, community board and government	(-G; -L; local; focal)	<b>Lack of networks and weak institutions:</b>  Failure to attract a local actor network and further legitimize the potential of BMG in Brooklyn
Residents perceive incumbents as more trustworthy than small retail companies and are obliged and incentivized to trade electricity with the utility through the net-metering scheme, with a better financial outcome than P2P	(-L; -M; local; focal)	<b>Lack of institutions and markets:</b>  Existing regulations, incentives and relations motivate residents to remain customers of the incumbents
REV funding only available via incumbents	(-R; local; focal)	<b>No access to financial resources</b> Lack of financial resources
Incumbents own the grid infrastructure and have exclusive rights to trade electricity in Brooklyn	(-R; -E; local; focal)	<b>No access to physical artefact</b>  No access to grid infrastructure for P2P trading trial in Brooklyn and
<b>SPATIAL BROADENING</b>		
Media attention to BMG project attracts collaboration with research institutes, utilities, energy communities in other countries	(+ G; + N; + K; global; focal; supporting)	<b>Reinforced network and knowledge:</b>  New partnership with researchers abroad leads to improved P2P-related knowledge and internationally diffused knowledge via a joint research paper
New actor network allows access to electricity systems abroad for P2P trading platform experiments	(+ E; + R; global; focal; supporting)	<b>New physical resources:</b>  Access to electricity microgrids, solar and battery systems in other countries, more experimentation with P2P trading
Successful search for financial support and expertise from multinational companies and investors	(+ R; + K; global; focal)	<b>New financial resources and knowledge:</b>  Capital to further improve blockchain-based P2P trading platform and related knowledge
Global interest increases the legitimacy of the BMG project and the P2P trading platform	(+ L; global; focal)	<b>Reinforced institutions:</b>  P2P trading perceived as a potential solution for the electricity sector challenges outside BMG

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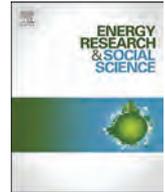
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# Paper III





## Original research article

# Is peer-to-peer electricity trading empowering users? Evidence on motivations and roles in a prosumer business model trial in Australia



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## ARTICLE INFO

## Keywords:

Prosumer  
Consumer role  
Blockchain  
Peer-to-peer electricity markets  
Sustainability transitions  
Innovation diffusion

## ABSTRACT

Peer-to-peer (P2P) electricity markets have attracted significant attention as a promising model enabling the integration of distributed energy sources by creating consumer-based electricity markets. Despite the significance of users in this model, knowledge is still lacking as to who the users interested in P2P electricity markets are and what role they can play in building them. We aim to fill this knowledge gap by providing evidence from the first real-world trial of a P2P electricity market facilitated by blockchain technology across a regulated electricity network. We apply sustainability transition and innovation thinking to analyse the trial participants as users shaping the P2P-related innovation process. Supported by our empirical results, we found that users joined the P2P market trial to learn and co-create the future of prosumer-centred electricity markets. We also found that if P2P is to enter the mainstream market, the assistance of other actors (e.g., intermediaries and activists) is important in order to cross the chasm to reach the majority of users and move from a learning and probing phase to breakthrough and wide diffusion.

## 1. Introduction

In traditional electricity systems, end users act only as passive consumers and receivers of electricity supplied from centralised generation via transmission and distribution grids [1]. This traditional model is being challenged as falling prices of small-scale solar photovoltaic (PV) systems and batteries motivate households and commercial properties to install their own on-site generation capacity. This is transforming traditional end users into active parts of the electricity system [1-3], earning them the title of prosumers – actors who both produce and consume electricity [4-6].

In countries such as Australia, nearly one quarter of households have installed PV systems [7] and prosumers are remunerated for excess energy production through government-sponsored feed-in-tariff (FiT) or buy-back schemes via existing electricity retailers. Here, the high level of PV penetration is affecting the technical and economic stability of the centralised electricity system [8], making subsidies and retailers' default purchase of self-generated energy exported to central grids unsustainable [9]. However, as subsidies decline and eventually expire, prosumers are left in a post-subsidy era with no alternative revenue model for their excess electricity [4]. There is increasing interest in post-subsidy market models that could create new value streams for prosumers [1,4,5,10], better reflecting the bidirectional

nature of the new electricity system [11] and facilitating the transition to a distributed and clean electricity system [12,13]. One such business model innovation is the peer-to-peer (P2P) market model [5,10,14-18], which in principle allows prosumers and consumers to trade with each other without needing an electricity supplier or retailer as middleman. The middleman is replaced with a third-party digital platform, such as a blockchain-based platform, that allows prosumers and consumers to interact directly and negotiate better prices for their electricity, in contrast to relying on the offer from a licensed supplier [5,14]. It is believed that P2P markets will create future electricity markets with users at their heart, democratising local energy provision [15]. In addition, the P2P model could improve access to affordable clean electricity for those users who do not own renewable energy technologies. This concept has been described as energy and flexibility justice [19-23].

While the concept of P2P electricity trading has recently attracted increasing research interest [18,24-27], it has only existed in the form of conceptual models and experiments in closed environments such as embedded networks [15], university campuses [17,28], and organised energy communities in islanded micro-grids [5,16,26] where P2P sharing and trading occurs in the form of a computational simulation, or behind the utility meter in environments shielded from incumbents and regulations [29]. The P2P case study described here provides

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evidence from the first real-world P2P electricity trading trial facilitated by blockchain technology, which allows consumers and prosumers to trade electricity over the regulated electricity network, directly affecting their electricity bills.

Existing research into the P2P model is limited by its concentration on the technological and pricing aspects of P2P electricity trading. Much less attention has been paid to real-world prosumers and consumers (here collectively referred to as electricity users), i.e., individuals or groups that use electricity as well as associated technologies (e.g., solar panels) to consume, produce, and distribute energy.<sup>1</sup> The users in the P2P model are no longer passive consumers of the output (as in traditional business models), instead being directly involved in the P2P value exchange and thus central to its successful development [31]. Ahl et al. [24] reported that the relationship between electricity users and blockchain-based P2P business models (and vice versa) has yet to be empirically studied. Furthermore, they also found no published research into why and how consumers would want to participate in P2P market innovation. This paper aims to fill these research gaps and provide knowledge of how users can contribute to P2P model-related innovation processes that go beyond merely consuming [10,24,30]. By doing so, we hope to assist the research community, policy-makers, and industry actors to grasp the potential implications of this business model [24].

We have looked beyond the techno-economic literature to better understand and conceptualise the relationship between users (here, trial participants) and the development of a business model innovation (i.e., the P2P market trial). We engage with the sustainability transition and innovation diffusion literatures, which provide us with a conceptualisation of users that goes beyond the one-dimensional view of users as playing a role only in consuming innovations [30]. In this body of literature, scholars emphasise that users are important change agents, enacting agency throughout the innovation process, from the development of niche market ideas to adopting the niche innovations in everyday practice [32]. However, earlier studies have largely emphasised the role of users in supporting product innovation, while user contributions to new business model development remain under-explored in the transition literature [12]. Existing business model innovation research is still mainly concerned with the roles of firms, managers, entrepreneurs, and advocacy organisations in the process of business model implementation [13,33]. This paper attempts to fill this research gap by conceptualising P2P electricity trading as a niche business model innovation within a broader transition to sustainable energy systems [4,32,35] and by placing users at the centre of our analysis.

The aim of this study is to investigate the motivations and roles of users in developing P2P electricity markets. We provide evidence from the first real-world example of P2P electricity trading via a blockchain platform, located in Fremantle, Western Australia (WA). This aim is fulfilled by addressing the following research questions:

- 1 Who are the electricity users who are willing to experiment with P2P electricity trading and what motivates them?
- 2 What roles do electricity users play in shaping P2P electricity trading-related innovation?

The paper is structured as follows: In Section 2, we introduce the background to the P2P market model and its potential to support the renewable energy transition. In Section 3, we look more closely at how users are conceptualised in the transition and innovation literatures, before synthesising these literatures into a conceptual framework for analysing the empirical case. Section 4 introduces the research design, methodology, and case study, followed by the empirical results in Section 5. The results are analysed and discussed using the conceptual

framework in Section 6, while the conclusions are presented in Section 7.

## 2. Peer-to-peer electricity trading models

Environmental concerns, technological innovation, and the impacts of prosumers on markets and system operability have led to increasing interest in distributed renewable electricity systems as alternatives to the dominant centralised model of electricity production and consumption [34,35]. Growing numbers of scholars and industry actors are emphasising that new distributed grids will require marketplace innovation to reflect the decentralised infrastructure and the changing character of users who, by adopting distributed energy technologies, have become active market participants who can produce, sell, and buy electricity as well as reap benefits from their demand flexibility [4,11,15,19,20]. Yet many challenges remain, including finding business models that can fairly distribute costs and benefits among a large number of self-interested market participants [24] and facilitate energy and flexibility justice [19,20]. Several prosumer-focused solutions are being proposed, with different levels of interaction and levels of dependence on the existing energy system [4,5]. This paper examines an autonomous P2P model,<sup>2</sup> defined by Parag and Sovacool [5], that in theory allows prosumers and consumers to interconnect and trade directly with each other. This model is perhaps the farthest from today's electricity market design [4], serving as a starting point for establishing the P2P trial that is our case study.

The research literature defines the P2P electricity market as an autonomous P2P network of prosumers and consumers, often compared to an Uber or Airbnb model for the electricity sector [5]. Influenced by ideas of the “sharing economy”, a software-enabled P2P market model allows consumers and prosumers to buy and sell self-generated electricity and other services, such as flexibility or demand response, in an open electricity market across the regulated distribution network [10,18,24,36]. Blockchain technology is the software platform considered to enable the P2P marketplace [14,24,27,36]. Blockchain is a decentralised Internet protocol that could, in theory, enable transactions of monetary and non-monetary digital assets<sup>3</sup> directly between peers without the necessary involvement of a middleman, such as a licensed energy retailer [14,36]. Due to its ability to create smart contracts and ledgers, blockchain algorithms could replace the need for a licensed retailer to overlook and verify contractual agreements between peers [27].

Like other new technologies and business models, the P2P model is still unsupported by existing regulatory structures, financial institutions and lacks societal awareness or acceptance [24]. Ruotsalainen et al. [29] identify the importance of considering that the P2P market model currently only exists as a vision of a desirable future without accounting for existing electricity sector actors and infrastructure. Embedding the P2P model in real-world settings across the public grid infrastructure entails significant caveats and complexities that must be resolved if the theoretical benefits are to be realised [4,5].

An increasing number of scholars and industry actors believe that the P2P model is unlikely to result in the complete collapse of the incumbent electricity sector; instead, utilities and public authorities may continue to exist alongside prosumer networks. However, the future

<sup>2</sup>The P2P model is the most radical prosumer-based business model innovation, in which prosumers and consumers trade directly with one another in a seamless network without a need for the large grid market. Other prosumer-based models are “prosumer-to-interconnected or islanded microgrids” and “organised prosumer groups market”, both including different levels of interaction between prosumer networks and the large grid market [5].

<sup>3</sup>Digital assets that can be traded on a blockchain are not limited to financial transactions (e.g., payments for electricity). In the energy sector, other non-monetary assets that could be traded are, for example, demand-side and flexibility services, energy certificates, carbon offsets, and/or storage services [37].

<sup>1</sup> Definition inspired by Schot et al. [30].

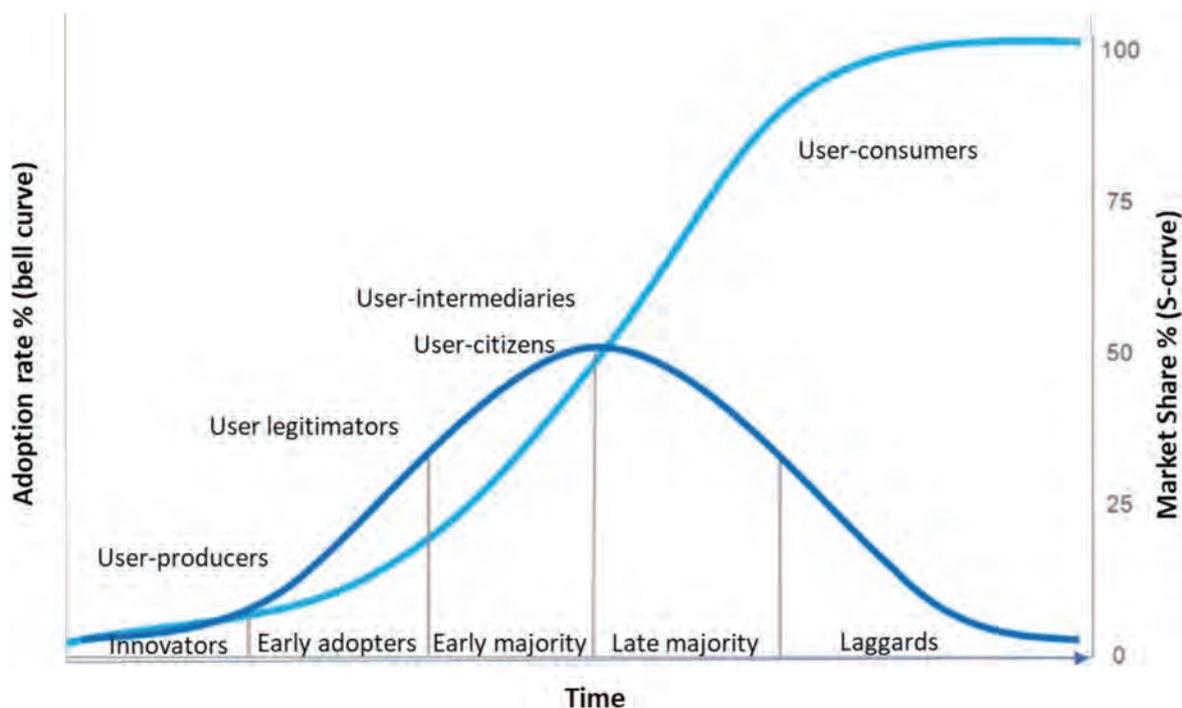


Fig. 1. Categorisation of users along the innovation adoption bell curve [50] (x-axis labels) and typology of user at different points of the innovation S-curve [30] (S-curve labels).

roles of various actors in a P2P trading model are not yet known [10,29]. We do not wish to study actor roles in the future P2P market (assumed to be a mature and established system design). Instead, we examine the transition and innovation processes leading to this market, and the specific roles prosumers and consumers can play in developing P2P markets by studying their motivations, expectations, and conduct in a real-world P2P trial. Specific technical details and critique of the blockchain-enabled P2P transaction model lie outside the scope of this study.

### 3. Achieving transition through business model innovation

As described in the previous section, the P2P model offers several potential social and technical benefits for the future of distributed energy systems [5]. Yet the challenge remains to understand how this niche business model innovation can break through and challenge the dominant electricity market model, and to identify the roles users can play in this process. The sustainability transition and innovation literatures offer useful frameworks with which to study the role of niche innovations in systemic sectoral transitions. The multi-level perspective (MLP) [38] has been one of the most prominent frameworks in this field, treating technological change as an interaction between three analytical levels: the niche, regime, and landscape. The socio-technical regime consists of actors, institutions, and infrastructure aligned around a dominant design. The regime can be challenged from the niche level, a protected space in which radical technological innovations emerge and grow. Regime change can also be affected by external landscape forces, emerging from the broader socioeconomic system (e.g., political agenda). A regime transition is a complex co-evolutionary process that involves fundamental reordering of the social and technical components of a socio-technical system. The MLP is described in more detail in seminal papers by Geels and Schot [39], Rip and Kemp [40], Geels [38], and Smith et al. [41].

While MLP emphasises building new regimes, which takes decades, we argue that this perspective can be useful in understanding more recent innovations within the context of long-term systemic change. The ability to see the “context of a transition” can be useful when

analysing specific technological novelties. This is evident in most single-case studies using MLP, for example, examining the struggle of plant-based “milk” against entrenched dairy milk [42] or the niche-regime interaction of solar PV technology in the Netherlands [43]. However, existing transition research has concentrated on novel technological products within niches as drivers of change. Scholars have stressed that new technologies alone will not suffice to achieve systemic change, noting the importance of business model innovations because they connect multiple actors, mediate between the production and consumption sides, and support the introduction of novel technologies in the market. [12,13,31,33].

Business model-oriented transition research became established with the analysis of energy service companies in the UK [13,44], new business models for whole-house retrofitting in the Netherlands [12], and distributed business models under the *Energiwende* in Germany [31]. Similarly, we consider business models to be niche innovations in their own right. We therefore use MLP to position our case study in the broader electricity sector transition, in which the centralised energy market is challenged by innovative electricity market models emerging as niche innovations. While this study focuses on the P2P model, we understand that different business model innovations are competing, interacting, and complementing one another in gradually developing the future market model for a decarbonised electricity sector [13,45,46].

#### 3.1. Users in niche business model innovation

Transition thinking has recently been refined by integrating business model innovation ideas [12,13]. Existing transition studies have focused on the roles of firms, entrepreneurs, managers, and advocacy organisations when implementing new business models in the context of a sector in transition [4,12,13,31,33]. In the transition literature, business models are traditionally regarded as integral to firms, as a means to deliver customer value, with customers seen as passive business model adopters. If the dominant business model logic in the electricity sector is to be broken, more knowledge is needed of the role users can play in business model innovation as they evolve from being

mere consumers to being key actors in the electricity market.

Although not specifically emphasised in research into business model innovation, the system-building role of users in the energy system transition has been highlighted by Schot et al. [30], who, using the MLP framework, defined a typology of users who support new technologies in different innovation phases along the innovation S-curve [30,47-49]. In their conceptualisation, users can act as producers, legitimators, intermediaries, citizens, and consumers (see Fig. 1). While Schot et al. [30] claim that this user typology matters in long-term systemic transition, they also cite examples of its application to relatively specific and recent niche developments related to small-scale consumer-side renewables. We accordingly argue that this user typology can be applied in studying early-stage innovations as well.

This framework offers a user-to-system perspective in which users are one of the system builders, breaking down the structures of dominant regimes. For example, user-legitimators focus on convincing regulators, while user-citizens focus on opposing incumbents. The users in this framework are important in aligning system components for successful systemic innovation. Though it provides important insights, this perspective pays insufficient attention to micro-dynamics and agency among the users themselves, which are important when studying small-scale local innovations. The diffusion of innovation literature highlights the importance of the user-to-user influence on innovation [50]. In this body of literature, the most widely applied user categorisation was developed by Rogers [50], who divided users into ideal types of adopters ranged along a bell curve based on innovativeness, i.e., the different time points when particular users adopt an innovation give them different influences on its development and diffusion. Here, users range from the most innovative innovators, through early adopters, early-majority adopters, and late-majority adopters, to sceptical laggards (see Fig. 1).

As Roger's bell curve is a derivative of the S-curve, we propose that these typologies can be synthesised into the categorisation of user roles in niche development processes depicted in Fig. 1. Both these

categorisations support the view that users are not a homogenous group with a single role but are heterogeneous actors who play different roles in supporting innovations. By combining these perspectives, we emphasise that users can play a role in both system- and micro-level (i.e., user-to-user) dynamics. Both these categorisations can be plotted over time, creating the foundation for our analytical framework (see Fig. 2).

As indicated earlier, sustainability transitions and innovation occur over time, conceptualised as the phases of system innovation. Various authors have described the technological innovation phases; for our framework, we apply the four-phase model developed by Geels [51] (described in Table 1), because it includes the probing and learning phase as a separate category (Section 3.2).

### 3.2. Analytical framework

While the work of Schot et al. [30] and Rogers [50] emphasises user contributions to all innovation phases, other scholars emphasise the user role in specific phases of the innovation process. Through a literature review, we strengthen our initial analytical framework, shown in Fig. 1, broadening our view of how users are conceptualised in specific innovation phases; the end result is depicted in Fig. 2 and summarised in Table 2.

In the first phase of innovation, when the novelty is emerging, researchers have noted the importance of users in inventing and creating novel solutions and routines [30]. These users can either be self-motivated, or can be identified by other actors, such as private firms, in order to customise the new technology and improve its quality, performance, and user-acceptance before introduction in the mainstream market [52]. These users are often cosmopolitan, connected internationally to a small group of innovators with whom they share interest in and enthusiasm for novel ideas and technologies [50]. They can understand and apply complex technical knowledge and cope with a high degree of uncertainty. To afford potential losses resulting from supporting an innovation, they usually have substantial financial

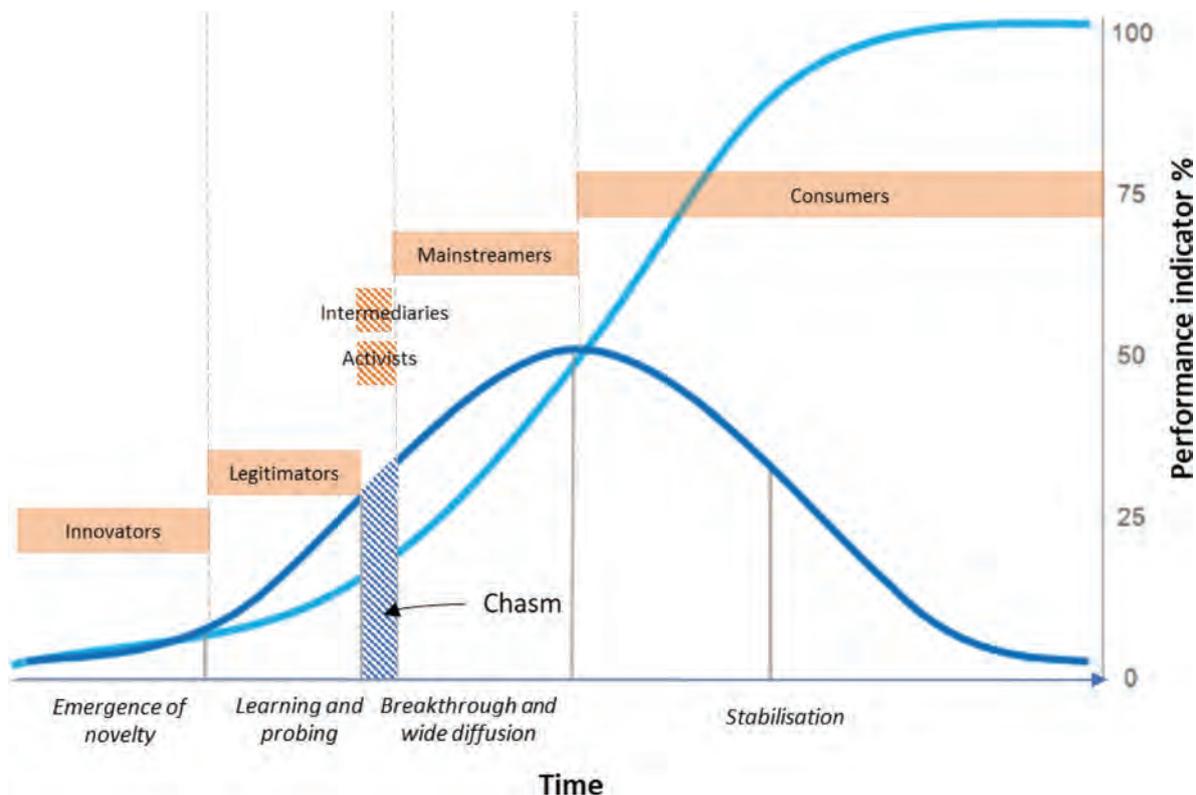


Fig. 2. User roles (graph labels) across four phases of innovation (x-axis labels), showing the innovation phase in which each user type is most active. This schema includes the chasm to be crossed to move from learning and probing to breakthrough and wide diffusion with the assistance of user-intermediaries and activists.

**Table 1**

Four phases of system innovation, adapted from Geels [51].

Phase	Characteristic
<b>Phase 1.</b> Emergence of novelty	An innovation emerges to solve a problem or offer a new alternative to the dominant regime, i.e., sector. It is nurtured by a small actor network (of technology pioneers and innovators) sharing expectations of the future performance of the innovation. To improve the innovation's price and performance, they experiment to improve the design and accommodate user preferences.
<b>Phase 2.</b> Probing and learning	The supporting network evolves into an established group or community of specialists, producers, and consumers. These actors work together to improve the innovation through learning about market preferences and understanding the necessary legislative change.
<b>Phase 3.</b> Breakthrough and wide diffusion	With the help of external pressures and internal momentum, the innovation gains more actor and legislative support, which improves the price/performance ratio and achieves economies of scale and learning. The linkages and co-development of new system elements increase, building new infrastructures, new governmental agencies, and professional organisations.
<b>Phase 4.</b> Stabilisation of the new regime	A new socio-technical regime is created around the innovation with new infrastructure and new widely adopted user practices, policies, and regulations.

resources [50]. Alternatively, these users seek and utilise new supportive institutions such as tax reductions and subsidies to support an innovation [30]. Extensive research has long acknowledged users' co-creation role in how both systems and technologies are developed, adopted, and appropriated by society [53-60]. Existing literature refers to these users as user-innovators [50], producers [30], enthusiasts, or product designers [56,59,61-64]; in our framework, we refer to them as *innovators* (Fig. 2).

In the second innovation phase, users are important in supporting the application of the innovation in a local context, legitimising it. Compared with users in the first phase, these users are locally integrated and have more influence on their proximate environment. They adopt the innovation soon after launch because they see a compelling reason to use it and are willing to accept the related uncertainties and costs in exchange for future benefits [50]. They embed

the innovation locally, reducing the innovation-related uncertainty by learning about and probing the innovation, making errors and improving innovation-related knowledge [30]. With their local influence, they can convince people and increase expectations of the relevance and significance of the innovation. They create narratives to align opinions about the innovation among their peers and other system actors [30,50,65,66]. These users try to stimulate acceptance of the innovation in their peer networks by encouraging imitation and competitive reactions among most users, playing a crucial role in creating conditions for the wide diffusion of the innovation [66-70]. Existing literature calls them early adopters [50], user-legitimizers [30], entrepreneurial users, and lead users [57,71,72]; we call them *legitimizers* (Fig. 2).

By considering how the existing literature identifies the way in which users contribute to development in different innovation phases,

**Table 2.**

Summary of the user roles across the transition phases with descriptions of how these users contribute to the innovation and transition process.

Transition phase	User role	User role defined in the existing literature	Contribution to the innovation and transition process
Emergence of novelty	<b>Innovators</b>	<ul style="list-style-type: none"> <li>• User-producers [30]</li> <li>• Innovators [50]</li> <li>• Product designers [50, 56, 59, 61-63]</li> <li>• Energy enthusiasts [64]</li> </ul>	<ul style="list-style-type: none"> <li>• Invent and create new technical and organisational solutions and routines</li> <li>• Use supporting institutions (e.g., tax reductions and subsidies)</li> <li>• Enthusiasm for new ideas; understand and apply complex technical knowledge</li> <li>• Look for ideas outside of the local context</li> <li>• Can cope with high uncertainty</li> <li>• Have substantial financial resources</li> <li>• Embed innovation in the local context</li> <li>• Reduce uncertainty by making errors and learning</li> <li>• Convince and increase expectations of the relevance and significance of the innovation</li> <li>• Stimulate acceptance of the innovation among their peer networks</li> </ul>
Probing and learning	<b>Legitimizers</b>	<ul style="list-style-type: none"> <li>• User-legitimizers [30]</li> <li>• Early adopters [50]</li> <li>• User-entrepreneurs, entrepreneurial lead users [57,71,72]</li> <li>• Opinion leaders [65,66]</li> </ul>	<ul style="list-style-type: none"> <li>• Create space for alignment of new actors, institutions, and technologies</li> <li>• Voice expectations, interpretations, and uses of new technologies to the regime actors</li> <li>• Enrol new actors, creating networks between them</li> <li>• Cooperate with other actors such as firms and (non) governmental organisations</li> <li>• Involved in transition politics</li> <li>• Mobilise social movement for reform</li> <li>• Actively try to overcome resistance of incumbent actors</li> <li>• Dissatisfied with current regime</li> <li>• Important in creating network effects among users</li> <li>• Adopt just before the average member of a system</li> <li>• Seldom hold an opinion-leadership position</li> <li>• They have great willingness to adopt but seldom lead</li> <li>• Buy products and embed them in their daily practices</li> <li>• Adopt just after the average user, after innovation-related uncertainty is reduced</li> <li>• Use the innovation due to peer pressure or because it has become the dominant choice</li> </ul>
Breakthrough and wide diffusion	<b>Intermediaries</b>	<ul style="list-style-type: none"> <li>• User-intermediaries [30]</li> <li>• Energy user communities [76-79]</li> </ul>	
	<b>Activists</b>	<ul style="list-style-type: none"> <li>• User-citizens [30]</li> <li>• Grassroots movements [76,81-84]</li> <li>• Activist groups [30,80]</li> </ul>	
	<b>Mainstreamers</b>	<ul style="list-style-type: none"> <li>• Early-majority users [50]</li> </ul>	
Stabilisation of the new regime	<b>Consumers</b>	<ul style="list-style-type: none"> <li>• User-consumers [30]</li> <li>• Late-majority users [73]</li> <li>• Market product consumers [86,87]</li> <li>• Market participants [25]</li> <li>• End-users [88-91]</li> <li>• Consumers with preferences, needs, behaviours, and practices [92]</li> </ul>	

we can see how existing categorisations and descriptions overlap. We can also identify disagreement regarding what it takes to move from one phase to the next. While Rogers' [50] categorisation suggests that early adopters can take an innovation from niche to wide diffusion by acting as influential opinion leaders, evidence shows that the diffusion process is not always as linear as this theory predicts [73]. A relevant criticism comes from Moore [73], who has claimed that, in some cases, an innovation that is well received by early adopters will not necessarily succeed among most users due to significant differences between their motivations for adopting the innovation, creating a chasm (see Fig. 2) between these two user groups [73]. Moore [73] theory explains the issue of bridging the chasm between early adopters and early-majority users, noting that an early adopter looks to other early adopters for validation, whereas members of the traditional user group look to other traditional users for validation that the business model is worth adopting and/or promoting. It is also important to note that Rogers' [50] perspective assumes that early adopters have a good position from which to access the rest of their social network of peers within a firm or industry.

The users' importance in bridging the chasm by enabling the breakthrough to pass from experimentation to wide diffusion has been emphasised by Schot et al. [30]. They label these users *intermediaries*<sup>4</sup> and *activists*, terms we decided to adopt in our framework. Intermediaries represent those users who not only attempt to communicate with other more sceptical users, but also create space or serve as a bridge for alignment between different actor groups, institutions, and technologies to support the wide diffusion of the niche innovation. They are active in communicating innovation-related preferences and expectations with existing regime actors to appropriate and align existing regulations and standards, thereby promoting the innovation [30]. Another example of user-intermediaries cited in the literature is that of energy user communities [76-79]. Activists play a crucial role in enabling the niche innovation breakthrough by being involved in transition politics. These users are generally dissatisfied with the existing regime, actively lobbying for reform to overcome the regime resistance and weaken the position of incumbents. These users have previously also been called activist groups [30,80] and grassroots movements [17,76,81-85].

After a successful breakthrough is achieved, users start playing an important role in the wider diffusion process by adopting the innovation in their everyday practices. This category was emphasised by Rogers [50], who called these users early-majority users, seeing them as crucial for creating a network effect to mainstream the innovation. Based on their role, we therefore call these users *mainstreamers* (Fig. 2). While they have great willingness to adopt an innovation, they seldom hold strong opinions or leadership positions and take longer to decide to adopt an innovation. These users wait until other users develop and experiment with an innovation to improve its price and performance before they adopt it [50].

After the innovation has achieved wide diffusion, the stabilisation phase follows. In this phase, users play the most important role by buying products and embedding them in their daily practices. In this phase, *consumers*, as they are called in our framework, adopt the innovation just after the average user, once innovation-related uncertainty is reduced. They do so because it has become the dominant choice or because of peer pressure. Existing literature describes these users as late-majority users and laggards [50], consumers [30,50,86,87], market participants [26], and end-users [88-91].

<sup>4</sup> The role of an innovation intermediary is not limited to users. Extensive literature on intermediary actors in sustainability transitions identifies the intermediary roles of specialised private and public organisations, government-funded agencies, consultancy firms, as well as individuals such as managers and academics [74,75].

## 4. Methodology

### 4.1. Case study: Western Australia and the case of the RENeW Nexus project

The Renewable Energy and Water Nexus (RENeW Nexus) project was implemented in Fremantle, WA. It consisted of an early trial of a blockchain-based P2P trading model in real-world conditions, operating across the regulated electricity network and affecting participants' electricity bills. The aim of RENEW Nexus was to test both the technical and social aspects of P2P trading. Considering the social aspects, which are the focus of this paper, the project aimed to understand why and how participants engaged in P2P trading as well as how the P2P model itself affected participants' engagement with the novel trading option.

The project consortium comprised a city council, a land developer, two universities, a blockchain start-up, as well as an electricity network operator, retailer, and generator. While the retailer is also the largest generator in the state's electricity market, constituting a combined retail and generation organisation, for the purposes of this trial, it is treated as a retailer alone and is referred to as such. Existing regulations require that residential users must purchase their electricity from the public retailer. The retailer's involvement in the trial was therefore essential to allow payment of the half-hourly P2P trades, which were settled in the end-of-month retail electricity bills.

The retailer provided secondary meters to display real-time data to the participants and to manage the customer relationship and billing. It also acted as a buyer of last resort for unsold solar exports, a seller of any shortfall electricity that could not be supplied by peers at any time, and an enforcer of consumer protection rules. While the active P2P trading component of the RENEW Nexus project is outside the scope of this paper (Fig. 3), this information is provided to explain the relevance of the middleman to a trial of an autonomous concept.

The trial was run in the City of Fremantle, which offers a suitable context for sustainability-oriented innovation, given its history of political and civil sustainability leadership. The city's higher number of prosumers and lower energy grid electricity consumption than state averages [93] strengthens its suitability for trialling the P2P electricity trading model.

### 4.2. Participants in the P2P trial

Voluntary participants in the P2P trial in Fremantle were sought via announcements on social media and the city council's website as well as through word of mouth. Fifty participants in total – forty prosumers and ten consumers – self-nominated for inclusion in the trial. A participant represents a household rather than an individual; the choice of the household level for analysis was influenced by the context of the electricity sector, in which the household remains the main unit of analysis. The prosumer participants were home owners, which was necessary to allow for the installation of updated metering infrastructure and was typically a prerequisite for having a solar PV system. As shown in Fig. 3, the numbers of trial participants declined to twelve prosumers and six consumers following presentation of the P2P trading tariff structures. Readers are referred to Section 5.4 for reasons why participants chose to withdraw and to Appendix A for details on the specific P2P trading approach and associated pricing structures used in the trial.

### 4.3. Research design

This paper presents a single-case study analysis based on a mixed-method research design [94-96]. One benefit of single-case studies is that they can be particularly useful in exploratory work and in generating new hypotheses [97]. While we are aware that the generalisability of single-case study findings can be limited, the case chosen is exemplary, reflecting a real-life phenomenon not studied in the past [94], i.e., the world's first P2P model of electricity trading across the public electricity

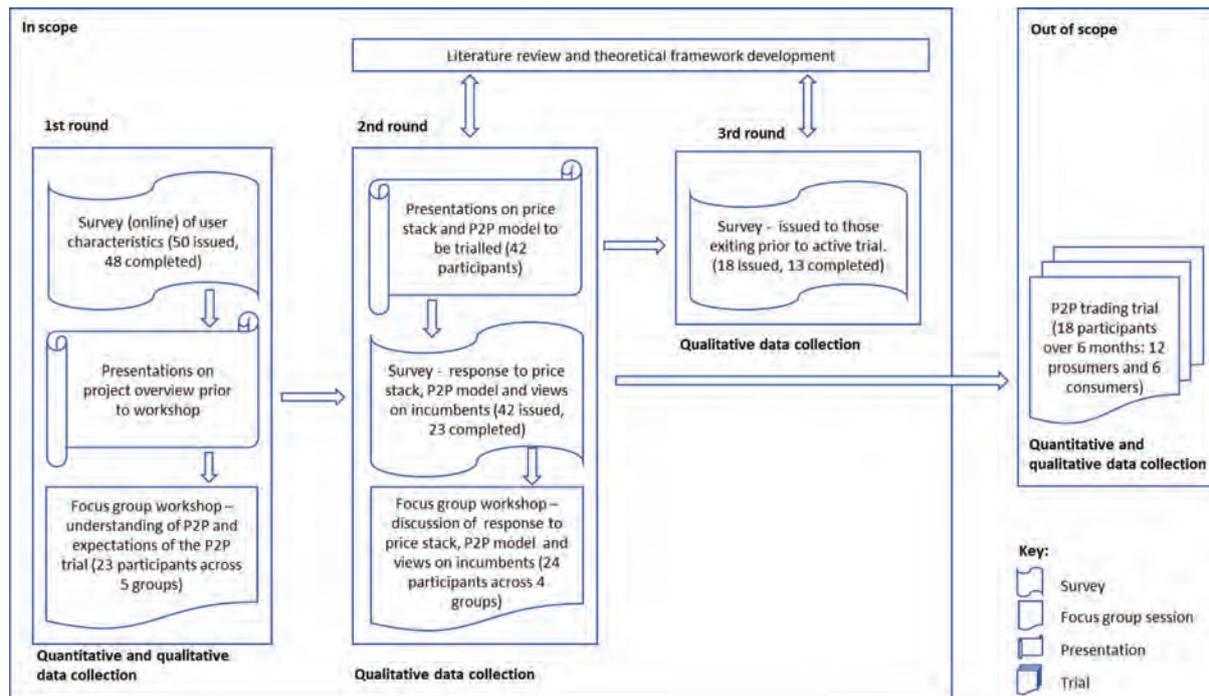


Fig. 3. Stages of qualitative and quantitative data collection up to the commencement of the live P2P trial. This paper focuses on research findings stemming from the data collected in the “In scope” box. The P2P trading trial results are out of the scope of this paper.

grid. While the sample is small, at the time of writing, it represented the only participants globally who were actively P2P trading across a regulated electricity network using blockchain technology. The absence of other comparable real-world case studies precluded employing a comparative case study methodology. Considering these weaknesses, scholars seeking to apply the present findings should consider the nature of the community in which the trial was undertaken [98] (see Section 4.1).

An inductive research approach was selected, starting with exploratory data collection that would guide us to suitable conceptual perspectives, serving as a foundation for our analytical framework [99]. Data were collected in three separate rounds using mixed methods to gain a broader perspective on our research object [100]. These rounds included three surveys and two focus group discussions with the self-nominated participants, as detailed in Fig. 3. Questions in the first survey and first focus group session (Appendix B) were exploratory and designed to suit a diverse range of research aims for the broader RENEW Nexus project. The successive survey instruments (Appendices C and D) and focus groups were designed to test emergent theories and our evolving analytical framework. The benefit of having used different data collection methods is that they allow triangulation of our primary sources [96], especially given that secondary sources relating to users of P2P electricity trading models are still lacking [100]. Fig. 3 summarises both the focus of each data collection activity and the numbers of participants in each activity.

While surveys were conducted with individuals each representing a household, the focus group sessions were conducted with individuals in groups of four or five with an independent facilitator allocated to each table. At the first focus group workshop, each participant provided independent written responses to the two questions (regarding participants’ understanding of P2P and their motivations for participating) on Post-it notes. Each note was then discussed at each table to identify common themes and areas for extrapolation. All written notes were later themed and coded using NVivo 12 qualitative analysis software. At both focus group workshops, audio recordings of the discussions at each table were transcribed verbatim into NVivo 12. The same coding categories used for the written responses were then applied to each transcript. Coded themes from the written responses can be considered more representative of individual thoughts, whereas those mentioned during the

focus group discussion drew out issues more important to the groups.

## 5. Results

### 5.1. The first P2P electricity trading users

According to the survey, the participants had a median household income of over AUD 156,000 per year. This is 48% greater than the median household income for Fremantle residents [101], indicating that the users involved in the trial were from relatively financially secure households.

Eight prosumers had acquired their PV systems in 2009 or earlier, while over 50% of all prosumers had installed rooftop PV systems between 2016 and 2018 (Fig. 4).

The survey revealed that the participating prosumers perceived themselves as having a good understanding of PV technology and of how to make the most of their self-generated electricity. In fact, 67% of prosumer households revealed that they often or very often adjusted their consumption patterns to use more electricity during the daytime; 55% claimed to set their appliances on a timer to increase the consumption of self-generated electricity.

### 5.2. Motives for trialling P2P electricity trading

The initial survey asked participants about their attitudes towards the incumbent electricity sector in WA in order to explore whether these had affected their motivations for joining the trial. The results indicate that 58% of participants were dissatisfied with the existing electricity retailer, prosumers generally being less satisfied than consumers (Fig. 5). The most common reason for dissatisfaction was financial, related to high grid electricity prices (AUD 0.28/kWh) and low financial compensation for the renewable energy generation (the FiT is AUD 0.07/kWh). For a full breakdown of the tariffs relevant to the P2P trial in the local electricity market, see Appendix A.

A significant number of respondents also mentioned dissatisfaction with the network grid operator’s supply charges. Concerns were raised that the supply charges were passing through transmission costs that

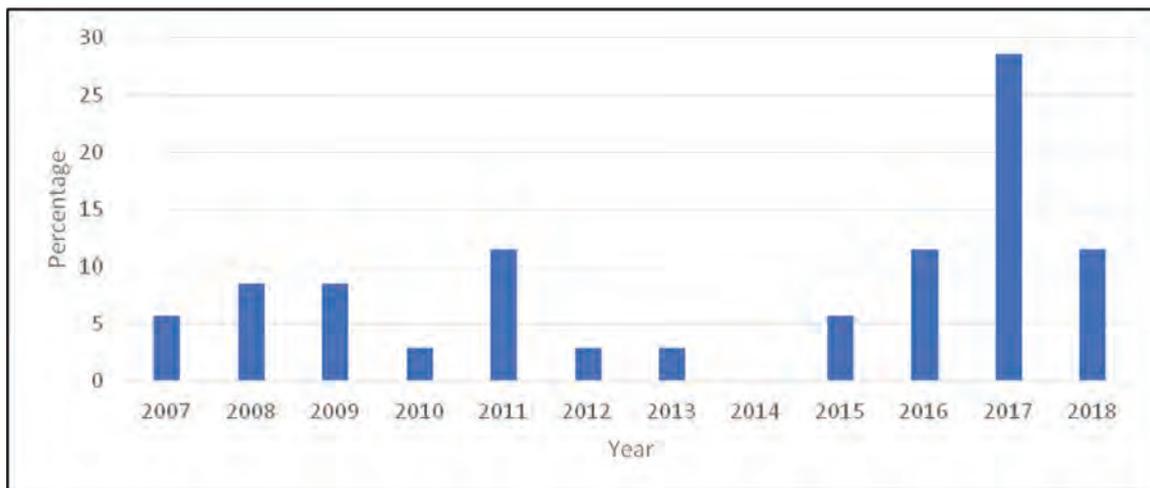


Fig. 4. PV installation year for the prosumer households.

participants perceived to be unnecessary in the context of the high levels of local renewable energy generation.

Other less frequent reasons for dissatisfaction with the electricity retailer concerned the lack of detailed electricity usage information in electricity bills, lack of incentives to save electricity, and perception that the retailer/generator does not invest enough in renewable energy production (Fig. 6).

The results of the first focus group workshop revealed that the largest single motivation for joining the trial was participant interest in knowledge acquisition, including the opportunity to learn about: personal electricity use and the electricity system in general; what will happen after the FiTs expire; and the potential solution offered by P2P trading (see Fig. 7). The second strongest motivation was the chance to be “ahead of the curve” and trial a cutting-edge technology. Interactions between participants during focus group discussions reflected a sense of excitement at being part of a cutting-edge innovation. There was also a collegial tone, as many participants were early adopters of rooftop solar technology and shared enthusiasm for renewable energy and sustainability, with the P2P trial seen as embodying these principles. This is shown from the following quotations recorded from each workshop table:

Light a fire that could go global quickly ... and have a rapid transition to a clean energy future.

I feel good that Fremantle is starting this and we can say, you know, that you are proud of this.

In 30 years’ time when it is common practice – knowing that you were at the beginning.

Sends a very clear message to the government that people are interested in sustainability and they want better policy.

Love being involved in stimulating renewable uptake.

The participants were motivated by the potential to steer the sustainability transition towards a more socially equitable and clean energy system by demonstrating the successful application of a P2P trading model. Around half of the participants were motivated by efficiency improvements, described both in terms of financial efficiency, which might be achieved by eliminating the retailer/middlemen, and in terms of energy transfer efficiency, with more local solutions and less need for long-distance transmission. Notably, during the focus group discussion, only 25% of respondents stated that they were motivated to join the trial to save money or by the expectation of being financially better off, and this was mentioned apologetically:

This is going to sound really terrible, but one of my motivations was to get cheaper power.

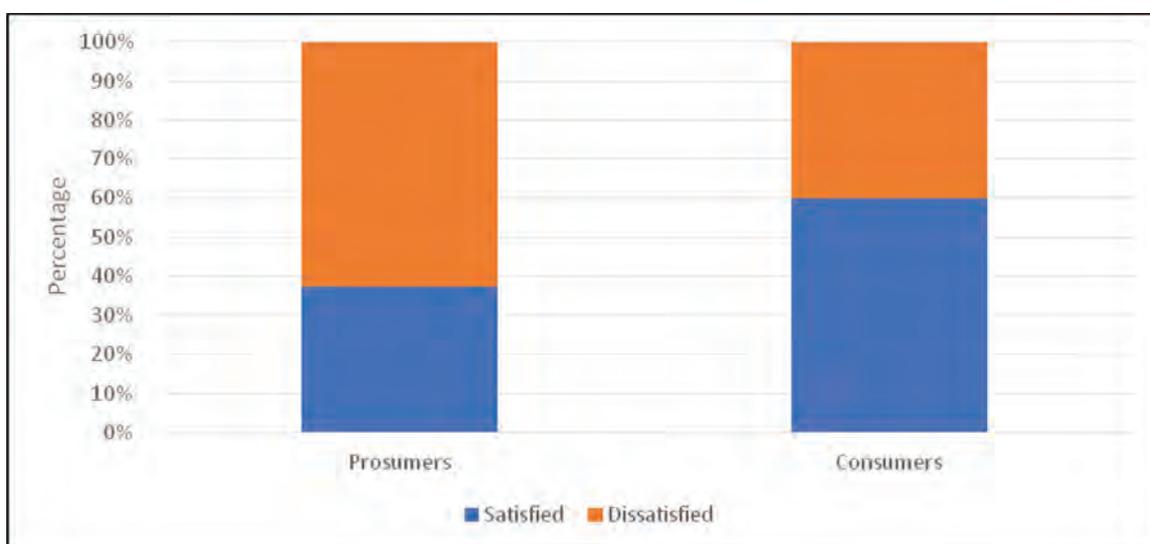


Fig. 5. Participant satisfaction with the current electricity retailer.

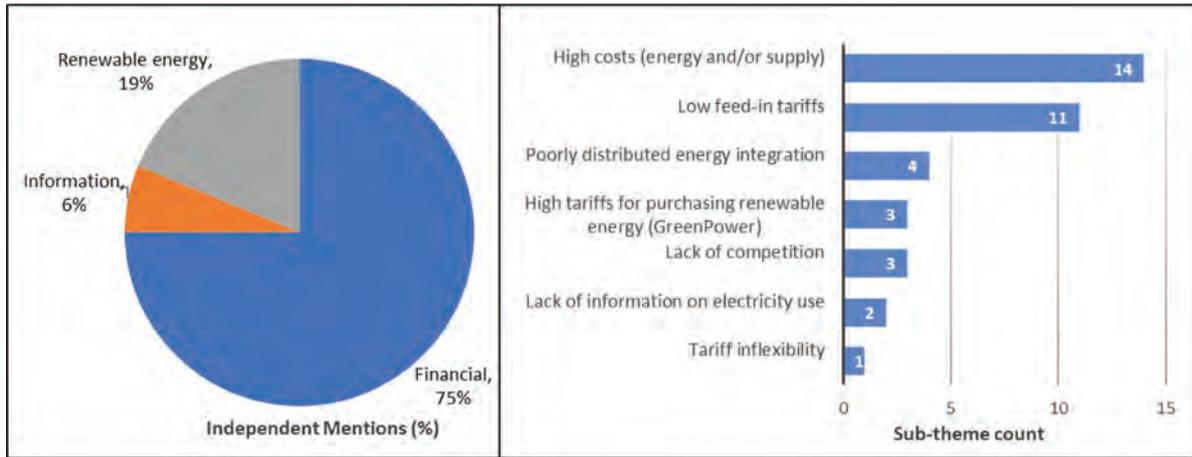


Fig. 6. Reasons for participant dissatisfaction with the electricity retailer: key themes (left pie chart) and broken down into sub-themes (right bar chart).

Despite this apparent irrelevance to the financial implications of the P2P model, many follow-up questions at the end of the session were related to potential financial implications of the trial.

5.3. User expectations of P2P electricity trading

Asking participants about their expectations revealed that they had good knowledge of P2P trading and clear expectations about the future potential and performance of this new trading model. The most frequently voiced expectations concerned local community trading, flexible and lower prices, and improved system efficiency. Eight participants independently noted that they expected the P2P scheme would reduce the need for involvement of the existing retailer. This view was then generally agreed on during the focus group discussions, with the following quotation being indicative of the expectations raised during discussion:

So you're providing your neighbours with some of the electricity you acquire through your PV panels, and not necessarily going through the retailer and the main energy companies. So I don't understand the software involved with it, but I understand it is about sending power from your PV panels to your neighbours and cutting out the middleman.

Seven participants independently noted expectations related to decentralising and localising the market, improving use of the local distribution network, and the possibility of local electricity sharing:

This way of working means that you're not beholden to the big picture of power. It's really very local.

Six participants related P2P trading to the specific use of blockchain

technology and crypto currencies (Fig. 8). Fewer expectations concerned the potential of P2P trading, for example, to increase the use of the distribution grid infrastructure, increase adoption of renewable energy production and batteries, and ensure a secure trading platform.

5.4. User reaction to the design of the P2P electricity trading model

Following the first focus group workshop, the design of the P2P electricity trading system was negotiated and developed by the project consortium and later introduced to the participants during the second workshop. A notable shift in user willingness to participate occurred when they received detailed information about the final design of the P2P trading model. Appendix A details the pre-existing tariff structure and a comparison with the P2P pricing design that was trialled.

The consortium-developed tariff design adopted in the trial evoked concerns among the trial participants, particularly in terms of the impact this would have on any remaining FiTs they were entitled to. This was mostly the case for small electricity users and those receiving the legacy AUD 0.4/kWh FiT, which they would have to forfeit if they joined the trial. A price forecast model presented at the workshop showed that, with the new fixed daily charges, participants who were large electricity users would benefit, whereas households that currently purchased and sold small amounts of electricity, and thus used the grid less, would be disadvantaged by participating in the trial.

Responses to the survey administered immediately after the presentation demonstrated that attendees understood the justification for the new daily charges embedded in the P2P model, i.e., that they were important for maintaining the distribution system and ensuring

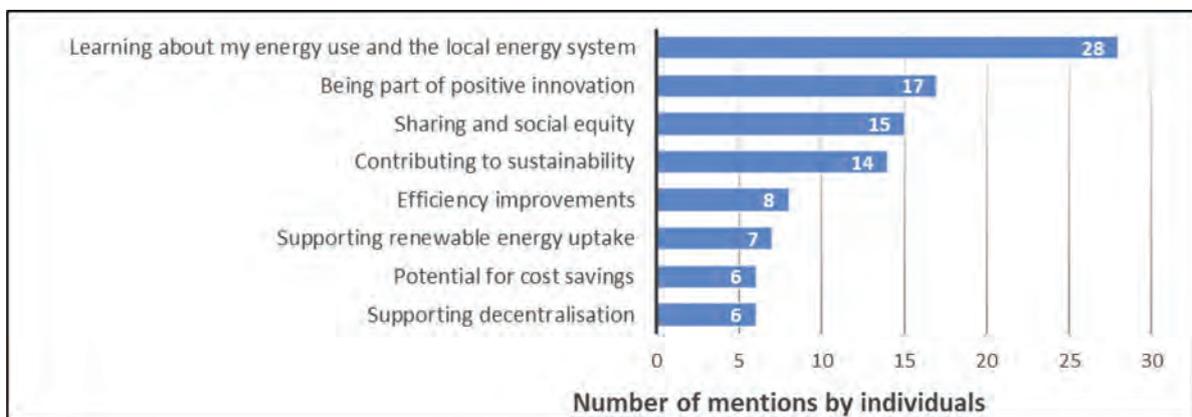


Fig. 7. Motivations for participating in the P2P trial, showing the number of times individual participants mentioned the themes during independent note-taking in the first focus group workshop.

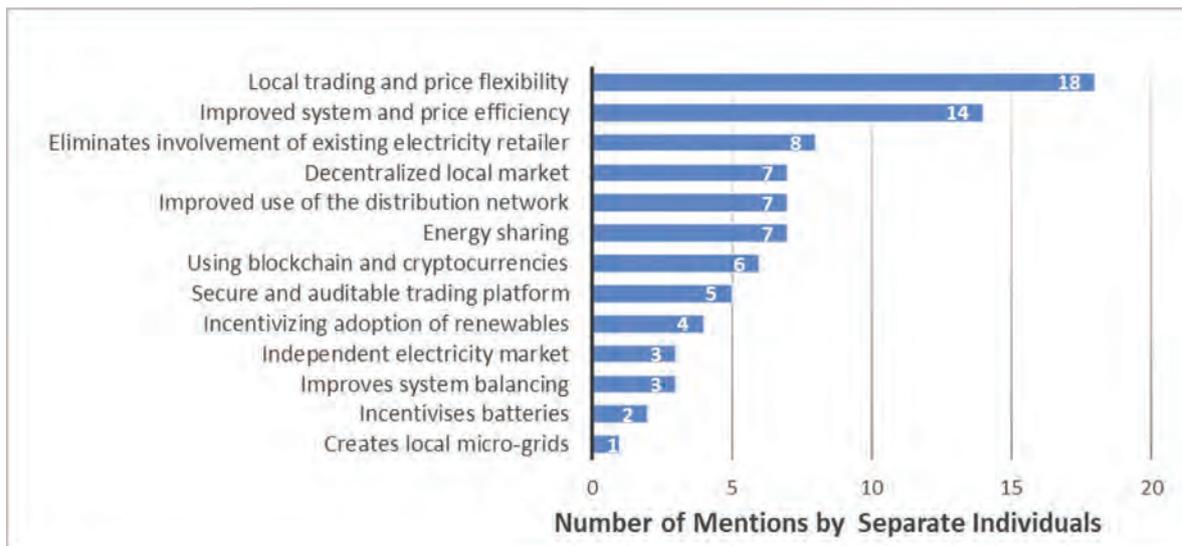


Fig. 8. Participant expectations of P2P electricity trading based on the number of times individual participants mentioned the themes during independent note-taking in the focus group workshop.

adequate generation capacity. The general acceptance of the P2P trading charges to support the broader electricity system was matched by nearly unanimous agreement that electricity should be made available to everyone in the community at reasonable prices.

Despite understanding the basis for higher prices, the participants expressed concern that the trial would reward big electricity users and penalise small ones. Many of these participants said that the design benefited the incumbents and lacked appropriate compensation for small residential electricity producers and consumers. Many of them thought that P2P trading should be subsidised to encourage uptake, as had occurred previously with solar PV.

The mood of participants was less positive in the second focus group workshop than in the first. This was expressed during the focus groups in terms of the final P2P model not aligning with participants' initial expectations. This misalignment is evident in Table 3, which contains contrasting quotations from the first and second workshops. Discussion in the focus groups indicated ongoing enthusiasm for P2P trading as a concept, but people were unsure of its benefits for themselves. Many stated that they would need time to review the information before committing to participate in the active trial.

Table 3.

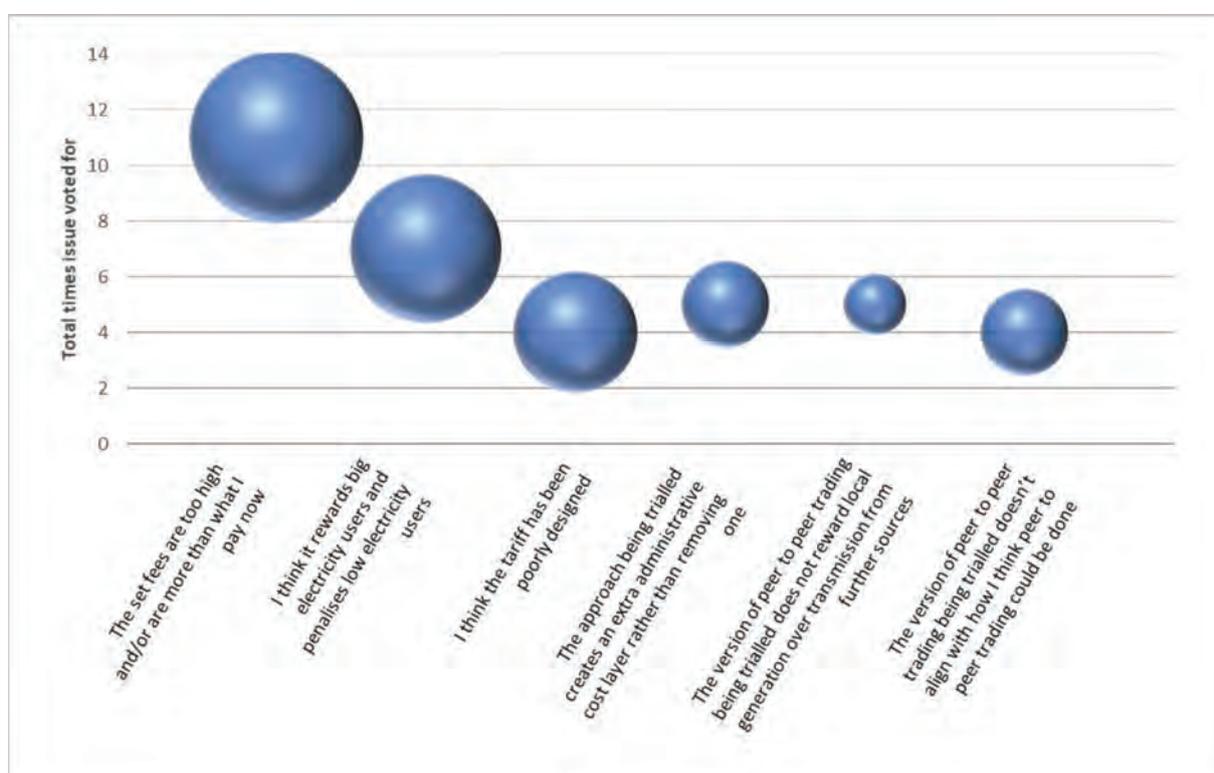
Quotations from the first and second focus group workshops showing the divergence between initial expectations (first workshop) and the realities of the P2P market model to be trialled (as understood by participants in the second workshop).

First focus group session	Second focus group session
I feel strongly about the sharing economy, and this is another way of sharing.	We're looking at something that's competitive with one another. And it – to me, it just doesn't actually sit right to have that, the spirit of it doesn't gel.
I love the idea of hooking into the shared community battery ... and just the actual value of sharing for a common cause. Yeah, we all have these systems. If we can share our energy, it makes so much more sense than having all these individual unique systems that we've got to pay for, look after, so it's a common cause.	It is very market-driven.
So, people who want to buy electricity can trade online, and ideally get slightly below the wholesale price, and ideally we get paid more than what the retailer, the monopoly, offers.	It's a lot like ... stock trading.
	Because for all my good intentions, I'm working full-time, I've got two children to look after and there's a lot of things to do in the day – I don't, can't guarantee I'm going to get the time to sit down, look at, open the platform and compare the platform with the current buy and sell prices for what I'm producing and change the price.

**Table 4.**

Key themes emerging from the workshop in which the P2P trading model and associated tariff structure were revealed to trial participants.

Theme	Summary
<b>Financial incentives matter</b>	<i>Worse Off:</i> If people are going to be worse off financially, then they would be less likely to participate. Fixed charges were understood but discouraged participation.
<b>Alignment with community values</b>	<i>Subsidies Required:</i> All groups thought that P2P trading should be subsidised to encourage uptake, as occurred with solar PV.
	<i>Design is too market driven or not community oriented enough:</i> Many participants joined on the basis of supporting the local community and broader social equity issues. The design is too market driven with no ability to trade with individuals of one's choice.
	<i>Social equity:</i> The design is similar to the stock market; the uneducated or disadvantaged will be less able to trade effectively and therefore will be further disadvantaged.
<b>The P2P market design</b>	<i>Need to support community trading:</i> Participants were willing to accept the small additional costs of P2P in the trial to demonstrate the benefits of P2P for the community sharing of electricity, in the expectation that it would lead to lower costs in the longer term should the P2P network be scaled up.
	<i>Different design required:</i> Participants liked the concept of P2P but thought it would be better suited to either closed networks, such as trading within apartment blocks, or to those who have batteries and can sell their excess electricity during peak times.
	<i>Reflect local movement of electricity:</i> Some wanted the design to reflect cost savings from reduced electricity transmission, and others wanted the fixed capacity charge to be increased to encourage energy-efficiency outcomes.
	<i>Risk too high for prosumers:</i> Some felt that prosumers were taking on too much risk by offering their own electricity production and selling into an unknown market with a limited number of consumers, which could lead to reduced returns on their investment.



**Fig. 9.** Survey results concerning reasons why people dropped out of the trial. Respondents could select multiple reasons and then rate them in order of importance. The position of the bubble on the y-axis indicates the number of times the reason was selected, whereas the bubble size represents how often the reason featured as one of the top four reasons for each respondent withdrawing from the trial.

The various opinions about the pricing design of the trial expressed by focus groups during the second workshop were mirrored by responses obtained in the exit surveys. The strongest reason why participants withdrew from the trial was that the P2P trading design was too expensive and/or unaligned with the participants' initial expectations about the future potential of the innovation (see Fig. 9 for a summary).

## 6. Analysis and discussion

In the following section, we analyse the results and discuss them within the context of our analytical framework (Fig. 2).

### 6.1. Roles of P2P trial participants in innovation processes

Our findings indicate that the users in the P2P trading trial are

financially secure households with a high interest in social equity and transitioning to decarbonised energy systems. They have good knowledge of their local context and the issues that they would like to help resolve. An important attribute of the trial participants is their good understanding of renewable energy technologies and their consumption and production patterns. They are also strongly motivated to learn about their own electricity use and broader innovations in the electricity sector, without being discouraged by initial complexities and financial losses. They also want to be "ahead of the curve" and have first-hand experience of a cutting-edge technology. These findings indicate that they aspire to be *innovators* (Fig. 2).

However, while they are interested in supporting the emergence of the niche P2P market and are self-motivated to do so, they are neither independent inventors nor creators. Instead, they show great interest in learning about the innovation and in embedding it in the local context.

This points to the trial participants being *legitimizers* (Fig. 2), as described in Table 2. They strongly believe their participation could increase outside expectations and therefore support the transition to more socially equitable and local renewable energy systems through demonstrating the P2P model.

According to the results, most of the trial participants share a degree of dissatisfaction with the incumbent electricity companies, whom they perceive as controlling and undervaluing the price of self-generated renewable electricity. Although this finding recalls the role of *activists* (Fig. 2), i.e., users actively speaking out against the *status quo* and incumbents, the dissatisfaction is strongest among prosumers and mostly concerns the low financial reward for self-generated electricity. These users differ from grassroots movements and activist groups in that they are not a self-organised group of consumers defining their identity through fighting the establishment to allow for the future of P2P trading. These participants are not stubbornly acting against the incumbents; instead, they prefer acting with the incumbents *via* the project consortium to improve the quality, performance, and user-acceptance of the model before its potential introduction in the mainstream market. However, the initial design of the P2P trading model was developed with little consideration of user input and the co-production process was weak, resulting in user criticism of poor system design with inappropriate pricing. These factors contributed to a high number of dropouts from the project. This result supports existing literature that identifies the importance of collaborating with users to help co-create the innovation design and improve user acceptance [56,59,64].

Although all trial participants initially appeared to be *legitimizers* of P2P trading, fewer than half of them remained in the trial after the introduction of the P2P tariff structure that indicated likely financial losses. Those who exited were unprepared to adopt the new approach until financial uncertainties and risks declined. While these users did not wish to legitimise the innovation, they could still play an important role in a later stage of innovation as *mainstreamers* (Fig. 2), i.e., users contributing to wider diffusion, after the price–performance ratio has improved.

Our analysis uncovers important findings in relation to the hypothesis of the chasm (see Fig. 2), i.e., a gap between the experimentation and wide diffusion phases [73]. We found that the two groups of trial participants seemed to have different motivations for adopting the innovation, being on the opposite sides of the chasm. However, none of the trial participants expressed interest in helping to bridge the chasm by aligning other actors or recruiting other users in the community. This bridging role needs to be filled by another/external actor, an *intermediary actor* [12,102], which in our case could be the project consortium, primarily the retailer and network operator, due to their direct access to most customers. They could bridge the chasm by taking the lessons from the *innovators* and *legitimizers* to the *mainstreamers* and *consumers*.

However, the chasm will not be bridged until the project consortium acknowledges the roles the trial participants wish to play. Our findings point to a misalignment between how consortium members perceive the participants' involvement and how the participants want to be involved. Our results indicate that most trial participants viewed themselves as an active part of the trial, contributing to learning and locally implementing the new business model as *innovators* and *legitimizers*; in contrast, the project consortium viewed the participants merely as *consumers*, playing a role in consuming the new market product. Incumbents, such as the utilities in the consortium, often strive to induce the users to conform to their view of the niche market solution rather than working with them in a co-creation process [103]. This discrepancy in the perception of the user's role was likely a main reason for the high dropout rate and the perception of a weak trial design. While at first glance, high prices seemed to have been the main reason for losing almost half the initial trial participants, our analytical framework helped us understand that the high drop-out rate could also have been a consequence of the consortium side failing to consider the user role.

Regarding our conceptual starting point in transition thinking, our analysis confirms the importance of viewing electricity users as agents

shaping the sustainability transition process, as proposed by Schot et al. [30]. However, our empirical results indicate that their conception of the user role entails several limitations. First, they assume that users involved in innovation always seek to have specific system-level influence as an organised group with a clear identity related to the innovation [30,50,63]. Our results instead indicate that users can advance transition efforts without necessarily being the instigators or drivers of a transition. Instead, users can support the transition by adopting the innovation and collaborating with other project actors, provided the innovation appears to align with their idealised vision of the future and/or is financially beneficial to them. They need not be part of a collective movement, but rather can be organised and assisted by another intermediary actor in the system [48,102,104]. Second, their conception places users in idealised categories that are exhaustive and often mutually exclusive. Our results suggest that the participants in the P2P trading trial do not belong to a certain group or conform to a user category with a single role, but instead assume multiple key roles in the innovation process, often as individuals [32]. Our findings support the recent conclusion of Sopjani et al. [32] that users can assume multiple roles simultaneously within transition processes.

In addition, the user typology developed by Schot et al. [30] is useful for analysing the user-to-system dynamics, though it ignores the micro-level agency and user-to-user interaction through the different innovation phases (see Section 3.2). Complementing the transition perspective on users with innovation diffusion research and with additional user-related literature (see Table 2) has been helpful in emphasising that trial participants can both shape the wider socio-technical system change as well as influence their peers in the innovation process.

Perhaps our biggest contribution to the user-focused transition literature is the application of our analytical framework to a case of business model innovation. While an increasing number of studies analyse the role of managers, private firms, and entrepreneurs in business model innovation processes, we have shown that successful business model innovation requires attention to users as explicit transition-shaping agents.

## 6.2. Policy implications and areas for further research

The present findings have several policy- and industry-related implications. First, our theoretical framework suggests that in innovation trials, it is important to consider the innovation phase when designing a project and recruiting trial participants. Very-early-stage projects may be best served by targeting users wishing to co-create and legitimise an innovation and who are specifically interested in learning about and probing it. It is also essential for recruiters to understand the important roles of these users, namely, to facilitate learning processes, embed the innovation locally, and raise expectations directly related to local issues. The actor consortium could have involved participants in the initial design processes to increase the trial success, which directly depends on the consumer's image of what a P2P market design should be like. For the Fremantle trial community, this included aspects of social equity and sharing energy within the community, aspects that the eventual market design failed to deliver.

As the high rate of drop-outs from the project demonstrated, finding users who are interested in supporting early innovation processes is not easy, as most users tend to get discouraged by high uncertainty and/or lack of alignment with their underlying values and expectations. While this is not surprising, it emphasises the need to involve trial participants in the tariff design process to minimise their disappointment and reduce the number of drop-outs.

Furthermore, early efforts should be made to target the recruitment of local opinion leaders, i.e., those whose views future customers will value and listen to. In addition, effort should be made to recruit users who wish to intermediate and lobby for the innovation. These represent the users essential for taking the innovation to the breakthrough and wide diffusion phases. This could include the recruitment of institutionalised user communities already committed to the transition, such as the energy communities recognised in the UK [82,105], the

Netherlands, and Germany [106]. More effort could have been made to include a public participant as a prosumer, such as the City of Fremantle and its facilities, given that they have local influence, could have acted as an intermediary, and would have balanced the residential participants with complementary load profiles.

When it comes to areas of future research, future trials of P2P market models should strive to accommodate a range of users and load profiles, thereby demonstrating marketplace structures closer to real-world conditions. The fact that this was not done in the present trial was partly due to the inherent inflexibility of the regulatory environment, but was also a by-product of the tight project timelines. The tight timelines precluded the resolution of constraints, collaborative design, and the strategic recruitment of participants. Future projects should allow sufficient time to work through and resolve these issues. Another area that should be analysed is the choice of technology employed – in this case blockchain – and its ability to fulfil the specific needs of P2P market participants. We believe a more careful study should be made of whether the blockchain ledger is well suited to users' intentions to create a local community electricity market with local benefits. This is important to consider, as blockchain technologies have evolved to suit adversarial contexts in which trading is verified by computer code rather than by social agreement, making it potentially at odds with the underlying values of trial participants.

Future studies could also address aspects outside of the scope of this study. Analysing users involved in prosumer-based electricity markets elsewhere in the world, in both local and broader regional electricity markets across different geographical regions, could strengthen the present findings. Positioning these studies within the analytical framework outlined here could improve our understanding of user interest in and adoption of the P2P model and allow for further testing of the relationships between user roles and transition phases.

While this study has provided important insights into the roles of first users in transition processes, it has not been possible to demonstrate the potential systemic effects or broader benefits of scaling up P2P electricity markets. Empirical studies of these matters must wait until there has been greater uptake of P2P electricity markets. Conclusive results will require substantially longer time horizons that are more consistent with broader transitions.

## 7. Conclusions

This paper provides new insights into the role that electricity users can play in innovation, paving the way to a fossil-fuel-free electricity system. Using the empirical case of a P2P electricity trading innovation trial in Western Australia, we present new findings about what

## Appendix A. P2P Tariffs

Pre-existing tariffs comprised a subsidised renewable energy buy-back rate, a daily supply charge, and a charge based on the kilowatt hours of usage. The daily supply charge comprised a state government-subsidised network supply fee, while the electricity charge comprised a bundle of both energy- and non-energy-related expenses. The largest non-energy expense was related to recovering costs associated with capacity payments made to all generators in the network. These are part of the local capacity market designed to ensure sufficient generation capacity in the market to meet the demand during peak periods that last for only a few hours each year, typically on the very hottest summer days.

**Table A1**

Pre-existing and trialled peer-to-peer tariffs (AUD).

Existing tariff items	Rate (AUD)	P2P trial tariff item	Rate (AUD)
Supply charge	1.015/day	Network supply charge	2.20/day
Electricity charge	0.2833/kWh	Capacity charge	1.10/day
		Peak (3–9 pm)	0.0909/kWh
		Off-peak	0.0572/kWh
Renewable energy buy-back rate (no feed-in tariff)	0.07135/kWh	Renewable energy buy-back rate	0.04/kWh
Renewable energy buy-back rate (with feed-in tariff)	0.4/kWh	P2P trading platform operator's charge (paid by buyer)	0.005/kWh
		P2P sale price	Set by participants

motivated users to participate in this novel trading model and about their role in its development and diffusion. This adds to our limited knowledge of the users interested in P2P electricity trading, a knowledge gap identified by Ahl et al. [24]. Our findings indicate that the users who joined the P2P trial were typically financially secure households with great interest in social equity and transitioning to environmentally cleaner energy systems. They have good knowledge of their local context and of the issues that they would like to help resolve.

In addition, by synthesizing existing concepts from the transition and innovation literatures, we constructed an analytical framework that allows for a more comprehensive understanding of the roles users can play in different innovation phases: from idea creation, through crossing the chasm, to integrating a novelty into everyday practices. We found that the users who joined the P2P trial wished to learn about a cutting-edge technology, locally validate and implement a new community-based electricity market model, and actively challenge the incumbent sector, with which they were dissatisfied. These participants remained dedicated, despite the innovation-related complexities of price and performance. While such users are crucial for the learning phase of innovation, our analytical framework indicates that they are unlikely to cross the chasm and reach the more hesitant mainstream users. Here, we suggest that the project consortium could potentially act as intermediaries where users cannot. The consortium could bridge the chasm between different users, helping take new innovations into the mainstream. However, the chasm can only be bridged if the consortium acknowledges the diverse roles users can play, instead of viewing them solely as passive consumers.

The conceptual contribution of this paper stems from a synthesis of the sustainability transition and innovation diffusion literatures that allows for both systemic [30] and micro-level understandings [50] of user roles in all stages of the sustainability transition process. This study has demonstrated that users are important not only in developing and adopting sustainable product innovation, but also in related business model innovation, through which value is created from new sustainability-oriented technologies [12,13].

## Acknowledgements and Conflicts of Interest

The RENeW Nexus project is funded by the Australian Government through the Smart Cities and Suburbs Program. There are no conflicts of interest between the funding source and the outcomes presented in this paper. Partners involved in the project were the City of Fremantle, LandCorp, Curtin and Murdoch universities, Power Ledger, Western Power, and Synergy.

As summarised in Table A1, the trial introduced time-of-use tariffs (9.09 cents/kWh peak and 5.72 cents/kWh off-peak), which had substantially lower per-unit costs than were payable by non-trial electricity users (28.33 cents/kWh). This was balanced by fixed daily charges (AUD 3.30/day) introduced during the trial to separate the real energy-related costs from the service- and capacity-related costs of energy supply. This tariff design allowed for trading of the energy-only component. The daily network and capacity charges were also designed to reflect the pricing model that both the network and retailer considered likely to be introduced before any P2P trading schemes were enabled within the jurisdiction. Notwithstanding, it is acknowledged as a potential limitation of the study that trial participants were required to pay an AUD 3.30 daily fee, versus those not in the trial, who paid AUD 1.015 per day. This tariff structure rewards the participants using more energy and would have resulted in cost increases for the households using less energy. Many of the initial trial participants were at the lower energy-use end of the Western Australian spectrum, as would be expected in a conservation-minded community.

Participants could set their own rates for the energy they intended to buy or sell on the P2P trading platform. Any excess energy not sold on the platform was bought by the retailer at a buy-back rate of 4 cents/kWh. The buy-back rate was set low to incentivise P2P trades. Participants could amend their buy and sell rates at any point for current and/or future half-hour trading periods.

Prosumers with the lowest sell prices had first priority in trading. When there was more supply than demand in the trading environment, electricity offered at the lowest sell prices was sold and that offered at higher sell prices was left over, to be bought by the retailer, which was the buyer of last resort. Consumers offering higher buy prices had the first priority in buying energy. When there was more demand than supply in the trading environment, the highest buy prices were accepted first and the lower buy prices were left over, to be accepted by the retailer. Sellers were charged a transaction cost of 0.5 cents/kWh by the P2P platform operator.

## Appendix B. Initial User Characteristics Survey Instrument

### Implied consent

- I have received information regarding this research and had an opportunity to ask questions. I believe I understand the purpose, extent and possible risks of my involvement in this project and I voluntarily consent to take part.

### Introduction

As part of the RENeW Nexus project, we are interested in getting a better understanding of your house design and daily energy and water consumption. Please help us by completing this 10 minutes survey.

### Demographics

1. What is your property address? \_\_\_\_\_
2. How many people live in your house?
  - Adults \_\_\_\_\_
  - Children (under 15 years old) \_\_\_\_\_
  - Children (15 and above) \_\_\_\_\_
3. What is your total annual household income (before tax)? *(drop down list)*
  - I prefer not to say
  - Up to \$10,399
  - \$10,400-\$15,599
  - \$15,600-\$20,799
  - \$20,800-\$31,199
  - \$31,200-\$41,599
  - \$41,600-\$51,999
  - \$52,000-\$64,999
  - \$65,000-\$77,999
  - \$78,000-\$103,999
  - \$104,000-\$129,999
  - \$130,000-\$155,999
  - \$156,000-\$181,999
  - \$182,000-\$207,999
  - \$208,000 or more

### House design

4. Please select your dwelling type *(drop down list)*
  - Separate house
  - Semi-detached, terrace house or townhouse
  - Apartment → Q6

5. How many storeys is your dwelling? *(drop down list)*
- One storey
  - Two or more storeys
6. How many bedrooms, bathrooms and living areas do you have?
- Bedrooms \_\_\_\_\_
  - Bathrooms \_\_\_\_\_
  - Living areas \_\_\_\_\_
7. In which year was your house built or last renovated?
- \_\_\_\_\_
  - I don't know
8. What is the NatHERS Star rating of your house?
- \_\_\_\_\_
  - I don't know

9. Does your house have insulation in the following locations:

	Yes	No	I don't know
Ceiling	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Roof	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Walls	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Floor	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

10. What is the size (kW) of your PV system?
- \_\_\_\_\_ → Q12
  - I don't know
  - I don't have one → Q13
11. Which year were you solar panels installed? \_\_\_\_\_
12. How often do you maintain your solar panels?
- Never
  - Every few months
  - Every few years
  - My solar panels are new
  - Other: please specify
13. What is the volume (L) of your rainwater system?
- \_\_\_\_\_
  - I don't have one → Q14
14. What is the approximate area (m<sup>2</sup>) of your roof?
- \_\_\_\_\_
  - I don't know
15. What is the approximate area (m<sup>2</sup>) of your outdoor irrigated garden?
- \_\_\_\_\_
  - I don't know

Fixtures and appliances

16. How many of these electric heating and cooling devices are present at your property?

Electric heating and cooling devices	0	1	2	3	4	5
Reverse cycle air conditioner (split system)	<input type="checkbox"/>					
Ducted reverse cycle air conditioner	<input type="checkbox"/>					
Ducted evaporative air conditioner	<input type="checkbox"/>					
Ceiling and/or pedestal fans	<input type="checkbox"/>					
Portable air conditioner	<input type="checkbox"/>					
Portable electric heater	<input type="checkbox"/>					
Portable oil heater	<input type="checkbox"/>					
Floor heater	<input type="checkbox"/>					
Other (please specify)	<input type="checkbox"/>					

17. How many of these electric appliances are present on your property?

Appliances	0	1	2	3	4	5
Fridge/freezer	<input type="checkbox"/>					
Electric oven	<input type="checkbox"/>					
Microwave	<input type="checkbox"/>					
TV	<input type="checkbox"/>					
Home entertainment system	<input type="checkbox"/>					
Computers	<input type="checkbox"/>					
Clothes dryer	<input type="checkbox"/>					
Washing machine	<input type="checkbox"/>					
Dishwasher	<input type="checkbox"/>					
Pool pump	<input type="checkbox"/>					

18. How many of these fixtures are present on your property?

Fixtures	0	1	2	3	4	5
Pool	<input type="checkbox"/>					
Spa	<input type="checkbox"/>					
Toilet	<input type="checkbox"/>					
Shower	<input type="checkbox"/>					
Bathtub	<input type="checkbox"/>					
Sink/basin	<input type="checkbox"/>					

19. What is your water heating system? (drop-down menu)

- Gas – instantaneous or storage
- Electric storage
- Instantaneous electric
- Solar, electric boosted
- Heat pump

20. What type of lighting do you have in your house? Please select all that apply

- LED
- Halogen
- Fluorescent
- Incandescent

Routines and lifestyle

21. What does a normal weekday look like for you and other members of your household? Please check the boxes that apply for you and each of your household members.

	Off-site full-time worker	Off-site part-time worker	Work from home	Shift worker	I work varying hours	At home	Pre-schooler at home	Full-time student/day care	Part-time at day care
You	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Member 1	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Member 2	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Member 3	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Member 4	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Member 5	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

22. How strongly do you agree with the following statements?

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
Comfort at home in summer is important to me even if it means spending more on energy	<input type="checkbox"/>				
Comfort at home in winter is important to me even if it means spending more on energy	<input type="checkbox"/>				
I value money over comfort	<input type="checkbox"/>				
It is important for me to reduce my energy costs	<input type="checkbox"/>				
It is important for me to reduce my water costs	<input type="checkbox"/>				

Electricity practices

23. How do you and your household keep warm in winter? Please rank from what you do with more frequency to what you do the least

- We put warm clothes on
- We cover ourselves with blankets
- We close the windows and curtains
- We take advantage of the sun to heat the house during the day
- We take a warm shower or bath
- We turn the heater on
- We use a fireplace
- We have hot drinks/food
- Other: please specify

24. How do you and your household keep cool in summer? Please rank from what you do with more frequency to what you do the least

- We put lighter clothes on
- We open the windows at night for natural ventilation
- We shade our house during the summer
- We spray ourselves with water
- We turn on the fans
- We turn on the air conditioner
- We have a cold shower
- Other: please specify

25. How often do you/your household use the air conditioner in summer?

Very often	Often	Sometimes	Rarely	Very rarely
<input type="checkbox"/>				

26. When you use your air conditioner, what time of the day do you usually do it? Please select all that apply

- Mornings
- Afternoons
- Evenings
- Night
- All day

27. How often do you/your household use the heater in winter?

Very often	Often	Sometimes	Rarely	Very rarely
<input type="checkbox"/>				

28. When you use your heater, what time of the day do you usually do it? Please select all that apply

- Mornings
- Afternoons
- Evenings
- Night
- All day

29. [for prosumers] Are any of your appliances programmed to work on a timer? If so, please select which ones

- I don't have any appliances set on a timer
- Irrigation
- Pool pump
- Dishwasher
- Washing machine
- Heater or air conditioner
- Standby power
- Other: please specify

30. [for prosumers] Are you familiar with the solar panel technology and how it works?

- Yes
- No

31. [for prosumers] How often do you try to use appliances during the day when your solar panels are generating electricity?

Very often	Often	Sometimes	Rarely	Very rarely
<input type="checkbox"/>				

Water practices

32. On average, how many showers are taken in your house per day? \_\_\_\_\_

33. On average, how many washing loads do you do per week? \_\_\_\_\_

34. On average, how many times per week do you turn on the dishwasher? \_\_\_\_\_

Energy App

35. Would you be interested to see your electricity consumption in real-time?

- Yes
- No → Q39
- I don't know → Q39

36. Assuming you had the energy usage app on a mobile device, please order the following features in order of priority, from most important to least important.

- Energy usage/consumption today
- Energy traded this week
- Energy traded this week versus last week
- Savings this week/month OR season
- My current balance (\$\$)
- "How am I doing today?" (in terms of my energy usage goals)
- "How am I tracking?" (against similar households)
- Alerts/Notifications

37. How would you use the information about your electricity consumption if you could access it in real-time? Please select all that apply

- I would keep an eye on it out of curiosity
- I would change the way I use certain appliances to reduce my bills
- I would try to identify where the electricity is coming from
- I don't think I would use it, I'm too busy
- I don't know
- Other: please specify

Service providers

38. Are you satisfied with the current electricity services provided by Synergy (e.g. tariffs, service, model)?

- Yes
- No → Why not? \_\_\_\_\_

39. Are you satisfied with the current water services provided by WaterCorp (e.g. tariffs, service, model)?

- Yes
- No → Why not? \_\_\_\_\_

**Appendix C. Second Survey Instrument – Testing how the P2P pricing design aligned with expectations and values and how this influenced perception of the incumbent utilities**

Please circle the relevant options for questions 1 to 3:

- 1) I am currently registered as a:
  - A. Prosumer
  - B. Consumer: or
  - C. Not yet registered in the trial.
- 2) I attended the August RENew Nexus trial workshop: **Yes / No**
- 3) Would you be prepared to pay more for energy if you knew it was produced within your local community from renewable sources? **Yes / No**
- 4) If you answered yes to question 3, then please indicate how much more you would be prepared to pay for renewable energy produced within your local community:  
\$ \_\_\_\_\_

On a scale from 1 to 5, please circle the number that best corresponds to your thoughts in response to the following questions.

5) I think that peer to peer energy trading will result in more solar PV being installed on domestic rooftops than if peer to peer trading wasn't available.

<b>Strongly agree</b>					<b>Strongly disagree</b>
1	2	3	4	5	

Can you briefly describe your reasons?

6) I think the Western Power grid charge\* proposed for the RENew Nexus trial is fair and reasonable.  
(\*The grid charge is to cover Western Power's costs in providing and maintaining the poles and wires that transport electricity to each dwelling/business).

<b>Strongly agree</b>					<b>Strongly disagree</b>
1	2	3	4	5	

Can you briefly describe why you gave it this rating?

7) I think the capacity charge\* proposed for the RENew Nexus trial is fair and reasonable.  
(\*The Government makes a capacity payment to all electricity generators on the grid to ensure that there is enough generation capacity to meet the peak grid demand (usually on very hot summer days). This payment is to ensure the financial viability of some generators that may only be required on a few very hot days every year or two. Synergy's purchase costs of renewable energy certificates is also being covered by the Capacity Charge. In the trial's electricity bill, these costs are being spread across all electricity users and recovered on an equitable basis).

<b>Strongly agree</b>					<b>Strongly disagree</b>
1	2	3	4	5	

Can you briefly describe why you gave it this rating?

8) I think the Synergy Everyday off peak and Everyday peak tariffs\* proposed for the RENew Nexus trial are fair and reasonable.  
(\*The Synergy Everyday tariffs relates to what you pay Synergy for the actual kilowatts of electricity that you consume that are in addition to those supplied by trial participants. These kilowatts are produced by the mixture of all generators on the grid. Energy will be charged at 9.9 cents per kilowatt hour during peak times and 5.72 cents during off peak hours.)

<b>Strongly agree</b>					<b>Strongly disagree</b>
1	2	3	4	5	

Can you briefly describe why you gave it this rating?

9) I think the default Synergy Buyback Rate\* proposed for the RENew Nexus trial is fair and reasonable.

(\*The default buyback rate is the price that Synergy will pay you for the excess solar PV from your system if you don't find a buyer from within the trial at your preferred sale price. This is expected to be 4 cents per kilowatt hour).

<b>Strongly agree</b>					<b>Strongly disagree</b>
1	2	3	4	5	

Can you briefly describe why you gave it this rating?

10) I think the transaction charge\* as proposed for the trial is fair and reasonable.

(\*This is the fee that Power Ledger will charge for hosting the trading platform that allows you to trade energy with your community peers).

<b>Strongly agree</b>					<b>Strongly disagree</b>
1	2	3	4	5	

Can you briefly describe why you gave it this rating?

11) I think that we shouldn't be charged the capacity charge\* as part of our electricity bill if we're doing peer to peer trading.

(\*As for question 7, above, the Government makes a capacity payment to all electricity generators on the grid to ensure that there is enough generation capacity to meet the peak grid demand (usually on very hot summer days). This payment is to ensure the financial viability of some generators that may only be required on a few very hot days every year or two. Synergy's purchase costs of renewable energy certificates is also being covered by the Capacity Charge. In the trial's electricity bill, these costs are being spread across all electricity users and recovered on an equitable basis).

<b>Strongly agree</b>					<b>Strongly disagree</b>
1	2	3	4	5	

Can you briefly describe why you gave it this rating?

12) I think that we shouldn't have to pay Western Power grid charges as part of our electricity bill if we're doing peer to peer trading.

(\*As for Question 6, above, the grid charges is to cover Western Power's costs in providing and maintaining the poles and wires that transport electricity to each dwelling/business).

<b>Strongly agree</b>					<b>Strongly disagree</b>
1	2	3	4	5	

13) I think that electricity should be charged based on the time of use (such as cheaper in the middle of the night but more expensive at peak times) rather than a flat energy charge.

<b>Strongly agree</b>					<b>Strongly disagree</b>
1	2	3	4	5	

14) I think it's important that energy can be provided at a reasonable price to everyone in our community, including the poor and disadvantaged.

<b>Strongly agree</b>					<b>Strongly disagree</b>
1	2	3	4	5	

Can you briefly describe why you gave it this rating?

15) I think that the billing approach proposed in the RenewNexus trial closely aligns with my expectations of peer to peer trading.

<b>Strongly agree</b>					<b>Strongly disagree</b>
1	2	3	4	5	

Can you briefly describe your response?

16) I think it's important that I can go to my retailer or biller when I've got a problem with my bill to have my issue investigated/resolved (e.g. when I feel I've been charged too much; I haven't been paid enough for my PV exports; or I can't afford to pay my bill just now).

<b>Strongly agree</b>					<b>Strongly disagree</b>
1	2	3	4	5	

Can you briefly describe why you gave it this rating?

**Appendix D. Third Survey Instrument – Testing reasons for households exiting the trial**

Consent tick box

As part of the RENeW Nexus project, we are interested in gaining a better understanding of why householders have decided not to participate in the RENeW Nexus Plan peer to peer energy trading trial. If you would like to participate in the RENeW Nexus Plan trial but have not yet registered please do so via the Synergy link that was sent to you on the 31st October.

Thank you for your participation in the trial up to this point. If you maintain your decision not to participate in the RENeW Nexus Plan peer to peer energy trading trial, we encourage you to remain engaged with the project as it progresses. You are still able to monitor your generation and usage via the energyOS platform.

Property address (so we can match their results from the first survey)

Did you fill out the Survey Monkey questionnaire in August?

- If so, skip
- If not, do you have solar PV system? Y/N

I attended the August RENeW Nexus trial workshop and information session/s on 3rd August and/or 19th October (tick attendance)

Are you satisfied with the service provided by Synergy (e.g. tariffs, service, model)? - Y/N, open ended response

Are you satisfied with the service provided by Western Power- Y/N, (open ended response)

I would have participated in the RENeW Nexus Plan trial if: (open ended response)

Why are you choosing to not participate in the RENeW Nexus Plan trial (choose as many options as apply to you and then number your top 5 from 1 (biggest reason) to 5):

- I do not produce enough excess solar PV energy to trade
- I do not require additional energy than what I currently generate
- I do not wish to virtually purchase energy from other participants
- It looks like too much extra work for the potential savings
- The version of peer to peer trading being trialled doesn't align with how I think peer trading could be done
- I thought peer to peer trading would be more community oriented, but this is very impersonal and "free-market", kind of like the stock exchange
- The approach being trialled creates an extra administrative cost layer rather than removing one
- Using the peer to peer trading platform looks too difficult
- The peer to peer trading platform does not show me what I want to see
- The version of peer to peer trading being trialled does not reward local generation over transmission from further sources
- It doesn't allow me to trade with the person/people of my choice
- I think it rewards big energy users and penalises low energy users
- I think the tariff has been poorly designed
- I think the set fees are too high
- The set fees are more than what I pay now
- The set fees are outside of my household budget
- There isn't scope for me to change my energy use patterns, so I wouldn't get much value out of the peer to peer trading
- I cannot see how this will help the transition to a cleaner energy future

Answer strongly agree, agree, neutral, disagree or strongly disagree to the following:

- Comfort at home in summer is important to me even if it means spending more on energy
- Comfort at home in winter is important to me even if it means spending more on energy
- I value monetary savings over comfort
- It is important for me to reduce my energy costs
- It is important for me to reduce my water costs

Have you looked at the energyOS platform to view your energy usage patterns over the past couple of months? Yes/No  
If yes, did using the energyOS platform influence your energy use at home? (open ended response)

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- Comfort at home in summer is important to me even if it means spending more on energy
- Comfort at home in winter is important to me even if it means spending more on energy
- I value monetary savings over comfort
- It is important for me to reduce my energy costs
- It is important for me to reduce my water costs

Have you looked at the energyOS platform to view your energy usage patterns over the past couple of months? Yes/No  
If yes, did using the energyOS platform influence your energy use at home? (open ended response)

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# Paper IV



# **The challenge of peer-to-peer electricity trading pilots: Review of systemic problems in the US and Australia**

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## **Abstract**

While electricity production and supply are increasingly distributed, changes in the market structure are lagging behind. The centralised market arrangements are not built to coordinate two-way electricity trading between distributed renewables and storage owned by a diversity of residential and commercial prosumers. An increasing number of scholars and industry actors are calling for new prosumer business models that can better reflect the market value of distributed energy sources. Blockchain-based peer-to-peer (P2P) electricity trading is one such business model that, in theory, allows individual prosumers and consumers to trade electricity between each other without the need for an electricity retailer. However, there are numerous challenges to the diffusion of blockchain-based P2P models in the electricity sector. This paper applies the framework of systemic problems to explore the institutional, market structure, actor interaction, capability and infrastructure-related challenges. The analysis confirms earlier evidence that technical problems are not independent of the social and malfunctioning in one part of the system invokes problems in other parts. This study concludes that P2P electricity trading models should be treated as pilot projects rather than tests of commercial solutions. Niche markets and regulatory sandboxes were found vital in providing a space to improve the technical performance and pricing design without the influence of dominant market players with vested interests in the centralised

market structure. Shielded experimentation was found key for enabling reflexive processes, creation of shared expectations, joint agendas for action and technological coordination.

## 1 Introduction

In many parts of the world, people are moving away from fossil fuel-based electricity generation in the effort to fight climate change. This trend leads not only to increased uptake of renewable energy sources but also to the emergence of alternative electricity system configurations and associated business models. One such alternative is the distributed electricity system configuration, supported by a growing penetration of small-scale electricity production, storage and metering technologies ‘at the edge of the network’, turning an increasing number of previously passive electricity consumers into active prosumers, producing their renewable electricity (Morstyn et al., 2018; Parag and Sovacool, 2016; Tushar et al., 2018).

The future of distributed electricity system calls for *prosumer business models* (Brown et al., 2019; Mengelkamp, Schlund, et al., 2019; Parag and Sovacool, 2016) that can better capture the value from an increasing number of small-scale and intermittent electricity sources. Existing market arrangements are not built to coordinate two-way electricity trading between distributed renewables and storage owned by a diversity of residential and commercial prosumers (Morstyn et al., 2018; von Wirth et al., 2018). Prosumers still rely on governmental subsidies (Brown et al., 2019) that do not reflect the real market value of their self-generated electricity.

However, while the technical configuration of the grid is changing, the centralised market structure remains unchanged (Koirala et al., 2016), forming institutional path-dependency, i.e. reinforcement of institutions and practices over time (Garud et al., 2010), and a carbon lock-in (Unruh, 2000), slowing down the diffusion and integration of distributed energy technologies.

Previous research has shown that path-dependency can be broken, and new paths can be created by collective ‘systemic’ action and innovation processes (Bergek et al., 2008b; Garud et al., 2010; Mahoney, 2000; Rosenbloom et al., 2019). The novel path creation can lead to a ‘whole system transition’, which is a gradual and cumulative process that results from a co-evolution of

technological artefacts, actors and institutions that support a novel technological solution (Geels, 2002; Loorbach et al., 2017).

In order to identify the source of lock-in effects, the innovation system perspective provides a tool to analyse what hinders the development and diffusion of innovations. In fact, the framework for innovation system failures and problems has been proposed as an alternative to the market failures framework to identify systemic factors that block the development and diffusion of emerging technological solutions (Arrow, 1972; Bergek et al., 2008a; Hekkert et al., 2007; Weber and Rohracher, 2012; Woolthuis et al., 2005). The systems perspective provides a holistic guidance for both policy interventions and business opportunities (Negro et al., 2012).

This study uses the systemic problems framework developed by Negro et al. (2012) to analyse cases of blockchain-based peer-to-peer (P2P) electricity trading models in the US and Australia to reveal what hinders the development and diffusion of this particular prosumer business model. Concrete challenges are identified and compared across the cases to deepen the understanding of change processes that are required to support the uptake of prosumer business models.

## **2 Local prosumer energy markets**

While the technical set up of the electricity systems is increasingly distributed, the allocation and pricing are still based on top-down market structures, which only provide prosumers with an option to buy and sell electricity to the grid for a fixed price. A prosumer-centric ‘bottom-up’ structure is believed to empower prosumers by making them active participants directly influencing and shaping the market (Sousa et al., 2019). By participating in the market, residential and commercial prosumers can increase the value of their self-generated electricity by providing essential grid flexibility services to the rest of the electricity network (Lavrijssen and Carrillo Parra, 2017) – a possibility that remains untapped (Kubli et al., 2018).

Extensive literature has dealt with the potential technical, economic, social and environmental value of prosumer market models for individuals, community as well as for the ‘larger’ electricity system, i.e. the established market actors and electricity network (see Table 1). It is important to note that evidence of such benefits as of 2020 exists mainly at the conceptual level or in micro to

small-scale prototypes, and further experimentation is needed to explore the presumed potential in a variety of real-world conditions.

**Table 1.** Summary of the benefits of a prosumer market model mentioned in extant literature<sup>1</sup>

Benefits	Individual/ community	The rest of the system
Technical	<ul style="list-style-type: none"> <li>▪ Flexible and adaptable use of small-scale renewable technology</li> <li>▪ Small-sale production units and storage integrated into the dynamic grid infrastructure</li> <li>▪ Ability to switch between carriers on a minute-to-minute basis</li> <li>▪ Increased system efficiency through local supply-demand matching</li> <li>▪ Improved local grid resiliency in the events of power supply issues from the larger grid</li> </ul>	<ul style="list-style-type: none"> <li>▪ Shave peak loads in the distribution grid network through local storage and demand management</li> <li>▪ Provide additional capacity in time of power shortage at the distribution and transmission level</li> <li>▪ Help stabilise the larger grid and reduce blackouts (through reactive power from solar panels for example)</li> <li>▪ Improves visibility of distributed energy sources to better reflect the local supply scarcity and surplus in real-time</li> <li>▪ Improves the ability to react in (near) real-time to volatile and intermittent power generation</li> </ul>
Economic	<ul style="list-style-type: none"> <li>▪ Small-scale production and storage directly included in the market (reduce the threshold for smaller actors to enter the market)</li> <li>▪ Provides price incentives for market participants towards the provision of demand flexibility, balancing and ancillary services (implicit, i.e. variable pricing; and explicit, i.e. provide services through an aggregator; demand response)</li> <li>▪ Price determined by the market participants (individuals or communities)</li> <li>▪ Increased value/revenue for self-generated electricity and storage</li> <li>▪ Reduce energy costs for market participants (by reduced public grid tariffs and more efficient local energy use for example)</li> <li>▪ Improve local economy (supports local businesses)</li> </ul>	<ul style="list-style-type: none"> <li>▪ Provides price incentives to reduce peak demand as well as supply in times of power shortage</li> <li>▪ Avoids the death spiral for utilities and increased energy prices for the poorest consumers</li> <li>▪ Reduce infrastructure costs</li> </ul>
Social	<ul style="list-style-type: none"> <li>▪ Energy democracy (market participants can interact without centralised control or intermediation)</li> <li>▪ Choice of an energy supplier based on personal/community preference and need</li> <li>▪ Reduce energy poverty through local sharing and trading</li> <li>▪ Strengthens community values and ownership</li> </ul>	<ul style="list-style-type: none"> <li>▪ Improves social welfare for vulnerable individuals and groups (cheap and clean energy services provide new opportunities for vulnerable individuals and groups, e.g. women in developing countries)</li> </ul>
Environmental	<ul style="list-style-type: none"> <li>▪ Steers market and user practices towards reducing CO2 emissions/fossil-fuel-based energy</li> </ul>	<ul style="list-style-type: none"> <li>▪ A cheaper and faster way to decarbonise the grid</li> <li>▪ Reduces need for fossil fuel-based peak power plants</li> </ul>

<sup>1</sup> References: (Brown et al., 2019; Hackbarth and Löbbe, 2020; Hahn et al., 2017; Hahnel et al., 2020; Karlsson et al., 2020; Kirchhoff and Strunz, 2019; Koirala et al., 2016; Lavrijssen and Carrillo Parra, 2017; Lehtonen and de Carlo, 2019; Mengelkamp, Gärtner, et al., 2018b; Mengelkamp, Schönland, et al., 2019; Mengelkamp, Staudt, et al., 2018; Morstyn et al., 2018; Morstyn and McCulloch, 2020; Powells and Fell, 2019; Singh et al., 2018; Smale et al., 2019; Sperling, 2017; Tushar et al., 2018; von Wirth et al., 2018; Wilkinson et al., 2020; Wörner, Meeuw, et al., 2019; Wörner, Ableitner, et al., 2019)

Although local prosumer market models are increasingly cited as key enablers of the energy transition, an official definition of this new market arrangement has not yet been established. Peer-to-peer arrangements can differ based on the type of market interaction. Individual prosumers and consumers can trade directly with each other, they can pool and redistribute their resources locally, or sell them to the ‘larger grid’, i.e. the established electricity system (Parag and Sovacool, 2016). In this paper, we analyse real-world projects that trial autonomous P2P electricity trading models, in which prosumers and consumers trade directly, with a support of a blockchain-based trading platform, that can, in theory, reduce the need for the intermediation of an electricity retailer.

### 3 Conceptual starting points and methods

New technological solutions initially face system-level challenges because the institutions, market structure, actor interactions, knowledge and physical infrastructure are not aligned to accommodate the novelty. It is undoubtedly the case for the electricity systems that are not impartial and embody institutional arrangements of a multitude of ownership, operation and control structures that dictate the redistribution of costs and benefits among the involved actors. In the past, the structure was centralised with the ownership, operation and control in the hands of vertically integrated electricity utilities. Today, renewable and distributed energy technologies are disrupting the centralised model of electricity production and supply. But while the technical infrastructure is changing fast, the market change is lagging behind. In this paper, we apply the innovation system problems framework developed by Negro et al. (2012) to explore the reasons behind the slow development and diffusion of prosumer business models<sup>2</sup> (Table 2). The concept of *systemic problems*<sup>3</sup> was developed as an alternative to the neoclassical ‘market failures’ framework, which is not able to capture the complex interplay between the path-dependency of the dominant system and the disruption of technological novelties in particular contexts. In contrast to market failures, systemic problems framework can better guide transformative innovation

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<sup>2</sup> This framework was initially developed to analyse diffusion of renewable energy technologies but nothing in theory prevents us from using it to analyse diffusion of new business models, which can be viewed as an institutional dimension of a system built around renewables.

<sup>3</sup> In the literature, similar list of systemic problems were termed as ‘system failures’ (Weber and Rohracher, 2012; Woolthuis et al., 2005). The Technological Innovation System (TIS) framework provides a similar framework for identifying blocking mechanisms (Bergek et al., 2008a; Hekkert et al., 2007)

policies, which intend to achieve a ‘whole system transformation’, including the technical, institutional and social dimensions.

**Table 2** System problems (based on Negro et al. 2012)

<b>Systemic problems</b>	<b>Empirical subcategories</b>
<b>Hard institutions (regulatory framework)</b>	Inconsistent, lacking long-term policies, laws and regulations Regulations only support innovative solutions if they contribute to solving a pressing problem  Misaligned policies on governmental levels and on sectoral levels Lack of financial support mechanisms for innovative solutions (FiTs, tax exemptions, venture capital etc.)
<b>Soft institutions</b>	Lack of shared expectations, negative attitudes, opposition among actors
<b>Market structures</b>	Structure favours incremental innovation and large-scale solutions; Incumbents as executors of the market reform
<b>Weak interactions</b>	Individualistic entrepreneurs No networks and platform for collaboration Lack of knowledge diffusion between actors Lack of attention to the need to experiment
<b>Strong interactions</b>	Strong dependence on government action or on incumbent actors The established network does not allow for the entrance of new actors
<b>Capabilities/capacities</b>	Missing or fragmented technological knowledge among engineers and policymakers The weak ability of entrepreneurs to pack together and formulate a clear value proposition to lobby the government Lacking users to formulate a demand Lack of skilled staff
<b>Knowledge infrastructure</b>	Wrong or no specific knowledge produced at universities and knowledge institutes Gap or misalignment between knowledge produced at research institutes and what is needed in practice
<b>Physical infrastructure</b>	No access to existing electricity infrastructure Existing infrastructure is not interoperable with the old Fragmented ownership of key infrastructural components <sup>4</sup>

### 3.1 Case studies: Blockchain-based P2P electricity trading

Cases presented in this study are both trials of P2P electricity trading between residential prosumers and consumers. The Brooklyn Microgrid (BMG) project was designed to trial a P2P virtual market model for an islanded community microgrid in New York City (NYC)

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<sup>4</sup> The problems related to physical infrastructure were revised to suit the case of P2P electricity trading.

(Mengelkamp, Gärtner, et al., 2018a; Orsini et al., 2019). In a similar fashion, the RENEW Nexus project in Fremantle, Western Australia (WA), was also a P2P virtual market trial at a city level, only without the component of the islanded microgrid (Maisch, 2018). In both projects, the blockchain-based platform was developed by a start-up company, Lo3Energy in NYC and Power Ledger in WA. The blockchain technology was used for P2P electricity trading to allow households, of both prosumers and consumers, to share a common ledger that allows them to trade with one another. While in theory blockchain enables a community of households to trade without an electricity retailer, the retailer had to be involved due to regulations. The size of both trials can be considered small, with 60<sup>5</sup> residential and commercial buildings in BMG and 18 residential households in RENEW Nexus. A blockchain-based ledger was installed on smart meters that were used to model and calculate the electricity prices in the virtual P2P marketplaces.

### 3.2 Data collection and analysis

The analysis is based on a range of qualitative data sources gathered between 2017 and 2018<sup>6</sup>. The data collection started by collecting information in forms of online reports and white papers about two blockchain-based P2P electricity trading pilot projects. Document analysis was followed by a field visit in NYC and Australia, where semi-structured interviews were conducted with actors involved in the projects, constituting the primary data source of data. Interviews were complemented with field observations from the location of P2P trading trials, community meetings and meetings of project partners, where accessible. Between 2017 and 2018, 28 semi-structured interviews were conducted, 14 from each case. The selection of interviews was based on the actor relevance to the projects and their willingness to act as informants. The interview sets for both case studies include a variety of actors, ranging from residents, commercial participants, utility companies, blockchain software developers as well as politicians. In 2018, interviews and field observations were complemented with surveys and group discussions with project participants in the RENEW Nexus project. Throughout the data collection process, the sample from the RENEW Nexus became ‘richer’ as the experimentation continued and scaled-up from P2P electricity

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<sup>5</sup> The informant from Lo3Energy stated that there are “about 60” buildings with installed meters in December 2017. The exact numbers have not been disclosed. However, because the project never went ‘online’, the implications of the size are unknown.

<sup>6</sup> The data was originally gathered for Hojkova et al. (2020) and Wilkinson et al. (2020), but analysed separately for this study using a different theoretical lens.

sharing inside a housing development (see Hojckova et al., 2020) to the city level. The BMG project, on the other hand, was put on hold in early 2018. All the data was compiled, interviews transcribed and categorised based on their relevance to ‘systemic problems’ defined in the framework developed by Negro et al. (2012).

## **4 Results and Analysis**

### **4.1 The BMG project**

The BMG project started as an entrepreneurial initiative of a blockchain start-up, Lo3Energy, to apply blockchain to solve real-world challenges in NYC’s electricity system, with a particular focus on local grid resiliency. Before arriving in Brooklyn, Lo3Energy already had established strategic cooperation with Next47, a subsidiary of Siemens, that agreed to provide technical and financial support for Lo3Energy’s ambitions in NYC.

At first glance, NYC provided both hard and soft institutional support for a P2P electricity trading trial. In NYC, the Reforming the Energy Vision (REV) provided a long-term regulatory and financial support for local, renewable distributed solutions, with an explicit focus on local community-based microgrids. The REV policy framework has become known worldwide as one of the most progressive energy strategies of its time and resulted in a large number of microgrid pilot projects. Lo3Energy established their microgrid project in Brooklyn in the hope to receive institutional support from both REV policies and local residents. Gowanus and Park Slope, areas of Brooklyn, were purposefully chosen as the locus of the BMG project due to high penetration of residential rooftop solar but also for strong community and sustainability values in the community. From the outset of the project, Lo3Energy had a strong focus on approaching residents, small business owners and community organisations in Brooklyn to create demand for their technology. A number of residents and businesses in the area agreed to participate in the trial and allowed Lo3Energy to install blockchain-based metering devices in their households and commercial buildings, getting access to essential metering data necessary for P2P electricity trading modelling. Despite gaining initial traction, the BMG project was soon faced with significant institutional problems. The institutional problems were not caused by a lack of political support, lack of funding or fierce resistance, but rather in that the REV policies were reinforcing the established market structure that favours incremental utility-driven solutions. While the market for electricity supply

in NYC is open for new energy service companies (ESCOs), the former monopoly utility, Consolidated Edison (ConEdison)<sup>7</sup>, still acts as an entry point to the wholesale electricity market and has a monopoly as a grid operator (Crowell, 2019). ConEdison's role is also reinforced in the REV policies, which appoint utilities as "Distributed System Platform Provider" (Department of Public Service, 2014, p.11).

The activities of Lo3Energy were hence constrained by the market structure with ConEdison at the top of it. Despite explicit policy support for microgrid solutions, changes on the public electricity grid were impossible without the consent of ConEdison. It became institutionally impossible to enable trading of self-generated electricity among the local residents without ConEdison. As one of the local ESCOs said, P2P electricity trading among individual prosumers and consumers was "illegal" (Interview 18). In fact, the prosumer-generated electricity could only be sold to ConEdison, which compensated prosumers through net-metering, i.e. retail price for feeding electricity to the utility grid. Net-metering is popular among the prosumers as it provides generous compensation for excess electricity from their rooftop PV panels and significantly reduce their electricity bills. Consequently, net-metering reduced incentives to opt for an alternative, non-utility driven business model and discourages prosumers from exploring the option to trade self-generated electricity in a P2P fashion. As a Community Board member in Brooklyn said, "no business model works without the utility due to the existing financial support for projects that involve the utility" (Interview 19).

Beside institutional problems, the BMG project suffered from both strong and weak interaction problems. Though the REV policies offered opportunities for innovative entrepreneurs, the established market structure in NYC remained a closed network of well-established market partnerships posing significant barriers to entry for new entrants with disruptive solutions. In this environment, individualistic entrepreneurs from Lo3Energy who came to Brooklyn with a clear ambition to eliminate ConEdison's role failed to win its partnership, which essentially restricted Lo3Energy's ability to build a supporting actor network and mobilise funding. The difficulty to establish new collaborations in Brooklyn was also recognised by the local government, the Brooklyn Borough Presidency, that established the Renewable and Sustainable Energy task force

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<sup>7</sup> ConEdison is not allowed to own largescale electricity production plants.

(RESET) to act as a mediator. As the RESET representatives said: “Good things are happening from several directions, but the connection is lacking” (Interview 17). However, RESET focused on encouraging collaboration between ConEdison and third parties (as guided by the REV policies) and thus did not challenge the central role of ConEdison in the innovation process. As a consequence, despite the residents’ willingness to participate in the BMG trial, Lo3Energy did not manage to establish committed partnerships with the local community or other local partners. Local actors perceived ConEdison as a trustworthy provider of an essential service that should be a part of any conversation about energy sector-related changes. Moreover, residents in Brooklyn did not see a need to eliminate or replace ConEdison with a P2P marketplace. In fact, residents viewed blockchain-based P2P electricity trading as less trustworthy due to blockchain’s association to bitcoin and the black market.

Given the difficulties to establish new collaborations, knowledge exchange, and fruitful cycles of learning were limited. While Lo3Energy developed the knowledge with international partners, ConEdison did not show interest in Lo3Energy’s knowledge. Instead of creating a partnership with Lo3Energy, ConEdison conducted research about blockchain-based solutions internally.

Eventually, the institutional and market structure related problems brought the BMG project into a standstill. However, Lo3Energy continues its efforts to turn their vision of P2P electricity trading into reality. In 2018, they approached the Public Service Commission, the energy market regulator in NYC and started a petition requesting a ‘regulatory sandbox’ to demonstrate the technical and socio-economic benefits of the blockchain-based P2P marketplace in NYC.

#### 4.2 The RENeW Nexus project

In contrast to NYC, the broader institutions and market structure in Western Australia may appear averse to radical innovation. Western Australia is one of the few states with no specific long-term renewable energy targets, and policymakers are openly supporting the fossil-fuel industry. Moreover, the electricity market is monopolistic, operated by two state-owned utilities, the grid operator Western Power and gentailer<sup>8</sup> Synergy. On the other side, however, WA has fast-growing

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<sup>8</sup> A term used to describe an actor that is both a power producer and retailer.

market demand for residential solar and batteries as the sunny weather combined with high electricity prices create perfect market conditions for distributed energy resources (DERs) (Green, Newman 2017).

Similar to the BMG project, the RENEW Nexus project initially started as an entrepreneurial initiative of Curtin University researchers that were looking to turn their new knowledge into a real-world application. With established relations and local knowledge, they succeeded in creating a local supply chain of public and private actors that together implemented the first P2P trading model in the White Gum Valley (WGV) housing project in Fremantle. The reliance on utility monopolies was circumvented by finding a niche for P2P trading in private embedded electricity grids inside apartment buildings, behind the utility meter, where P2P electricity trading faced no formal institutional roadblocks. Residents in an apartment building could create a ‘citizen utility’, responsible for managing electricity trading within their own private microgrid without the involvement of Western Power and Synergy, and associated retail costs and grid tariffs (Green and Newman, 2017b).

The WGV project created a space for building a new actor network for the P2P model. Curtin researchers created a collaboration with housing developers, the city government of Fremantle, a solar and battery expert and a blockchain company, all involved in creative problem solving through finding knowledge synergies. The collaboration also led to mobilisation of financial support from the individual companies involved in WGV, but also a public grant from the Australian Renewable Energy Agency (ARENA). The collaboration between Curtin researchers and blockchain experts eventually resulted in the establishment of a new company, Power Ledger, a blockchain start-up with a special focus on P2P electricity trading platform development. Being a blockchain-based business, Power Ledger launched an Initial Coin offering (ICO)<sup>9</sup> and received around 30 million dollars in private funding for development and implementation of their trading platform.

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<sup>9</sup> An Initial Coin Offering (ICO) is the cryptocurrency industry’s fund-raising tool. In a ICO, a company aims to raise money to create a new cryptocurrency coin, app, or service.

After the demonstration of P2P electricity trading behind the meter in the WGV project, the Australian government together with local partners granted eight million dollars to scale WGV up to trial P2P electricity trading across the city of Fremantle in the RENEW Nexus project<sup>10</sup> (Power Ledger, 2017). New financial resources conditioned the consortium of actors to sign an official contract that increased the actor commitment to the trial.

At this point, the WGV actor-network developed enough strength to attract the attention of monopoly utilities Synergy and Western Power. In contrast to the BMG project, the incumbents chose to collaborate with the new actor-network. The incumbents showed interest in P2P electricity trading as a potential solution to network challenges posed by the growing share of residential PV and battery installations, namely growing demand peaks and grid defection. Researchers from Curtin University played an important role in this collaboration, as non-commercial mediators, who facilitated knowledge sharing and tried to break boundaries between competitive companies. As a result, the RENEW Nexus project involved both old and new actors from the start, both willing to exchange knowledge and challenge their established logics to explore the potential of the P2P trading innovation.

When the RENEW Nexus project started, the market relations on the supply side were already established, yet those on the demand side, with residential prosumers and consumers in Fremantle, still needed to be established. After a short period of a social media campaign, forty households both with and without rooftop PV panels voluntarily joined the project as participants.

Trialling P2P electricity trading across the city of Fremantle soon caused new institutional challenges, previously not experienced in WGV. In particular, redesigning the established market structure to appropriately compensate each party involved in P2P trading presented a new challenge. Especially because utilities had a difficult time letting go of uniform supply changes and grid tariffs. While Western Power was willing to settle for a daily fixed grid tariff and Synergy allowed for a time-of-the-day charge, P2P trading was still more expensive than business as usual for most of the residential prosumers with solar panel below 5kW. Only large prosumers with PV

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<sup>10</sup> The RENEW Nexus project involved partners and supporters including the Australian Government's Smart Cities initiative, AEMO, Curtin University, Murdoch University, DevelopmentWA, CSIROs Data61, Synergy, Western Power, energyOS and Power Ledger.

bigger than 15 kW benefited from the P2P pricing structure. It soon became clear that utilities were only willing to adjust pricing to the extent that allowed them to maintain their business model, at the expense of the small prosumers that ended up with higher electricity bills. The residents were also unsatisfied with Power Ledger's P2P trading platform that designed trading arrangements based on price signals in an anonymous market. This design was in conflict with residents' expectations to create a community sharing platform, where individuals could trade with chosen neighbours, or donate to a local school, irrespective of the price. Weak consideration for the project participants expectations and more expensive electricity bills resulted in a withdrawal of nearly half of the project participants, impeding both the learning outcomes and the legitimacy of P2P trading as a viable solution in Fremantle.

With the P2P trading being trialled across the public grid, new infrastructural complexities became apparent. First, by regulation, access to metering data was not equal to all parties, and utilities were given the regulatory priority to handle metering data first, before sharing it with other parties. Such a hierarchy in data flow obstructed the formation of autonomous P2P trading of prosumers and consumers. Second, the attempt to combine the old utility electricity meters and the new smart meters (AMI), to achieve fast data flows for real-time communication between P2P market participants, led to several infrastructural complexities. The existing utility meters in residential households were too slow for P2P trading. For this reason, a project partner energyOS donated new meters that were installed next to the utility meter to provide real-time data and customer interface. However, Power Ledger refused to integrate their platform in energyOS's meters that were deemed unreliable and easy to hack. Power Ledger instead proposed to install a third meter for the blockchain-based trading platform. The need for three different meters in each household made technical interoperability even more cumbersome and slow. Third, the absence of storage technologies in the technical infrastructure of the RENEW Nexus project also became an issue when involved parties realised that the load profiles of residential participants were almost identical, meaning that they all wished to sell and buy at a similar time of the day. It was later in the trial that the consortium understood the importance of creating variety between customer demand and prosumer supply by involving participants with different load profiles such as commercial buildings, schools and hospitals.

## 5 Discussion and conclusions

**Table 3** Systemic problem identified in our case studies

Systemic problems	Empirical subcategories	BMG.	RENeW Nexus
<b>Hard institutions (regulatory framework)</b>	Inconsistent, lacking long-term policies, laws and regulations		x
	Regulations only support innovative solutions if they contribute to solving a pressing problem		
	Misaligned policies on governmental levels and on sectoral levels		
	Lack of financial support mechanisms for innovative solutions (FiTs, tax exemptions, venture capital etc.)	x	x
<b>Soft institutions</b>	Lack of shared expectations, negative attitudes, opposition among actors	x	x
<b>Market structures</b>	Structure favours incremental innovation and large-scale solutions;	x	x
	Incumbents as executors of the market reform	x	
<b>Weak interactions</b>	Individualistic entrepreneurs	x	
	No networks and platform for collaboration	x	
	Lack of knowledge diffusion between actors	x	
	Lack of attention to the need to experiment	x	
<b>Strong interactions</b>	Strong dependence on government action or on incumbent actors	x	x
	The established network does not allow for the entrance of new actors	x	
<b>Capabilities/capacities</b>	Missing or fragmented technological knowledge among engineers and policymakers		
	The weak ability of entrepreneurs to pack together and formulate a clear value proposition to lobby the government		
	Lacking users to formulate a demand	x	
	Lack of skilled staff		
<b>Knowledge infrastructure</b>	Wrong or no specific knowledge produced at universities and knowledge institutes	x	
	Gap or misalignment between knowledge produced at research institutes and what is needed in practice		
<b>Physical infrastructure</b>	No access to existing electricity infrastructure	x	
	Existing infrastructure is not interoperable with the old	x	x
	Fragmented ownership of key infrastructural components	x	x

Table 3 shows the summary of systemic problems identified in our case studies. The comparative analysis strengthens the argument that technical problems are not independent of the social and malfunctioning in one part invokes problems in other parts of the system (Negro et al. 2012). Our case studies demonstrate the importance of fruitful actor interaction to break the path-dependency of the incumbent electricity system, redefine market roles, support knowledge creation and exchange and improve the performance of the physical infrastructure.

Regarding hard institutional problems, this study found that the presence of a long-term policy that supports distributed energy technologies does not automatically support P2P electricity trading

models. As was demonstrated in the BMG project, innovation policies can reinforce old practices and market relations in favour of incremental changes at the cost of more radical solutions. We assume that innovation policies are designed to put incumbents in charge of the innovation process, given their current role in operating and maintaining reliable electricity supply.

An important lesson from the BMG case is that entrepreneurs wishing to trial P2P electricity trading should not entirely hedge their bets on receiving public policy support. Entrepreneurs from the BMG project who were confident in receiving support from the REV policies experienced both strong and weak interaction problems as they stood little chance under the REV policies that secured the established position of ConEdison.

The RENEW Nexus project revealed that institutional and market structure-related obstacles do not automatically lead to a complete halt on P2P trading trials if innovators focus on fruitful actor interaction. Finding new collaborations, building business relations and discovering complementarities across sectors, were found to increase the chances to find a niche market for P2P electricity trading.

Our evidence shows that to reduce the influence of institutional and infrastructural problems, P2P models can, and should, initially be trialled on private grids behind the public utility meter, such as a university or military campuses, and embedded networks (Green and Newman, 2017a; Hirsch et al., 2018; Sioshansi, 2020). For P2P electricity trading in WA, the protection provided by the WGV housing development project allowed for the creation of a new supply chain and reduced reliance on the old one. As a consequence, P2P electricity trading soon attracted the attention of local incumbents, who joined the RENEW Nexus trial across the regulated grid.

In terms of capabilities, the study found that both projects lacked users to formulate demand. In line with previous research, our case studies indicate that interaction with the ‘customers’ of P2P trading is central to its successful development (Ahl et al., 2019; Hawlitschek et al., 2018; Lavrijssen and Carrillo Parra, 2017; Wilkinson et al., 2020). Our cases revealed that the user demand shall not be assumed but rather communicated and negotiated to avoid unexpected trade-offs and drop-outs. However, we also found that potential trade-offs and conflicts between the

community of users and the established market are inevitable. Here, trials behind the utility meter can serve as an opportunity to shape a new market structure that can balance the costs and revenue streams to ensure that the P2P market is attractive and sustainable for all involved actors across the production-consumption chain. Market structure creation also provides a unique chance to define roles of new actors, such as prosumers and software developers, whose role in the electricity sector still remains to be established (Lavrijssen and Carrillo Parra, 2017).

Our cases indicate that the influence of institutional and infrastructural problems can be reduced with the support of scientific evidence based on both quantitative and qualitative research. The participation of researchers in the RENEW Nexus project was crucial in providing specialist knowledge on, e.g. regulatory issues or sketching scenarios for the future. In this project, academics also played a role of a non-commercial actor mediating challenging negotiation between actors with diverse and often conflicting business models and expectations.

Evidence from both case studies indicates the need for careful consideration of the physical infrastructural preconditions already in the planning stage. It is necessary to assess which technical components are in place, which components that are missing, as well as whether these are accessible, interoperable and scalable. Our findings indicate that a good understanding of both the ownership and performance of technological components can significantly reduce infrastructural complexities in later stages of experimentation with P2P electricity trading. The data metering infrastructure is perhaps most important for P2P electricity trading and must therefore be interoperable as well as accessible to all involved parties to enable near to real-time electricity trading between prosumers and consumers.

To sum up, this study suggests that P2P electricity trading models should be treated as pilot projects rather than tests of commercial solutions. As most innovative solutions are costly and return on investment is uncertain, the involved actors must universally approach P2P electricity trading as a highly innovative and unique market opportunity in an early stage of development. Niche markets and regulatory sandboxes are important in providing a space for new market solutions to improve their price-performance ratio without the influence of the dominant market players with vested interests in the established market structure. Such shielded experimentation is

key for enabling reflexive processes, creation of shared expectations, joint agendas for action and technological coordination.

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Interview 5, Face-to-face interview with Yolk Developmnet Group Architect, Performed by Kristina Hojckova in February 2018.

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# Paper V



# **Building a global Super-grid: A sociotechnical systems perspective**

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## **Abstract**

One way to facilitate the transition towards an electricity system based on renewables is to increase the transmission capacity to deliver large amounts of electricity to consumer centres across the globe. This idea is often referred to as the global Super-grid, a vision of a transmission network of unprecedented geographical scope that uses advanced technology to balance spatially and temporally varying renewable energy supply and electricity demand. While proponents have argued that a global Super-grid is technologically possible and economically feasible since the 1960s, little progress has been achieved and new transmission lines delivering remote renewable electricity are being built predominantly within boundaries of single countries. The aim of this study is to explore drivers and barriers of the global-level transmission network development. Taking a sociotechnical systems perspective, the aim is fulfilled by exploring the interplay between the technical, economic, political and social dimensions of a novel technological system. The structure of the analysis is inspired by the Technological Innovation Systems (TIS) approach and organised around key innovation processes: (a) visions and technological foundations, (b) actor network creation around projects (c) experimentation and materialisation, (d) investment mobilisation for scale-up, (e) market formation and value creation, and (f) legitimisation. A conclusion from this sociotechnical analysis is that the proponents of the Super-grid need to acknowledge the political reality of technological change. The analysis suggests that if the Super-grid is to become the future of

the electricity sector, providing prosperity and empower the many, the discourse needs to open up, and move beyond ideas of ‘technocratic internationalism’ and take a broader set of social benefits, risks and trade-offs more seriously.

Keywords: energy transition, high-voltage transmission, Super-grid, technological innovation system

## **1 Introduction**

Power system engineers have argued that an electricity system powered entirely by renewable energy can be attained by building transmission interconnections across the world and linking them into a global Super-grid (Dutton and Lockwood, 2017). A global Super-grid would be of unprecedented geographical scope and use advanced technology to balance spatially and temporally varying renewable energy supply and electricity demand. Variants of this vision go back in history, with proponents dating back to the 1920s. In recent decades, it has attracted much interest among policymakers and members of the transmission industry, not the least as a solution to the climate crisis and need for rapid decarbonisation of the energy system. However, despite explicit international efforts to realise a global Super-grid, new transmission lines delivering remote renewable energy are being built predominantly within boundaries of single countries, or within limited regions.

A growing body of scientific literature provides a wide range of explanations for the weak progress towards the global Super-grid. A large part of the literature, based on an engineering perspective, claims that techno-economic aspects are not a barrier, blaming the lack of development on the ‘politics’ and unwillingness of nation states to commit (Boie et al., 2014; Fitch-Roy, 2016; Schmitt, 2018). Consequently, they urge national-level policymakers to put politics aside to allow for cost-efficient cross-border trading and flows of electricity. Since the inception of the Super-grid vision in the 1920s, advocates wished to depoliticise the transmission infrastructure in a spirit of ‘technocratic internationalisation’ (Schot and Lagendijk, 2008), i.e. the establishment of universal technological standards for grid operation, as an alternative to diplomacy and political negotiations.

Many social scientists, on the other hand, argue that deterministic views on technological development and lack of consideration of the socio-economic and political aspects represent a barrier as such. They insist one cannot eliminate politics from the equation but, instead, one needs to improve the understanding of the sociological, cultural and political complexities of the global transmission integration ambitions (Battaglini et al., 2012; de Rubens and Noel, 2019; Schmitt, 2018; Winther and Wilhite, 2015). Overall, this strand of research on Super-grid projects contributes important insights on factors that hinder development. Some conclude that it is a matter of nation states or a supra-national organisation to take the lead and commit to solving complex multi-stakeholder and jurisdictional processes required for the construction of the global Super-grid (de Rubens and Noel, 2019; Moore, 2017; Schmitt, 2018; Sunila et al., 2019). Other researchers think that the global Super-grid is bound to fail, due to the ‘megaproject’-related policy and management problems (Flyvbjerg, 2007; Van de Graaf and Sovacool, 2014), insufficient exogenous pressures on the industry (Schmitt, 2018) and increasing competition from other technological alternatives (Flynn, 2016; Van de Graaf and Sovacool, 2014).

With this study, we seek to complement current literature with a broad and systemic analysis of what drives and hinders the realisation of the vision of a global Super-grid. By applying sociotechnical systems thinking, we can pay equal attention to the techno-economic and the institutional-political dimensions, seeing them as co-constitutive. We assume that the interplay between actors, infrastructures, institutions and networks are bidirectional and localised to particular places, organisational levels, social and political arenas where the visions and plans are developed and debated, materialised and contested. While the global Super-grid as a vision of a full-scale transmission network and electricity market that spans all continents may never materialise, the ongoing developments along this trajectory already produce concrete technical, economic, political and social effects.

The empirical scope of most previous studies is limited to specific projects or regional visions, such as the Desertec, Rustec, (Boute and Willems, 2012; Schmitt, 2018), Gobitec (Van de Graaf and Sovacool, 2014), the US and Pan-european Supergrid (de Rubens and Noel, 2019; L’Abbate et al., 2019), Supergrid in the Americas (Aghahosseini et al., 2019), Eurasean (Bogdanov and Breyer, 2015) and Asian Supergrid, Australian-Asian power grid (Halawa et al., 2018), Europe North American interconnections (Purvins et al., 2018), China-EU transmission link (Ardelean and Minnebo, 2017) among others. Studies with a global scope

remain scarce and mostly focused on techno-economic aspects and descriptive accounts of drivers and barriers (Bompard et al., 2014; Breyer et al., 2020; Brinkerink et al., 2019; Chatzivasileiadis et al., 2013, 2017; Deane and Brinkerink, 2020; Rafique et al., 2018). An analysis with a broader sociotechnical systems perspective of the Super-grid at the global scale is still missing.

This qualitative empirical study is based on expert interviews, document analysis and literature review, that take stock of historical and current developments in the key technological components, visions, experiments and regional projects. The purpose is to explore drivers and barriers of building global electricity network from a systems perspective. To that end, the Super-grid is analysed as an emerging ‘technological system’ (Hillman and Sandén, 2008) of which the performance and growth are shaped by the interplay between the technical, economic, political and social dimensions.

## **2 Conceptual starting point and methodology**

The empirical case is analysed from a sociotechnical systems perspective with primarily two influences: Large Technical Systems (LTS) (Hughes, 1987), and Technological Innovation System (TIS) (Bergek et al., 2008b; Hekkert et al., 2007). Inspired by LTS, the sociotechnical system is labelled as a ‘technological system’ to indicate the analytical starting point in a specific technological novelty.<sup>1</sup> A technological system is made of heterogeneous technical and social structures, including actors, artefacts, knowledge, financial resources and cognitive, normative and regulative institutions, organised in value chains connecting production and consumption of a specific technology (Andersson et al., 2019; Sandén and Hillman, 2011). We take a broad view of technology and conceptualise it as a means to human purposes, such as electricity supply (Arthur, 1989).

Our second inspiration, the TIS approach, applies a sociotechnical systems perspective to analyse the emergence and diffusion of new technologies via a set of key system building processes termed ‘functions’ (Bergek et al., 2008a; Hekkert et al., 2007). The TIS approach is useful in this study as it provides an explorative ‘checklist’ of functions that help to identify

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<sup>1</sup> Other structures of the sociotechnical system, such as an actor group, knowledge or regulations, can also be used as an analytical starting point.

systemic drivers and weaknesses that influence the development of new technology. In this study, we use a variety of TIS functions that are relevant to the case, including (a) technological foundations and plans, (b) actor network creation around projects (c) experimentation and materialisation, (d) investment mobilisation for scale-up, (e) market formation and value creation, and (f) legitimation.

The global Super-grid is thus conceptualised as an emerging technological system, i.e. a production-consumption chain involved in building and implementing high-voltage transmission connections between production and consumption of electricity at the global scale. With the current electricity system as a starting point, we analyse the process of system build-up, that is, the process of accumulation and expansion of a sociotechnical system structure around a novel technology.

## 2.1 The object of study and system boundaries

In line with many scholars who study emergent technological systems, we take an interest in the pathways to the future energy system and see multiple possible trajectories and alternative future configurations. The global Super-grid is one of the multiple idealised end states, and in its most extreme form, it leads to a system with few centralised production units in one interconnected global grid supplying dependent consumers (Hojčková et al., 2018).

In the literature, there are at least two meanings attached to the term ‘Super-grid’: first, it refers to the spatial reach of transmission lines, where ‘super’ commonly means transmission over very long distances. For example, China is building the world’s longest and biggest high voltage direct current (HVDC) transmission network, which is often labelled the ‘Chinese Super-grid’. Long-distance transmission often also implies cross-country connections resulting in regional or continental Super-grids, with examples such as the pan-European Supergrid, the Asian Supergrid or Desertec. The visionary endpoint of a long-distance cross-country transmission network is the global Super-grid connecting suppliers and consumers on all continents. Examples of such visions are the Global Energy Network Institute model (Dekker et al., 1995), the Global Renewable Energy Grid (Safiuddin, 2017) and the Global Energy Interconnection (GEI) (Voropai et al., 2018). Second, the Super-grid is also used to refer to technological capabilities at the system level, with some components and functions already

existing and having ‘Super-grid grade’ capacity. Generally, high voltage direct current (HVDC) technology is considered a foundational component of the Super-grid since it allows for the transmission of larger amounts of electricity with lower losses and longer connections. However, not all HVDC links are as advanced. For example, conventional point-to-point HVDC links are less Super-grid grade than the multi-terminal HVDC grid that allows load balancing between more than two generation and points. For this reason, some argue that Europe is not yet having a Super-grid as its HVDC connections are only point-to-point. However, most often, the Super-grid is used to label technologies that allow for power transmission at very high voltage levels.

In this study, we use the term Super-grid to refer to large grids, crossing several countries, based on long-distance high voltage connections. In particular, we are interested in a grid spanning the world – the *global* Super-grid – as vision and logical end state, although its realisation is highly uncertain. While our primary spatial boundary is the entire globe, the developments at smaller geographical scales are included as structural components accumulating towards the global system. The global Super-grid is, however, qualitatively different from the country- and regional-level Super-grids since it can take advantage of the synergies between time and climate zones across continents. To function well, the transmission network components, conventional and new HVDC components, need to be perfectly interoperable to enable instantaneous electricity transmission across long distances. The technological boundary includes the production-consumption chain involved in developing high-voltage transmission interconnections, the key technical component of the global Super-grid. It is worth noting that compared to most other products and value chains connecting suppliers and consumers, electricity supplied via a Super-grid has a high degree of ‘systemness’, due to dependence on a hard-linked physical infrastructure, with particularly strong interdependencies and complementarities among system components (Markard, 2011).

From a temporal perspective, the study in principle captures a system development since the creation of the early vision of continental grids in the 1920s until the beginning of 2020. However, the bulk of the analysis is focused on the last two decades, aiming at identifying drivers and barriers enabling or hindering a development towards a future goal – the full-scale global Super-grid. In this sense, it is a prospective study based on a retrospective analysis of historical developments and recent activities.

## 2.2 Data collection and analysis

The analytical framework (see above) influenced the data collection processes by guiding the questions and selecting the themes of interest. Data was gathered in two steps. As a first step, 15 semi-structured interviews were conducted with power system experts from leading companies, researchers and representatives from transnational industry organisations. The choice of respondents was motivated by their expertise and experience with Super-grid-related developments. All interviews were transcribed and analysed using the Visual Understanding Environment (VUE) software as a coding tool to categorise data thematically based on key structural components and later in terms of their contribution to innovation processes. In the second step, the authors jointly analysed and discussed the interpretation of the findings. Since the interviews provided a picture that was strongly influenced by the transmission industry perspective, this data was triangulated with participatory observation during the CIGRE International Symposium and International Smart Grid Action Network workshops in 2019, as well as with a broad range of secondary sources such as scientific literature, industry reports and web-based news articles. While potentially limiting the depth of the analysis, the use of a broad range of data allowed us to get an overview of a vast empirical field at the global scale of observation.

## 3 Analysis

The following analysis is organised around key innovation processes: (a) visions and technological foundations, (b) actor network creation around projects (c) experimentation and materialisation, (d) investment mobilisation for scale-up, (e) market formation and value creation, and (f) legitimation). The first two sub-sections (3.1 and 3.2) provide an account of how early visions and ideas co-evolved with technical developments, and how actor networks formed and engaged in knowledge formation. Following suit, section 3.3 explores the attempts and challenges involved in going from plans to experiments and construction, where actors need not only motivation<sup>2</sup> and knowledge but the capability to act upon these. Connected to this, section 3.4 analyses the mobilisation of funding and how current financial structures

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<sup>2</sup> Motivation of actors to join the system development is in the TIS approach captured with the function ‘Influence of the direction of search’(Bergek et al., 2008a) and ‘Guidance of search’ (Hekkert et al., 2007). In our analysis, the process of motivating and attracting new actors is implicit in other processes (a-f) rather than a separate process. For illustration, actors can be motivated to support the new technology through visions, legitimation processes but also through new financial resources.

enable and block the huge investments involved; and section 3.5 analyses the progress and difficulties in creating markets for electricity trading across national and regional boundaries and jurisdictions. Whereas all sections touch on political tensions, section 3.6 goes deeper and directly addresses the geopolitical dimensions that work for and against the legitimization of competing visions for the Super-grid.

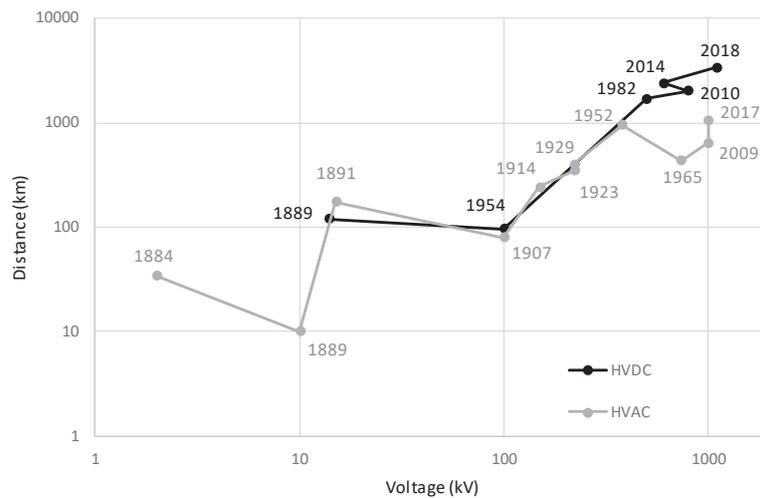
### 3.1 Visions and technological foundations

The vision of extending the electric grid is as old as the grid itself and from what Nelson and Winter (1977) would call a ‘natural trajectory’ within the transmission industry. The engineering logic runs: the larger the grid, the better matching between low-cost supply and demand for electricity. At the beginning of the 20<sup>th</sup> century, low costs were achieved by getting access to large-scale hydro and coal power outside of the demand centres. In more recent interpretations, “low cost” could refer to supplying the world with abundant variable renewable energy resources from remote locations. From the engineering perspective, the size of the grid is only limited by the capacity of available transmission technology.

The early visions of grid extension guided the technical development, which in turn expanded the ambitions and spatial scale of the visions. Exemplifying this feedback between technological development and vision, the increased voltage levels<sup>3</sup> in the first decades of the 20<sup>th</sup> century (Figure 1) led visions of large transnational grids to spread within the power system community. While a handful of connections existed across borders in Europe at the end of World War I, the interwar years saw the emergence of international organisations promoting continental grids, with the most prominent example being the “European Super Power System” proposed by the German engineer Oskar Oliven in 1930. These ideas were supported by a broader discourse on ‘technocratic internationalism’ anchored in the idea that grid networks formed a more efficient pathway to prosperity and peace than capricious politics and diplomacy (Schot and Lagendijk, 2008). However, growing nationalism and the interest of nation states to keep control of critical infrastructure was a strong counterforce, and eventually, the nationalisation of electricity systems came to dominate the century.

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<sup>3</sup> The cost-efficiency of the transmission line length depends on power losses that are inherently linked to voltage level.



**Figure 1.** As voltage levels have increased, so has the length of transmission links. While HVAC dominated development in the 20th century, the development of very long-distance connections in the 21st is mainly based on HVDC technology (data points represent a selection of individual transmission links of exceptional length or voltage at the time of construction).

Nevertheless, technology development continued, and the voltage and length of transmission lines increased (Figure 1). In the mid-1960s, the architect and futurist Buckminster Fuller envisioned a global grid enabled by “ultra-high voltage”<sup>4</sup> (Fuller, 1969, p.189-191). The global grid was imagined to not only balance the demand for electricity across regions and time zones but also swiftly “cancel out the ideological differences of the respective beneficiary peoples” (ibid p.190). In the book “Critical path”, Fuller (1981) developed a detailed vision based on the “dymaxion” projection of a world map, where the world’s electricity demand is covered by renewable energy from distant locations. His vision is firmly located within the discourse on technocratic internationalism, now supported by the advent of computers (our italics): “I, therefore, predict that before the end of the 1980s the computer’s *politically unbiased* problem-solving prestige will have brought about the world’s completely integrated electrical-energy network grid. This world electric grid, with its omni-integrated advantage, will deliver its electric energy anywhere, to anyone, at any one time, at one standard rate” (Fuller, 1981, p. xxxi). In the 1980s and ’90s, small pockets of the electrotechnical community nurtured Fuller’s vision, e.g. the Global Energy Network Institute (geni.org, 2016).

A game-changer came with new development in HVDC (high voltage direct current) technology. At the dawn of the electricity systems in the late 19<sup>th</sup> century, alternating current

<sup>4</sup> Ultra-High Voltages (UHV) is an expression referring to a range of voltages above 800kV.

(AC) became the dominant design, and in 2019 it still accounted for some 97% of high-voltage transmission in Europe (Andersen and Markard, 2020). Despite the dominance of HVAC technology, the HVDC technology continued to develop, but only in small niches<sup>5</sup> (Figure 1). Interest in connecting large remote solar and offshore wind farms strengthened the motivation to improve HVDC technology, leading to new developments. For connecting remote areas, the HVDC holds a substantial advantage compared to HVAC technology in its ability to transmit a large amount of electricity over long distance overhead, on the ground or undersea. In 1992, engineer Gunnar Asplund at the electric power company ABB proposed an electric grid stretching across Europe to North Africa transmitting solar energy up to the South, hydropower from the North and wind power from the West (Interview 2, 2019; Lundberg, 2016). When ABB in 1997 introduced HVDC Light, based on Voltage Source Converter (VSC) technology, which solved the previously problematic connections to weak grid points, the HVDC technology entered a new era of continuous improvement and implementation (Figure 1). In 2017, the cost for an onshore HVDC line had decreased to almost half the cost for an HVAC line with the same voltage and capacity (Ardelean and Minnebo, 2017).

The advancements in HVDC technology directly correlate with increased ambitions to build a global Super-grid. The new VSC HVDC technology simplified electricity exchange in both directions (Interview 3, 2019), and the advancements in multi-terminal HVDC grids enable connections between three or more grids (ABB, 2018) as well as allows for both full-length and segmented operation that eliminate the risk of whole system shutdowns (Ardelean and Minnebo, 2017). These technological capabilities, considered to be of Super-grid grade, improved the feasibility of a global grid.

Though most recent technological development indicate that the global Super-grid has reached an important turning point, some technical aspects remain to be solved. For an illustration, onshore HVDC lines are limited to 3000 km long sections. Ardelean and Minnebo (2017) found that building a single connection between western China and eastern Europe, over 6500 km, is currently inefficient, as each segment of HVDC lines require a VSC converter, each of them increasing losses and costs (Fitch-Roy, 2016; Interview 6, 2019). In addition, it remains unclear how much and which of the existing transmission connections should become a part of the Super-grid (Interview 10, 2019). While some propose combining existing HVAC grid with

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<sup>5</sup> HVDC due to comparatively high costs and limitations of the line-commutated converters (LCC) in connecting weak grid points, in which voltage fluctuations are larger (Andersen and Markard, 2020).

new HVDC to decrease costs (Fulli et al., 2011), others make an opposing claim, arguing that integrating the existing HVAC with the new HVDC technologies is difficult and costly (Flynn, 2016; Interview 2, 2019). Experts also voice that a shift towards multi-terminal HVDC grids is necessary to isolate failures and avoid the ‘domino effect’ of widespread blackouts (Interview 15, 2019).

### 3.2 Actor network creation around projects

Since the turn of the 21<sup>st</sup> century, the Super-grid system build-up has moved beyond technical development and visions. New actors have been joining the network of Super-grid advocates to initiate and plan real-world projects. Besides the early mover ABB, other power equipment manufactures enter the field, including Siemens, Alstom and Prysmian in Europe, General Electric from the US and the Asian companies Hitachi, Mitsubishi Electric and NR Electric. Chinese power companies have joined the race of developing the most advanced version of VSC HVDC technology (Interview 3, 2019). The growing number of manufacturers resulted in continuous technical improvements, lower prices and increasing market demand (omrglobal.com, 2019). Technology manufacturers have also played a key role in promoting Super-grid visions around the world. The vision of a 100% renewable European Super-grid developed at ABB in the 1990s (Section 3.1) later inspired the Desertec project (Interview 2, 2019). The Desertec project, established in 2009 by industrial actors and researchers from Europe and the Middle East and Northern Africa (MENA) region planned to build an HVDC connection supplying Europe with solar electricity from the North African region. Though the Desertec project was never materialised, it created a significant boost in actor network creation, knowledge development and a broader actor interest.

In parallel with the Desertec project, European Commission’s (EC) showed interest in the European Super-grid, as a viable solution to achieving EU’s ambitions to increase renewable energy generation and integrate the energy market across its member states. With a supranational political structure in the EU, the idea of using the electric grid as a unifying transnational infrastructure, already proposed in the 1920s, gained new momentum. In 2012, the European Commission launched a research initiative called e-Highway 2050 that aimed to incentivise European researchers, TSOs and manufacturers across the member states to generate ideas and evaluate the feasibility of a modular plan to build an integrated European transmission network for renewables by 2050 (entsoe.eu, 2019). The e-Highway 2050 project

increased the mandate of the European Network of TSOs for Electricity (ENTSO-E). Around the same time, 'Friends of the Supergrid' (FOSG) was established as a network of European equipment manufacturers, TSOs, utilities, investors, developers and consultants to advise the EC in the planning process (FOSG, 2016). In parallel, research institutes have been established within European states, such as the Supergrid Institute in France (Interview 15, 2019). We thus see support within the EU for the idea that regional grids can strengthen European integration while also achieve the energy transition, which also results in significant actor network creation.

ABB's vision also influenced developments in Asia, where following the Fukushima accident in 2011, electrical power industry actors and investors sought alternative solutions to eliminate their reliance on nuclear power plants (Interview 1, 2019; Interview 2, 2019; Interview 3, 2019). At this time, ABB's effort to expand the VSC HVDC market complemented the ambition of a Japanese entrepreneur and investor Masayoshi Son to find alternatives to nuclear power generation. He established the *Renewable Energy Institute* (REI) as a platform to explore the possibility of building an Asian Supergrid - a vision to supply wind power from the Mongolian Gobi Desert and hydropower from Russian Irkutsk with HVDC grids to customers in megacities such as Shanghai, Seoul and Tokyo (Interview 1, 2019; Interview 2, 2019). Since its establishment, REI was joined by the Mongolian clean technology and infrastructure investor Newcom, the largest electricity provider in South Korea KEPCO, Russian power company PSJC Rosseti, and the State Grid Corporation of China (SGCC) in leading and financing the Asian Super-grid initiative (renewable-ei.org, 2020).

Inspired by the REI, in 2016, the State Grid Corporation of China established its own organisation, the *Global Energy Interconnection Development and Cooperation Organization* (GEIDCO), to promote the Chinese vision of *Global Energy Interconnection* (GEI), the global version of the Asian Supergrid and an incarnation of Buckminster Fuller's global vision. REI joined GEIDCO as one of its council members, and Masayoshi Son became vice-president of GEIDCO, while the chairman of the SGCC Liu Zhenya became the president (Christoffersen, 2008; renewable-ei.org, 2020). When the Chinese government officially became a supporter of the global Super-grid, it resulted in increased technological knowledge development and actor network expansion. Through the 2010s, GEIDCO hired 2,000 engineers on and funded more than 300 professors and 1,000 graduate students at Chinese universities to conduct research and development of most advance transmission technologies (Belt and Road News,

2019). According to Scopus, 41% of research about multi-terminal HVDC grid technology between 2000 and 2019 was conducted by researchers in China. In 2018, GEIDCO also founded its own scientific journal – the Global Energy Interconnection- to publish GEI-specific research ([gei-journal.com](http://gei-journal.com), 2020). As of 2020, GEIDCO website ready-made packages of continental Super-grids (Interview 14, 2019). Packaged solutions have already been offered to decision-makers in North America, the European Union, and Venezuela, among others (Fairley, 2019; [geidco.org](http://geidco.org), 2020). Following China’s activities, the European Commission initiated research projects ‘Migrate’ and ‘Promotion’ to encourage European researchers, TSOs and manufacturers to collaborate and assess the feasibility of multi-terminal HVDC technology ([h2020-migrate.eu](http://h2020-migrate.eu), 2019; [Promotion-offshore.net](http://Promotion-offshore.net), 2019). The EC conducted feasibility studies of a cross-continental connection with the US and China from the EU’s perspective (Ardelean and Minnebo, 2017; Bompard et al., 2014; Interview 6, 2019; L’Abbate et al., 2019; Purvins et al., 2018).

That the global Super-grid vision has gained global scientific attention was apparent when it became a focal point of discussions in the International Council on Large Electric Systems (CIGRE). CIGRE, established at the inception of the industry in the 1920s, connects transmission system researchers, system operators (TSOs and DSOs), decision-makers and manufacturers from 90 countries that meet and exchange knowledge during annual conferences. In 2016, CIGRE established a dedicated working group, appointed to carry out a feasibility study by experts from countries of all continents, on the techno-economic challenges and benefits of the concept of a *Global Electricity Network* (CIGRE WG C1.35, 2019). The inclusion of CIGRE in the quest for the global model of the Super-grid increased actors network development, yet also increased the variety of Super-grid designs.

While Super-grid plans and projects have multiplied, these are mainly developed within a strong network of transmission industry with the competitive advantage of being the key insiders, with the exclusive ability to manage the scale and costs associated with the key components of the Super-grid (Flynn, 2016). As a consequence, new knowledge is shared among a small group of monopolies and policy leaders, who design and plan the Super-grid without much interaction with actors in the rest of the system such as retail companies, small entrepreneurial firms, local political institutions, civil society and environmental groups (Gupta, 2015; Ralph and Hancock, 2019; Van de Graaf and Sovacool, 2014; Verbong and Geels, 2010; Weaver, 2018; Winther and Wilhite, 2015). Because the barriers to entry for

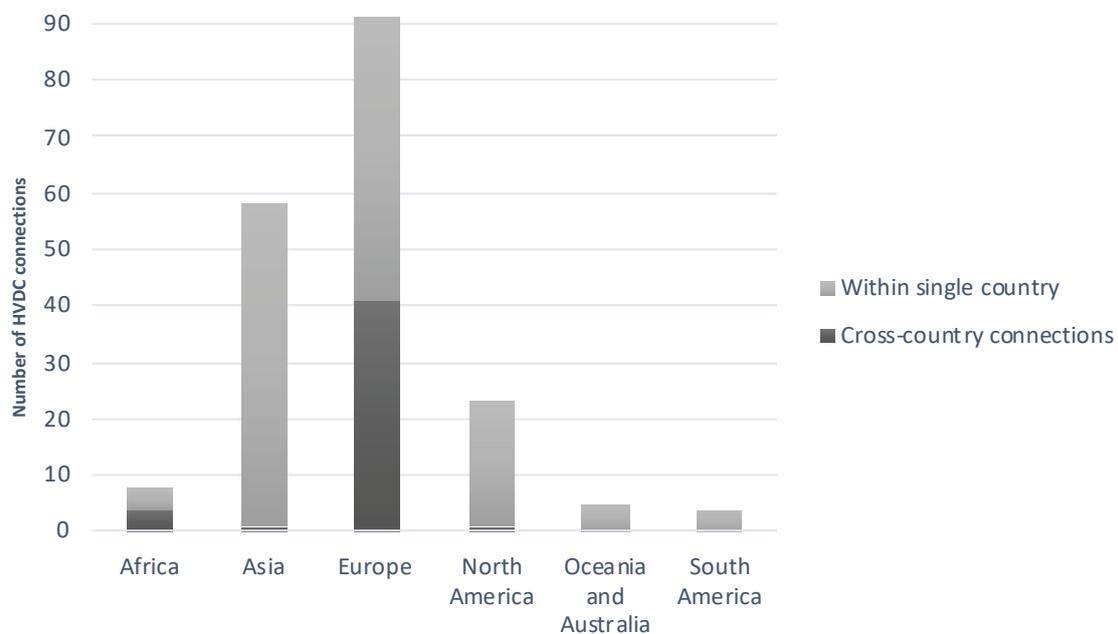
outside actors remain very high, the knowledge development and planning activities have not been a target of political debate and scrutiny, as new actors could not challenge the established logic and practices.

### 3.3 Experimentation and materialisation

Millions of kilometres of transmission lines globally constructed over the course of the 20th century supposedly provide a material foundation for a global Super-grid. But to solve new challenges of connecting remote renewable energy sources across very large geographical areas, additional testing is key to improve the knowledge and costs of interconnecting the existing and the new transmission lines into a seamless network. However, due to the size, high capital costs, construction time, and potential widespread societal consequences, testing and constructing new transmission lines is a lengthy and expensive process, in which each stakeholder must make a binding, long-term commitment (Interview 3, 2019).

Despite the inherent challenges of experimenting with large-scale infrastructures, countries and regions employ different strategies to enable testing of Super-grid components and sub-systems, i.e. regional Super-grids. Most notably, China seems to be willing to take risks associated with demonstrating the most advanced technological components in exchange for becoming a global market leader (Kynge, 2018; reuters.com, 2019; Wei et al., 2017). In 2019, the SGCC commissioned the world's longest HVDC connection of 3 324 km between the North and East of China, the *Changji-Guquan*, that outdistanced the previously longest 2 543 km HVDC line in Brazil (sgcc.com.cn, 2019). In addition, SGCC has in 2019 appointed ABB to construct the *Zhangbei project* demonstrating the largest multi-terminal HVDC grid, a potential technological prototype of the global Super-grid. China plans to finalise the GEI prototype by the Winter Olympics in Beijing in 2022 (Cornell, 2019; Interview 3, 2019). Transmission industry leaders from ABB expressed excitement about China-led demonstrations as these create an important benchmark for their technology and increase the willingness to adopt them in other countries and regions. As the ABB manager in China said: “In all humbleness, ABB proposed the Super-grid vision already 25 years ago and this is the first time it is being demonstrated”, emphasising the difficulties to enable experimentation and construction (Interview 3, 2019).

While China is successfully demonstrating technological components within its own borders, it has been less successful in integrating them with other countries in Asia and beyond (Figure 2). Despite the ambitious vision of building an Asian Supergrid (ASG), it has not gotten beyond the planning stage (renewable-ei.org, 2020). According to the chairman of GEIDCO, the second stage is expected to start in 2020, with focus on interconnecting national grids not only in Asia but also inter-continentially with the connections to European and African grids (Kynge and Hornby, 2018). However, some experts claim that the realisation of the Asian Supergrid has been hampered by GEIDCO’s intervention and changes to the initial plans for the Asian Supergrid that led to political tensions between the involved countries (Christoffersen, 2008; Interview 3, 2019).



**Figure 2** Overview of HVDC connections in different regions. Data includes existing connections as well as those under construction. Source: Ardelean and Minnebo (2017); Hassanpoor (2018)

In contrast to the Asian region with much of the transmission network to be developed, transmission grids in Europe are, to a large extent already built and synchronised across countries. The materialisation of the Super-grid in Europe thus has a different starting point. It is not a process of building an entirely new system, as in Asia, but a rather incremental improvement of the already existing one (entsoe.eu, 2019; Interview 1, 2019; Interview 14, 2019). Hence, the European region has been more successful in demonstrating cross-country interconnections (Figure 3). In addition, the EU provides the necessary platform for member

state negotiations, with the EC overlooking cross-country agreements and projects and reducing the risks for involved stakeholders. For cross-country connections specifically, the EC created the *Project of Common Interest (PCI)* framework to evaluate proposals and overlook their construction (ec.europe.eu, 2020). The PRI provides the benefit of faster permission process and improved regulatory treatment for selected projects, resulting in numerous point-to-point interconnections between countries being built or under construction (ec.europe.eu, 2020).

However, cross-country connections in Europe are still largely demonstrated using mature HVDC technologies, rather than multi-terminal HVDC grids. As a consequence, European experts are concerned that the EU is lagging 20 to 30 years behind<sup>6</sup> China in demonstrating the most advanced HVDC technologies (CIGRE, 2019; Collins, 2019; northseawindpowerhub.eu, 2020). As an interviewee said: “In Europe, we are too concentrated on being the first to achieve transnational interconnections based on the goal of the EC, but we need more multi-terminal HVDC grids” (Interview 15, 2019). China’s demonstration of the newest transmission technologies is increasing pressure on the EU institutions to support the construction of multi-terminal HVDC grids in the European context to catch up with their Chinese counterpart (Interview 6, 2019; Interview 15, 2019).

Similar to the EU, regions with already established supra-national cooperation, such as ASEAN (Association of Southeast Asian Nations) and GCC (Gulf Cooperation Council) have made progress in constructing and integrating transmission infrastructures among countries in their region. Using the established political and economic cooperation as a basis for institutional alignment and trust, the ASEAN Power Grid and the ‘Supergrid in the gulf’ started the process of regional grid integration since the beginning of the 1990s and early 2000s. However, due to the primary focus being reliability of supply and network synchronisation, the interconnections are to a large extent built with HVAC technologies, whilst construction of new HVDC links is a part of future plans (Al-Ebrahim, 2017; Energy Digital, 2015; fsr.eui.eu, 2019; Iea and Praktijnjo, 2015). As a consequence, neither the EU, ASEAN, or GCC regions are actively experimenting with or putting in place Super-grid grade technologies.

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<sup>6</sup> While research projects such as ‘PROMOTION’ (Progress on Meshed HVDC Offshore Transmission Networks) and initiatives like ‘the North Wind Power Hub’, are in charge of evaluating the meshed offshore HVDC grids that could link off-shore wind parks to several European countries in the North Sea region, these projects are still in the research and planning stage, with the actual construction expected in the next 20-30 years.

The American continent is not participating in the Super-grid race. In North America, the USA finds itself in a pressing need of upgrading its ageing transmission infrastructure built in the early 1900s. However, instead of taking a path of reshaping its architecture to integrate renewable energy sources and increase cross-border connections with Canada or Mexico, the industry has invested heavily into upgrading the existing network. Previous and existing attempts to build new HVDC transmission grids and interconnections have had little success, especially where these threaten to make present grids and electricity production plants obsolete (Lacey, 2019). For example, the Clean Line project of three transmission lines that would supply the US with wind power from the centre of the country met resistance from established TSOs and power producers with vested interests in the existing infrastructure and substantial political influence (Davidson, 2019).

Attempts to construct connections across regions and continents have repeatedly failed. The first example of an inter-regional project, the Desertec, ran into a stalemate in 2014. According to our interviewees, it failed due to a top-down approach of European stakeholders, who planned to construct large-scale solar parks in the Sahara region to supply Europe with cheap renewable electricity, without involving stakeholders in the Sahara region in designing the project (Interview 1, 2019; Interview 5, 2019). Another example of a failed interregional construction effort is the ASEAN-Australia HVDC connection that could supply Indonesia's growing electricity demand with cheaper solar energy from remote areas in Western Australia. The project leader, Renewable Energy Hub, stated that the construction plans failed due to political disputes and lack of economic integration of the regions and thus could not demonstrate the benefits of the inter-regional connection (Halawa et al., 2018; Interview 13, 2019; Ralph and Hancock, 2019).

The materialisation of the global Super-grid is also hindered by existing transmission links being disassembled between disputed regions in order to connect with other 'more favourable' regions. An illustrative case can be found in the Baltic region, where national governments have disconnected from the former Soviet transmission network (Baltic countries, Kaliningrad, Belarus, Russia) and connected to the EU instead as to break free from depending on the Russian power supply and associated Russian influence on their politics (de Carbonnel and Sytas, 2018).

### 3.4 Investment mobilisation for scale-up

In order to understand the preconditions for financing the Super-grid development, it is helpful to understand the general investment in transmission around the world and the different historical and current starting points that shape the investment decision in different regions. Between 2018-2020, China and the US are responsible for more than 50% of the overall investment in transmission grids. In China alone, 30 billion dollars were invested in 2018 to address the rapidly growing electricity demand in the western parts of the country by connecting to remote renewable energy sources in the north. Though Chinese investment fell 11% in 2019, it continues to lead the transmission investment. Following decades of under-investment, the United States has between 2015-19 injected the largest share of the overall investment into upgrading its ageing transmission grids. However, principal drivers of the investment are to modernise, digitalise and bolster the existing grid, rather than building new transmission connections. The European Union had an 8% increase in transmission investment in 2018, but the 2020 report shows that European spending is gradually redirecting towards digital grid infrastructure at the cost of network expansion (IEA, 2019). According to our interviews, the majority of the investment goes into mature transmission technologies, upgrades and modernisation, while the investment in cutting-edge HVDC technologies is still small and allocated mostly to R&D and in-house technology trials (Flynn, 2016; Interview 3, 2019; Interview 15, 2019).

While the figures published by IEA (2019) demonstrate the magnitude of global investment in transmission infrastructure, it only provides data for investment in transmission infrastructure within boundaries of nation states (e.g. China, US) and regional unions (e.g. EU, ASEAN). The prevalence of transmission investment within countries and regional unions is not accidental. Mobilising secure financing for new transmission infrastructure, especially for interconnections between countries and regions, is difficult due to the absence of coherent global financing mechanisms. Historically, transmission networks have been built to serve the national market, establishing a strong state – electrical power industry nexus and established market relations through which TSOs have an easy time obtaining investment backed by the national government and paid by taxpayers, in exchange for reliable electricity provision (Van der Vleuten and Högselius, 2012). As a consequence, in most of the industrialised countries, grid-related investments are still regulated and secured at national levels. Incumbent grid owners and operators, the majority of which are still state-owned, therefore, have the best

conditions to invest into transmission networks through government-secured financing schemes. Private investors hence also tend to prioritise investments at the national level, reinforcing the old financing practices (Aubertin, 2019).

Investment trends demonstrate that the existing transmission infrastructure and the actor networks that operate and maintain them can become a barrier to global Super-grid development. According to Gold (2019), new transmission network developments are not hindered by a lack of funding as such. Instead, in the EU and US, the path-dependency of the established transmission system dictates resource mobilisation. The US provides a clear example, which despite being one of the largest investors in transmission infrastructure makes no contribution towards a global Super-grid. The established utilities have stronger incentives to upgrade the existing infrastructure assets than to invest in new cross-border connections, locking the US out of the global Super-grid development.

There is no doubt that as long as the path-dependency of nation-level financing persist, it hinders the creation of alternative financing schemes that would incentivise cross-border connections and trading. So far, the most progress has been achieved the EU, where a supra-national fund was created to pool and redistribute financial resources for cross-border construction projects (Iea and Praktiknjo, 2015). The EU funding instrument, *Connecting Europe Facility (CEF)*, presents a successful strategy to break the nation-level investment schemes by providing loans to both public and private investors, who aim to contribute to increased interconnectedness among European countries (ec.europa.eu, 2020).

In some regions, financing Super-grid development is hindered by insufficient financial resources available. Investment difficulties are most visible in the sub-Saharan African region, where large infrastructural investments are risky even when backed by national governments. According to the IEA (2019), the relatively immature transmission industry struggles to recover its costs under unreliable financial schemes, a situation someplace worsened by corruption (IEA, 2019). With a significant interest in building the global Super-grid, GEIDCO is providing financial support in countries where it is not available, especially if those are included in China's One Belt and One Road (OBOR)<sup>7</sup> infrastructural initiative (Simonov,

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<sup>7</sup> The Belt and Road Initiative, a renaissance of the Silk Road, is a massive infrastructure project that would stretch from East Asia to Europe.

2018). As a GEIDCO representative explained, GEIDCO views Africa as a suitable place for demonstrating the first continental grid and is willing to provide financial assistance to materialise it (Interview 14, 2019). It is estimated that the Chinese government will provide an investment of \$27 trillion by 2050 for the construction of the electricity infrastructure for OBOR, with \$7 trillion alone going into constructing cross-country transmission connections (Cornell, 2019; Liu et al., 2018).

While Chinese investments are welcomed in many countries that are vulnerable to persistent electricity shortages, critics warn that China's generosity represents a neo-colonial strategy and a way to gain control over the continent, and access to its vast natural resources, via infrastructure funding and ownership. Concerns are increasing that SGCC, through its investments, is securing ownership and thus control in public utilities abroad. For illustration, the SGCC has become a large utility shareholder in Brazil, Chile, Philippines, Portugal and Greece, among others (Kynge and Hornby, 2018). With a key role in other countries' energy systems, China gains the ability to exert influence on national decision-makers, potentially making them a part of the Chinese version of a global Super-grid (Okutsu et al., 2020).

### 3.5 Market formation and value creation

At the level of the technical configuration, the Super-grid system is coordinated in one hard-linked value chain. But in reality, the Super-grid would connect a large number of private and public asset owners, operators and end-users across multiple market structures and jurisdictions. How to create new market relations as well as share costs and benefits in the Super-grid market that crosses national and regional borders remains to be solved (Boie et al., 2014; Flynn, 2016).

The techno-economic models that are used to promote the global Super-grid presume *value creation at the whole system level* in a market that is controlled by a single, rational system planner, who optimises for global-level system energy efficiency and cheapest system costs (Jayadev et al., 2020). Techno-economic studies suggest, that a Global System Operator (Chatzivasileiadis et al., 2013) or a "United Nations Renewable Energy Organisation" (Safiuddin, 2017), needs to be formed to facilitate the coordination of complex multi-

stakeholder and jurisdictional or global market development and operation (de Rubens and Noel, 2019; Moore, 2017; Schmitt, 2018; Sunila et al., 2019).

However, optimisation models can only propose how the Super-grid system *should* work, without accounting for the challenges of coordinating diversity of national markets, political regimes and international hierarchies (Jayadev et al., 2020). As a consequence, how one actor in a global value chain can capture some of the created value in the system as a whole is unclear. Ralph and Hancock (2019) explain that creation of a global market is challenging because it puts nation states into a competition with other states that they might not always win. That is why, from a state's perspective, there is little incentive to join a global electricity market that creates value at the system level but a potential loss at the national level. Obvious market losers, such as excluded and transit countries, are also likely to oppose the development of a Super-grid unless there is an attractive compensation mechanism (Dutton and Lockwood, 2017; Interview 12, 2019).

As Boie et al. (2014) point out, transnational redistribution of tasks such as balancing services, transnational capacity allocation, congestion management, and infrastructure maintenance is difficult as system operation is traditionally planned and coordinated at national levels. Hence, striking a balance between redistributing costs and benefits at the whole system level, within national boundaries and between individual market participants is difficult and can become one of the reasons for disagreements and conflict (Ralph and Hancock, 2019).

The efforts to form a common electricity market in the EU can serve as an illustration of the difficulties in creating value at the whole system level. As Hoffrichter and Beckers (2019) show, EU-wide electricity trading at the transmission level requires central market planning to ensure reliability and security of electricity supply. However, centralised planning is in conflict with the market arrangements at the production, distribution and retail levels in most of the EU countries that are dictated by free-market competition. They add that a centrally planned EU market can potentially lead to resistance and withdrawal of participant countries as it is unlikely to account for national preferences and private interests adequately. The representative from FOSG underscores that strengthening the role of the Agency for the Cooperation of Energy Regulators (ACER) is key to incentivise EU countries to join the common market with EU-level benefits (Interview 4, 2019). Nevertheless, it has also been argued that the presence of a transnational market executor is no guarantee for strengthened cross-state cooperation as the

common energy market still has to become the priority at the national level (Fitch-Roy, 2016; Flynn, 2016; Van der Vleuten and Högselius, 2012).

Given the challenges to create new market relations without an effective way to share costs and benefits, industry actors, investors and policymakers seem to be pursuing an alternative pathway towards a renewable energy future that also allows keeping the benefits within national borders. To protect the national interest and economy from foreign competition, flexibility and efficiency measures at the distribution grid level have become a direct competitor to transmission grid extension and integration (Scholten and Bosman, 2016; Van de Graaf and Sovacool, 2014). The author of ABB's Super-grid vision and the CEO of Desertec have also refocused towards supporting demand-side solutions that can be kept within a single country boundary and still provide cheap and reliable electricity supply. In the EU, for example, grid extension is being replaced by grid digitalisation, storage and demand-side flexibility, solutions that require less upfront investment, have shorter lead time and are not heavily reliant on governmental support (IEA, 2020; Interview 2, 2019; Interview 5, 2019).

### 3.6 Legitimation

Being developed by the incumbents themselves, the Super-grid vision has been able to gain substantial institutional support without encountering much resistance from dominant or other novel technological innovations (CIGRE, 2019; FOSG, 2016; Interview 14, 2019). Formation of collective expectations and beliefs about the Super-grid as the only technologically and economically viable solution for the future was possible within the well-established networks of transmission researchers and industry (Interview 1, 2019). Inside these networks, the Super-grid gains its legitimacy through incumbent industry's reputation and historically proven 'standard of good practice' in the transmission system development, i.e. building large scale power plants and connecting them to demand centres. Super-grid advocates share a strong belief that transmission extension and integration is a cheaper and more efficient solution than small-scale local solutions (Interview 3, 2019) (see Section 3.1).

Super-grid advocates also share beliefs about the political implications of global electricity interconnection. As a REI representative said: "a transmission line is a perfect symbol of cooperation" (Interview 1, 2019). They believe that high levels of cross-country

interdependence are necessary to create new patterns of energy security featuring cooperation, mutual benefit and win-win results that could defeat current separatist and protectionist political tendencies (Interview 14, 2019). The logic is described by experts as a “deterrence strategy”, meaning that secure coordination is achieved through fear of compromising system security, as failure would affect parties at both ends of a grid connection with blackouts, and the rest of the system with load imbalances (Interview 1, 2019; Interview 12, 2019).

However, the vision of a global Super-grid has had mixed success in gaining legitimacy outside the actor network of its strongest supporters. Particularly gaining support from policymakers has been inconsistent and Super-grid advocates display a level of frustration with the weak level of policy support and commitment (Interview 4, 2019).

Chinese government owned GEIDCO has since 2016 made significant efforts to increased global legitimacy of the Super-grid vision. GEIDCO has been actively lobbying industry actors and governments around the world to join the global Super-grid system. GEIDCO has, to this purpose, set up seven regional branch offices on all continents to open and coordinate the dialogue among national governments (Interview 14, 2019). To this end, GEIDCO has established presence at the United Nations (UN) and became an official partner at the COP24 in 2018. As a result of their participation, the GEI Action Plan became a part of the global agenda document (unfccc.int, 2018).

The Chinese government believes in its system building role, as its “political system with central governance is the most suitable for the Super-grid” (Interview 14, 2019). Transmission industry experts interviewed for this study praise the ‘holistic control’ and long-term economic planning of the Chinese government and its success to demonstrate most advanced transmission infrastructure (Interview 3, 2019; Interview 10, 2019; Interview 14, 2019). However, the international scientific community is becoming increasingly critical of China’s strategy. Scholars warn that the institutionalisation of a global Super-grid could provide means for authoritarian regimes to reinforce their practices, to reorder global power hierarchies and obtain geopolitical dominance (Christoffersen, 2008; de Rubens and Noel, 2019; Gupta, 2015; Sovacool and Cooper, 2013; Van de Graaf and Sovacool, 2014). The concerns of using the Super-grid to obtain geopolitical dominance increased after China created GEI as a global version of the Asian Supergrid, and redrew initial grid lines to fit the One Belt One Road

(OBOR)<sup>8</sup> initiative (Christoffersen, 2008). Critics are also speaking up about the risks of turning a blind eye on the social and environmental implications of having an undemocratic government as a system builder in the naïve belief that engineering solutions are able to resolve political issues (Ralph and Hancock, 2019; Van de Graaf and Sovacool, 2014).

With mounting concerns over Chinese dominance in the global economy and international politics, many national decision-makers, particularly in western societies, are hesitant to support the global Super-grid. National governments are hesitant to compromise their national energy security, political control and military strength in exchange for a cheap and efficient electricity system achieved via transnational cooperation (Ralph and Hancock, 2019; Van de Graaf and Sovacool, 2014). History of military conflicts, exploitation, or fear of dependence on other countries work against the legitimacy of both regional and global Super-grid visions (Ralph and Hancock, 2019; Van de Graaf and Sovacool, 2014). To exemplify, a GEIDCO representative admitted that the GEI vision had achieved little success in the US due to worsening relations with China (Interview 14, 2019). In addition, territorial disputes between Japan, China and Korea pose a significant barrier to the construction of a regional network in Northeast Asia (Interview 12, 2019).

Some scholars argue that the public opposition and environmental concerns can have a delegitimising impact on Super-grid development in general (Boie et al., 2014; de Rubens and Noel, 2019; Lienert et al., 2015). New transmission grid projects have historically experienced public resistance and critique for lack of public consultation (Knudsen et al., 2015; Lienert et al., 2015). We can already observe that public consultations are not included in GEIDCO's activities, and GEI projects proceeded to construction in spite of strong local opposition (Kynge, 2018). As a GEIDCO representative explained, public consultations make the transmission network development 'difficult and slow,' and transmission projects in Europe are difficult to realise because "environmental concerns of the public are taken too seriously" (Interview 14, 2019). However, China-led GEI projects, some of which are constructed in the most ecologically fragile places, have not escaped the resistance from global environmental movements. About 14% of Chinese infrastructural projects in 66 countries have faced some kind of local pushback since 2013 (Kynge, 2018; Narain, 2020). Accordingly, we observe a

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<sup>8</sup> a global infrastructure development strategy adopted by the Chinese government in 2013 to invest in nearly 70 countries and international organizations. It is often referred to as 21<sup>st</sup> century Silk Road.

feedback between experimentation, lack of legitimacy and public resistance. Failure to address social and environmental impacts can lead to a growing public resistant against the global Super-grid, but more importantly, to long-term damage on the local communities and the environment.

#### **4 Discussion and conclusions**

The Super-grid is sometimes portrayed as the natural, or even inevitable next step in the development of electricity systems. It follows the logic that the larger the grid, the easier it is to balance supply and demand and to optimise the system, and hence society will follow a path towards continental and eventually global grids. The logic of a “natural trajectory” is often accompanied by *technocratic internationalism*, a view that technical systems crossing borders will automatically bring peace and prosperity and could somehow replace politics and diplomacy. While there is some truth in that gridlines are becoming longer, and some are crossing borders, the sociotechnical analysis presented here challenges the technocratic view and demonstrates that the normative issues are far from simple and straightforward.

The technical development of HVDC technology over the last three decades has increased the possibility of continental and global grid connections. While there are still technical difficulties to overcome, experiments with advanced technology are being conducted, and the number of long-distance connections is increasing. An advantage of the Super-grid vision is that it is backed by actors rooted in the existing value chain with access to large resources. This analysis supports previous findings that the transition in the infrastructure-intensive electricity sector is subject to strong material and institutional path-dependency (Markard, 2011). The established transmission system actors and strong private-public actor networks seemingly provide a head start through access to grids, technological expertise and funding. However, while building new HVDC interconnections on top of existing HVAC grids allows the industry to have a solid starting point for materialisation, the existing infrastructure can also slow down development due to the vested interests of actors who own and manage them and prefer to invest in mature technologies. Moreover, in most industrialised countries, transmission grids co-developed with the nation state in the 20<sup>th</sup> century and international connections have been a contested issue since the birth of the industry. The Super-grid is hence in competition with nation state centred systems of the past and present.

A related problem is the lack of new actors capable of experimenting without relying on public support. In many technological fields, innovation is driven by new actors with path-breaking ideas that can challenge systemic lock-ins. However, the scale of investment in each experiment, required connections to existing grid infrastructure, and access to planning and permission processes, create formidable barriers to entry for newcomers. The large investment and long lead times of each project also result in slow learning processes, compared to smaller-scale modular technologies.

Moving from national to international grids also requires new solutions related to the market formation and value appropriation. A global value chain for electricity would require new institutions setting standards and regulating trade. But since there is no supreme power and universal way to handle conflicts and trade-offs at the global level, as within nation states, there is no simple solution to this problem. This points to the larger geopolitical questions surrounding the global Super-grid. There are fears that the development of dependencies and need for global standards will not at all result in a system automatically generating benefits for all, once dreamt of by Buckminster Fuller, but a system dominated by a small number of powers creating economic and political benefits for the few. Through the course of history, governments have been using electricity infrastructures to achieve not only economic but also other political goals. This is likely a reason why China's effort to reduce variety by providing a standardised Super-grid design for all regions of the world is perceived as a suspicious political move.

Due to the geopolitical tensions and the key role of nation states in regulating electricity markets, the path-dependency in the industry and the institutional uncertainty, the development of a single globally interconnected electricity system is far from a given. Instead, system growth is uneven and fragmented across the world. Experimentation and construction of long-distance connections and Super-grid components are carried out within nations, or at most on a continental scale. At smaller regional level, in Scandinavia and Baltic region for example, countries are strengthening their cooperation through building cross-border transmission (Högselius, 2018). However, spatially scattered and locally shaped Super-grid developments are currently creating a variety of system designs and business models that might not easily be combined into one system.

At the same time, as shown in other studies (Blarke and Jenkins, 2013; Foxon, 2013; Hojčková et al., 2018; Verbong and Geels, 2008), the Super-grid is not the only future alternative and alternative system designs based on smaller-scale technologies are developing fast. It competes with visions of smaller scale smart-grid systems and local off-grid solutions, based on other technological solutions and supported by different actor groups and values. The Super-grid thus has to overcome a broad set of barriers to materialise, as well as it needs to develop at a certain pace, if not to be outcompeted by faster alternatives.

A conclusion from this sociotechnical analysis is that the proponents of the Super-grid need to acknowledge the political reality of technological change. Technology is never apolitical, and the developments of large technical systems are always co-evolving with the political and the social. If the Super-grid is to be a part of the future and contribute to mitigating climate change, providing prosperity and empower the many, the discourse needs to open up, and move beyond technocratic ideals of “optimisation”, “efficiency” or “economies of scale” and take a broader set of social benefits, risks and trade-offs seriously.

Academically, we find that most studies either take a techno-economic perspective or focus on the political and institutional barriers to the Super-grid trajectory. Based on sociotechnical systems thinking, we assume that technology and society co-evolve and attempt symmetric attention to social and material dimensions. This study is one of a few applying a sociotechnical system perspective and the only study so far to apply a global system boundary. Compared to studies with a national system boundary, we find among other things that the nation state shifts from being a unique actor with specific and far-reaching institutional capacity, to one actor among many that needs to navigate a larger sociotechnical landscape of international politics and economy. The analytical attention to cross-level and cross-country actor networks also show us how there are power relations and competing social forces *within* states that push in different directions (Johnstone and Newell, 2018; Newell, 2019). To make sense of this and other issues dictating sociotechnical change in a globalised world, we see a need for further conceptual development.

## Acknowledgements

This research was funded by the Swedish Energy Agency as part of the project, ‘New networks of power: on the emergence, diffusion and impact of alternative electricity system architectures’, and by the Kamprad Family Foundation as part of the project “Resistance and power – on smart grids for the many people”.

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# Paper VI



# Clarifying the focus and improving the rigour of sustainability transitions research on emerging technologies

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## Abstract

The technological innovation systems framework is used widely in sustainability transitions research on emerging technologies and supports a growing body of literature that offers valuable empirical insights and important policy recommendations. However, when reviewing how this literature uses core concepts from systems thinking, this paper identifies a number of fundamental ambiguities and contradictions. It is often unclear if technological innovation systems perform innovation, production or both, there is no agreement whether their components are social or sociotechnical, and functional processes used to analyze change are defined in a way that allows for different interpretations. Since these issues may cause confusion and hinder cumulative knowledge development and conceptual advancements, there is a need to clarify the focus and improve the rigour of sustainability transitions research on emerging technologies. To this end, this paper proceeds to argue for a sociotechnical and technology-oriented perspective, suggests and defines technological systems as suitable objects of study, proposes methodological guidelines for applying this construct to empirical investigations, and shows how it can be used to analyze innovation dynamics by deriving a typology of transformation processes. Although some ideas presented in this paper deviate from the extant literature, they are likely in line with how many scholars interpret and use the technological innovation systems framework. The contribution of this paper should accordingly be viewed not as a novel approach, but as an attempt to clarify and strengthen conceptual ideas that already support successful research.

## 1 Introduction

The last decade has seen the emergence of a diverse, vibrant and growing community of scholars engaging in sustainability transitions research. What unifies this community is a common interest in increasing the scientific understanding of how sociotechnical systems of production and consumption change in response to environmental and social sustainability challenges (Köhler et al., 2019). One of the main strands of sustainability transitions research focuses on the development and diffusion of specific technologies that may reduce environmental impacts and create socioeconomic benefits. These studies often employ the technological innovation systems (TIS) framework, which has gained prominence as an analytical tool for policy-oriented studies of technological innovation (Markard et al., 2012). In particular, the framework offers a typology of processes, commonly referred to as functions, that are important for the development, diffusion and utilization of new technologies (Bergek et al., 2008a; Hekkert et al., 2007). Analyzing functions enables the identification of problems in the innovation process, which has proven useful for deriving intervention strategies for policymakers and other actors that have an interest in promoting a specific technology (Borras and Edquist, 2013; Weber and Rohracher, 2012; Wieczorek and Hekkert, 2012).

Even though the TIS framework has been applied in several hundred scientific articles, including a wide range of empirical and conceptual studies, it has not escaped criticism. Identified weak spots, to name a few, include lack of attention to human agency and micro-level phenomena (Kern, 2015), biased or limited view on the role of geography (Coenen et al., 2012; Hansen and Coenen, 2015), and insufficient conceptualisation of incumbent industries and user structures (Markard and Truffer, 2008). Criticism along these lines have resulted in conceptual additions to the TIS framework and also guided empirical investigations towards new topics (Bergek et al., 2015; Markard et al., 2015).

Another line of criticism, which is much less spelled out in the literature, is directed at the heart of the TIS framework and concerns the fundamental system definition; what components the system consists of, and what purpose make them form a unified whole. First, there is no consensus in the literature about whether a TIS is a social or sociotechnical system. The foundational literature (Bergek et al., 2008a, 2008b; Carlsson and Stankiewicz, 1991; Hekkert et al., 2007; Markard and Truffer, 2008), which is cited by most scholars that apply the TIS framework, is largely in agreement that the system is social, and made up of actors, networks and institutions. An exception is Bergek et al. (2008b), who include technology as a structural component. While this approach has been adopted by many scholars in the subsequent literature, system definitions that focus on either social or sociotechnical components still exist in parallel.

Second, the system purpose remains ambiguous throughout most of the literature. The foundational literature points in different directions and shows considerable ambiguity as to whether TISs are systems that innovate, produce or both. The definition of system purpose is often sufficiently vague to allow for two different interpretations; one that views the system as an entity that *achieves change* through innovative activities, and another that also includes the production and consumption activities that are *subject to change*. Although this issue was discussed early on by Markard and Truffer (2008), subsequent TIS studies has failed to improve the conceptual clarity.

Third, and partly related to the second issue, there is ambiguity in the definition of TIS functions, which is the key concept used to analyze change. The typologies of functions commonly used in the literature have by some been referred to as “more or less arbitrary” (Fuchs et al., 2012, p. 12). Although this accurately highlights the absence of a deductive theoretical perspective that binds the system functions together, we do not see functions typologies as arbitrary. Foundational contributions identified key processes through extensive literature reviews and used these to construct categories that were considered appropriate (Bergek et al., 2008a; Hekkert et al., 2007). These categories were quickly adopted by sustainability transitions scholars and have ever since been developed pragmatically in a continuous scientific process. While one may criticize (or praise) the scholarly freedom of the process through which functions typologies have emerged, it is far from the guesswork suggested by the notion of arbitrariness. However, the very concept of functions is unclear and its relation to other parts of the TIS framework have not been thoroughly described. It is seldom made clear how and where system functions achieve change, and it is up for debate whether they should be understood and measured as causes or effects.

Quite surprisingly, these fundamental issues have been subject to very little debate. There has been some discussion at scientific conferences, but few scholars have tried to increase the conceptual rigour by proposing and motivating clear positions and definitions. A case in point is a special issue in *Environmental Innovation and Societal Transitions* from 2015, based on a debate at the International Sustainability Transitions conference in Utrecht the year before (Truffer, 2015). Here, leading scholars debated recurrent criticism against the TIS framework without any reference to ambiguities and contradictions regarding the type of structural components and purpose that define the system. Discussing whether this is due to the complexity or sensitivity of these

issues, whether they are not considered important, or whether they have simply passed unnoticed, is beyond the scope of this paper.

We do, however, argue that there is an urgent need to clarify the concepts used in the sustainability transitions literature on emerging technologies. To begin with, it is simply confusing to use the same concept for different things. This lack of precision makes the literature difficult to comprehend for practitioners, scholars in other fields and even empirically oriented sustainability transitions researchers. As two of the authors of this paper can testify from their own experience, it also makes it harder for junior scholars to enter the field. Another reason is that the lack of clarity and rigour hinders cumulative knowledge development. In particular, this concerns extensions and refinements of the conceptual framework, but we also believe that a more consistent analytical approach would benefit the transferability, comparability and generalizability of findings from empirical case studies. In addition, a clearer logic will benefit the growing strand of sustainability transitions research that develop computer models that simulate the emergence of new technologies (Holtz et al., 2015; Walrave and Raven, 2016) as well as support efforts to establish links between the literatures engaging with innovation studies and technology assessment.

The purpose of this paper is therefore to clarify the focus and improve the rigour of sustainability transitions research on emerging technologies. To that end, we will first discuss what it means to adopt a systems perspective on technological innovation, to give grounds for the need to clarify the fundamental definitions of the TIS concept. Based on this understanding, we proceed to elaborate on conceptual ambiguities and contradictions in the extant literature. We then argue that the sustainability transitions community should adopt a sociotechnical and technology-oriented perspective on emerging technologies, and suggest technological systems as suitable objects of study. We also elaborate on the main characteristics of technological systems, and propose methodological guidelines for applying this construct to empirical investigations. In addition, we show how this construct can be used to analyze innovation dynamics, by deriving a typology of transformation processes.

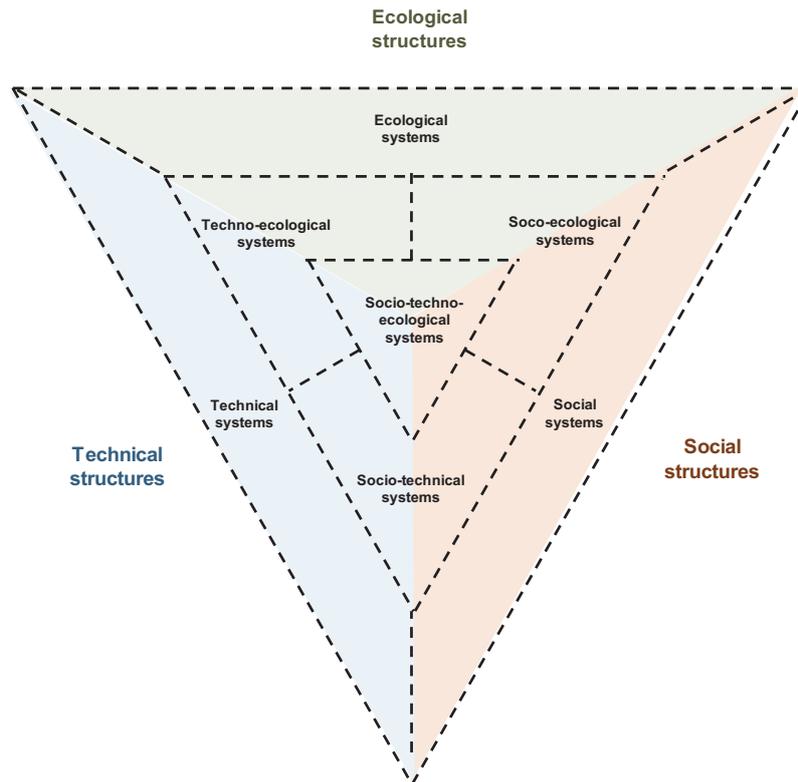
Although some ideas presented in this paper deviate from the extant literature, they are likely in line with how many scholars interpret and use the technological innovation systems framework. The contribution of this paper should accordingly be viewed not as a novel approach, but as an attempt to clarify and strengthen conceptual ideas that already support successful research.

## 2 Methodological starting-points based on systems thinking

It is apparent from the name that the TIS framework applies, or at least aims to apply, a systems approach. While systems studies, which emerged as a scientific field in the mid 20<sup>th</sup> century, has developed into a broad family of theories and methods, there are a few reoccurring core concepts. As further described below, we will take these as a starting-point for our review of the literature as well as for suggesting technological systems as a suitable object of study and proposing some methodological guidelines.

### 2.1 Applying systems thinking to technological innovation

The Merriam-Webster dictionary defines a system as “a regularly interacting or interdependent group of items forming a unified whole”. Specifying a system thus involves describing its constituent items and interconnections (Meadows, 2009). In the sustainability transitions literature, these are often referred as structural components. Based on the characteristics of these components, it is possible to distinguish between different types of systems; ecological systems consist of non-human life and its natural environment; technical systems consist of physical artifacts; and social systems consist of human agents as well as the agreements and shared meanings that govern their interaction (Ingelstam, 2012). In addition, there are systems that combine these basic types, such as socio-technical, socio-ecological, techno-ecological and socio-techno-ecological systems (Ahlborg et al., 2019). This typology of systems is illustrated in Figure 1.



**Figure 1. A typology of systems based on the character of their structural components.**

Although technological innovation is a phenomenon that involves structures from ecological, technical and social domains of reality, this does not necessarily mean that all these are included when applying systems thinking. On the contrary, it is possible to apply system definitions that focus on any combination of structures and thereby capture different aspects of the innovation process. As we will see in Section 3, varieties of the TIS framework is in fact used to study both social and sociotechnical systems related to technological innovation.

A system definition also requires a specification of why its structural components form a unified whole. This is typically done by referring to one of two properties, or to both in combination. First, a system is often united by a purpose or function (Meadows, 2009). Importantly, this neither implies that the system is “conscious” and has a “will”, nor that its components must share or even be aware of this purpose. It simply means that for something to be viewed as a system by an observer, it needs to have one or several functions.<sup>1</sup> Second, the interaction between elements in a system could be qualitatively or quantitatively different from the interaction between elements in the system and those in the system environment (Simon 1962). However, this difference can often, if not always, be derived from a shared purpose or function.

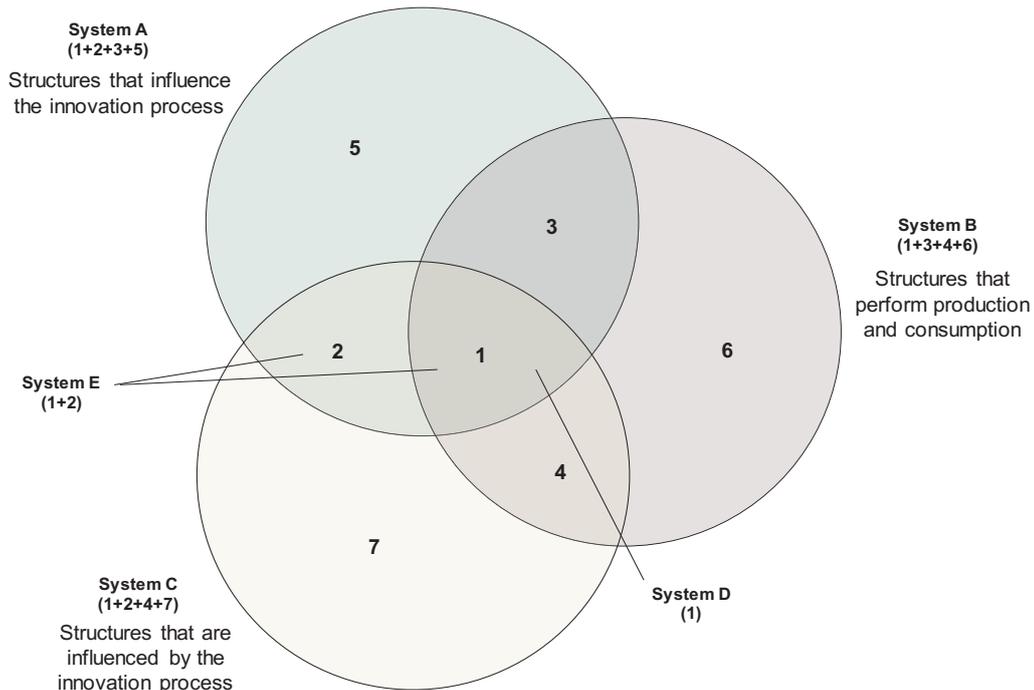
When applying systems thinking to technological innovation, it is important to acknowledge that relevant structures can relate to this phenomenon in at least three different ways. First, there is a set of structures that perform production and consumption activities related to the technology in focus. These activities are organized in value chains of interlinked processes that together describe how some focal product, such as electric vehicles or solar electricity, is created and used. In layman terms, this can be viewed as an industry, or a part of an industry centred on a technology, and its related market. Second, there is a set of structures that perform innovation activities related to the technology in focus. In other words, they develop and diffuse the technology in a way that implies growth or transformation of the first set of structures (i.e. that perform production and consumption activities). And third, there is a set of structures that are influenced by innovation activities related to the technology in focus.

The three sets are different with respect to what unifies their constituent components. But in contrast to the domains which capture ecological, technical and social structures, these sets partially overlap since many components have multiple relationships with the innovation process. For example, firms in an industry are often involved in both production and innovation activities, while being affected by their outcomes. Conversely, there may exist structures that only influence the innovation process, while not taking part in production and

<sup>1</sup> Note that nothing in principle prevents an observer from viewing any interacting items as a system.

consumption. Possible examples include a research department at a university, a tax law or a generic infrastructure. In addition, there are structures that are merely affected by innovation activities, without influencing them or being a part of the emerging industry. Examples include humans and animals harmed by pollution from increased production and consumption, or parts of society indirectly benefitting from a stronger economy resulting from such growth.

In Figure 2, we illustrate this by letting three overlapping circles represent the sets of structures described above. This results in seven non-overlapping segments (1-7) that each represent structures with similar relationships to the innovation process. By combining these segments, we may define systems with different purposes or functions. However, there are many possible combinations and we therefore highlight five systems (A-E) that have particular relevance for the continued discussion.



**Figure 2. Three overlapping sets of structures that, respectively, influence the innovation process, perform production and consumption activities, and are influenced by the innovation process. These result in seven segments (1-7) of structures with similar relation to technological innovation. By combining these segments, five systems (A-E) are defined. Notably, systems A, B and C correspond to the three sets of structures.**

Out of the systems highlighted in Figure 2, System B corresponds to the set of structures that perform production and consumption activities. The purpose is accordingly to create and use the focal product which defines the technology, and it may be viewed as an emerging industry and a related market. In contrast, System A corresponds to the set of structures that influence innovation activities that govern the development and diffusion of the technology. This implies that the purpose is to create, expand and transform System B. System C corresponds to the set of structures that are affected by innovation activities related to the technology. It accordingly has a different character, since its components are not united by a common purpose, but rather by a common source of influence (i.e. System A).<sup>2</sup> In relative terms, we may note that the purpose of System A is to *achieve change* of System B, System B is *subject to the change* caused by System A, and System C is *affected by the change* caused by System A.

Furthermore, System D is found in the intersection of System A, B and C (segment 1). It includes structures that both influence and are influenced by innovation activities, while also performing production and consumption activities. System E, lastly, is slightly broader since it also includes structures that only influence and are influenced by innovation activities (segment 2). These include a range of more general structures supporting or

<sup>2</sup> This means that one can question whether these structures should be referred to as a system. Nevertheless, we do so for the purpose of simplicity.

inhibiting innovation, and while not being involved in production and consumption of the focal product, they would nevertheless not exist without the technology, for example, a university research group focused on wind power development, which would not exist without wind power technology. System E thus includes structures that both influence and are influenced by what happens to the focal technology, and are accordingly unified by internal bidirectional interaction.

When applying this framework to the literature which engages with technological innovation, a few things can be noted already at the outset. To begin with, constructs such as national innovation systems, which capture a wide range of structures that create novelty in the economy, ideally “all determinants of innovation” (Edquist, 1997), typically refer to a System A (albeit with a very broad technological focus that includes all innovation activities in a country). But when it comes to technological (and sectoral) innovation systems, it is less clear what structures the word ‘system’ is intended to capture. The main reason for this is likely the overlaps and complexity illustrated in Figure 2. However, most scholars are likely to include the structures captured by System D and E in their conception of technological innovation systems. The remaining question, that will be further discussed later in the paper, is the status of the remaining parts of System A and B.

It should also be added that segment 3, 4 and 6 are less interesting from an innovation perspective. Structures in segment 3 influence the innovation process but are not influenced in return, while still being part of the industry subject to change. Structures in segment 6 constitute an inert part of the industry subject to change. While structures in segment 4 is also a passive part of the industry, which is influenced by the innovation process without influencing it in return. Notably, structures in segment 3 are hard to imagine, while structures in segment 4 and 6 could potentially be dismissed as non-existing in practice, given that even seemingly passive structures of a system tend to influence change of the same system, at least at some relevant scales of observation.

In contrast, Segment 7 is clearly interesting from an innovation perspective. However, specifically studying these indirectly affected structures is not primarily a task for the sustainability transitions community, but rather belongs to the technology assessment domain.

As demonstrated by the reasoning in this section, defining a system as an object of study for describing and analyzing technological innovation is far from straight-forward. The chosen construct can include different types of structural components (Figure 1), which may in turn be unified by different purposes or functions (Figure 2). There are accordingly ample possibilities to attach different meanings to the concept of “technological innovation systems”. From this it follows that ‘innovation system functions’ could mean different things for different authors and that system boundaries are defined differently (if at all defined).

## 2.2 Qualitative and quantitative method for reviewing the literature

In Section 3, we review the literature and try to disentangle what explicit and implicit system definitions that have been used by scholars that develop and apply the TIS framework. We draw upon the ideas presented in the previous section and focus on (i) the choice between including social or sociotechnical components and (ii) how the system purpose or function is defined (i.e. is the TIS associated with System A, B, D or E, or possibly any other combination of segments that can be derived from Figure 2). Furthermore, we briefly review how this affects interpretations of TIS functions.

The literature review was done in two steps. First, we performed a close reading and qualitative analysis of what we here call ‘foundational papers’. The reason we choose this term is that these are the most cited publications by scholars that develop and apply the TIS framework, which indicates an important influence on the subsequent literature. Second, we collected all scientific publications using the term ‘technological innovation system’. The search was performed in Scopus on June 25<sup>th</sup> 2019, using the specific search term “technological innovation system\*”. This resulted in 305 publications, out of which 225 were categorized as “Articles and reviews” and 80 as conference contributions, books and other publication types. From these search results, we defined and collected a corpus of 159 publications. The corpus was limited to articles and reviews published between 2009 and 2018 in peer-reviewed journals, and also excluded publications that did neither develop nor use the TIS framework (but rather some other concept or approach associated with the term). The collected publications were then read to quantitatively assess the extent to which scholars define TIS as a social or sociotechnical system, respectively. A similar attempt was made to quantitatively assess how the system purpose is defined, but due to the abounding confusion in the literature, this turned out to be difficult pursue at scale. Instead, a few clear examples was collected as evidence of diverging understandings. In addition to the quantitative analysis, a

sub-set of the corpus was read in more detail to inform the discussion about how the foundational papers have been interpreted and further developed by the subsequent literature.<sup>3</sup>

### 2.3 Approach to proposing a suitable systems construct and some methodological guidelines for sustainability transitions on emerging technologies

In the end of Section 3, we argue for the need to clarify the focus and improve the rigour of sustainability transitions research on emerging technologies, while we in Section 4 propose a way forward that we find particularly suitable. This involves arguing for foregrounding one particular type of systems construct as the object of study as well as elaborating on related methodological guidelines. The latter include what needs to be decided upon regarding the aim and scope of a given study, and how this translates to a system definition that clearly delineates the object of study. Our intention with the guidelines is accordingly to describe what needs to be stated in all empirical studies that use our suggested systems construct to investigate technological innovation. Methodological recommendations of this kind may facilitate cross-case comparisons and cumulative knowledge building, and have also proven successful in other fields of systems studies, such as life cycle assessment (see e.g. Klöpffer (2006)).

## 3 Ambiguities and contradictions in the technological innovation systems literature

To assess how core concepts are used in the TIS literature, we first review five foundational papers and then turn to patterns in the subsequent growing literature. We arrive at four areas in need of clarification and increased rigour.

### 3.1 Foundational papers

It is commonly accepted that the TIS concept was first introduced in a paper by Carlsson and Stankiewicz (1991), even though they actually proposed the concept of technological systems (Table 1). The authors define these as “a network of agents interacting in a specific *economic/industrial area* under a particular *institutional infrastructure* or set of infrastructures and involved in the generation, diffusion, and utilization of technology. Technological systems are defined in terms of knowledge/competence flows rather than flows of ordinary good and services.” (Carlsson and Stankiewicz, 1991, p. 111). They thus emphasize networks of agents as the main structural components, while institutions are treated as given and somewhat static, rather than interdependent and interacting system components. In addition, they quite clearly imagine a social system that lacks technical components, which stands in sharp contrast to other scholars who, in contemporary work, use the term ‘technological system’ to refer to a sociotechnical system (Hughes, 1987).

Regarding the system purpose, Carlsson and Stankiewicz (1991) are rather vague and arguably fail to clarify the relation between a technological system and an industry which employs technology to engage in production and consumption. On the one hand, the authors portray a technological system as similar to a national innovation system – albeit one that transcends national borders, focuses on a part of the economy (a techno-industrial domain) and pays more attention to micro-level developments – and appear to be mainly interested in what the system does, not in how it develops over time. This suggests that technological systems achieve, rather than are subject to, technological change (system A rather than system B). On the other hand, the authors refer to the utilization and exploitation of technology and refrain from restricting the system to novelties and innovations, which implies that established practices and products are in fact included as well. This indicates the opposite view, namely that technological systems are subject to technological change. A possible interpretation is that the authors understand technological systems as some kind of layer, domain or container in which new technologies are both generated and exploited. This is both in line with the proposed system definition and indicated by the fact that the discussion revolves around what happens in a loosely defined economic/industrial area, rather than with respect to one or several specific technologies.

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<sup>3</sup> The review was also informed by the authors’ accumulated experience from years spent working with the TIS framework and trying to apply it to empirical cases. Notably, the authors include one senior scholar with experience in the field going back two decades as well as two junior scholars that have strived to make sense of the extant literature during their PhD studies.

Throughout the 1990's and early 2000's, the concept was further developed and used in numerous empirical studies, mainly by a group of Swedish scholars (Carlsson et al., 2002). In 2008, this resulted in a publication that outlined an analytical framework for studying emerging technologies from a policy perspective, building on what was now referred to as technological innovation systems, TISs (Bergek et al., 2008a). Here, the authors propose that “the components of an innovation system are the actors, networks and institutions contributing to the overall function of developing, diffusing and utilizing new products (goods and services) and processes” (Bergek et al., 2008a, p. 408). They also describe a TIS as an innovation system focused on a specific technology, which is defined as either a product/artefact or a knowledge field. The publication thus advances Carlsson and Stankiewicz's (1991) system definition in three main ways. First, TISs are clearly associated with novelty and innovation, both in referring to new products and processes in the system definition and through the addition of innovation to the term technological system. Second, institutions are explicitly included as structural components next to actors and networks. And third, the system is focused on a specific technology, rather than any innovation activity in a loosely defined area. Moreover, it elaborated on an analytical approach focused on functional dynamics, which had been introduced in prior publications. The breakthrough insight behind the functions framework was that the performance of an innovation system cannot be evaluated by examining its structural composition, as had been common practice in the broader innovation systems literature, but rather requires a focus on how interactions among structural components influence different parts of the innovation process. To enable such process-oriented analyses, Bergek et al. (2008a) define functions as processes “which have a direct and immediate impact on the development, diffusion and use of new technologies, i.e. the overall function of the TIS as defined above” (p. 409). Based on an extensive literature review, they also establish a list of seven such functions (Table 2).

While advancing the framework in many ways, ambiguities with regards to the system purpose persist, even though it seems as if the authors view the development, diffusion and use of technology as a phenomenon that is achieved by, rather than occurs within, TISs (system A rather than B).<sup>4</sup> In addition, while stating only social components throughout the text, they in one place explicitly identify TISs as “socio-technical systems” (Bergek et al., 2008a, p. 408).

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<sup>4</sup> For example, the authors write that “TISs do not only contain components exclusively dedicated to the technology in focus, but all components that influence the innovation process for that technology” (p. 409), which clearly categorize TIS as a system B. However, they write things like “At some point in time, the TIS may be able to ‘change gear’ and begin to develop in a self-sustaining way as it moves into a *growth phase*” (p. 420), which seems to identify TIS with a growing industry, that is, a system A.

**Table 1. System descriptions in five foundational publications on technological innovation systems.**

Publication	System description
Carlsson and Stankiewicz (1991)	“A technological system may be defined as a network of agents interacting in a specific <i>economic/industrial area</i> under a particular <i>institutional infrastructure</i> or set of infrastructures and involved in the generation, diffusion, and utilization of technology. Technological systems are defined in terms of knowledge/competence flows rather than flows of ordinary good and services.” (p. 111)
Bergek et al. (2008a)	“The components of an innovation system are the actors, networks and institutions contributing to the overall function of developing, diffusing and utilizing new products (goods and services) and processes” (p. 408) “TISs do not only contain components exclusively dedicated to the technology in focus, but all components that influence the innovation process for that technology” (p. 409)
Bergek et al. (2008b)	“The components of a technological innovation system are the actors, networks and institutions contributing to the development, diffusion and application of a particular technology [...]. In line with a number of previous authors [...], we also include the technology as such among the components.” (p. 576) “[a TIS] focuses on the innovative activities within [a broader system that includes production and consumption activities]” (p. 576)
Hekkert et al. (2007)	“[a technological system is] a network of agents interacting in the economic/industrial area under a particular institutional infrastructure [...] and involved in the generation, diffusion, and utilization of technology. [...] it is useful to think in terms of technological systems as a special version of innovation systems. A technological system is a combination of interrelated sectors and firms, a set of institutions and regulations characterizing the rules of behavior and the knowledge infrastructure connected to it.” (p. 416)
Markard and Truffer (2008a)	“a set of networks of actors and institutions that jointly interact in a specific technological field and contribute to the generation, diffusion and utilization of variants of a new technology and/or a new product.” (p. 611)

**Table 2. Lists of functions proposed in the foundational literature on technological innovation systems.**

Bergek et al. (2008a)	Hekkert et al. (2007)
Knowledge development and diffusion	Entrepreneurial activities
Influence on the direction of search	Knowledge development
Entrepreneurial experimentation	Knowledge diffusion through networks
Market formation	Guidance of the search
Legitimation	Market formation
Resource mobilization	Resources mobilization
Development of positive externalities	Creation of legitimacy/counteract resistance to change

While Bergek et al. (2008a) only includes social structural components, a contemporary publication from the same research group introduces the idea of including technology as a structural component making the TIS explicitly sociotechnical (Bergek et al., 2008b). Moreover, the authors clarify the system purpose by first distinguishing between a TIS and a broader system that describes how a societal function related to a specific technology is fulfilled (through activities of innovation, production and consumption), and then confining the former to the innovative activities within the latter (hence they seem to refer to system D or possibly E). In

addition, they propose that functions “influence the build up of system structures” (Bergek et al., 2008b, p. 578), which goes beyond the descriptions offered by Bergek et al. (2008a). But while indicating that this structural build-up occurs in the TIS, Bergek et al. (2008b) do not offer an explanation to how this is linked to the more broadly defined system (system B?) where production and consumption activities also occur.

A few years before the publications by Bergek et al. (2008b, 2008a), the idea of studying innovation systems related to specific technologies had started to attract the attention of Dutch and Swiss scholars. They exchanged ideas and engaged in fruitful discussions with their Swedish colleagues, both at conferences and in some joint projects, which explains similarities across largely contemporary publications. Nevertheless, slightly different perspectives on TISs can be identified.

In 2007, the Dutch scholars presented their understanding of the functional dynamics approach to analyzing emerging technologies (Hekkert et al., 2007), which was inspired by earlier work by Bergek and colleagues. Referring to Carlsson and Stankiewicz (1991), Hekkert et al. (2007) describes a technological system as “a combination of interrelated sectors and firms, a set of institutions and regulations characterizing the rules of behavior and the knowledge infrastructure connected to it” (Hekkert et al., 2007, p. 416). This quite vague description of system components is later simplified to actors, networks and institutions. The authors point out that the term technological system is used by Hughes (1987) and others that study large technological systems (LTS), who include physical artifacts as system components. They therefore adopt the term Technology Specific Innovation Systems, to highlight that their understanding of innovation systems focuses on social rather than technical components. However, this term was in later publications abandoned in favor of TIS.

With regards to the system purpose, Hekkert et al. (2007) refer to the development, application and diffusion of new technological knowledge, which as discussed above leaves ample room for interpretation. It should be noted, though, that the authors cite Lundvall’s (2001) claim that “it is useful to think in terms of technological systems as a special version of innovation systems” (Hekkert et al., 2007, p. 416), hence comparable to national and sectoral systems of innovation, and thus leaning towards characterizing TIS as a system A.

Hekkert et al. (2007) seem to view functions as a way to categorize activities and events in innovation systems. This stands in contrast to Bergek et al. (2008a), since in their view any activity or event can contribute to several sub-processes in the overarching innovation process. The difference is even clearer when compared to Bergek et al. (2008b), where functions are defined based on their effect (new structure) rather than on their cause (activities). But at the same time, Hekkert et al. (2007) and Bergek et al. (2008a) derive similar list of functions, which indicates that their ideas are not too far apart (Table 2).

In contrast to their Swedish and Dutch colleagues, the Swiss scholars arrive at the concept of TISs as a way to integrate the separate research strands dealing with innovation systems and technological transitions. Markard and Truffer (2008a) define a TIS as “a set of networks of actors and institutions that jointly interact in a specific technological field and contribute to the generation, diffusion and utilization of variants of a new technology and/or a new product.” (p. 611). The authors accordingly imagine a social system that consists of actors, networks and institutions, which is in line with Bergek et al. (2008a) and Hekkert et al. (2007). They are, however, quite ambiguous as to whether the innovation as such, which most often has a partly technical character, should be included in the innovation system. As they put it: “We think that [this] has to be seen as an analytical choice. In reality, the results of the innovation process feed back directly into its determinants. Due to this close and critical interaction we suggest to regard the innovation itself as a part of the system, a part that is not genuinely different from other system elements except from the fact that it is the element an innovation researcher might be most interested in studying” (Markard and Truffer, 2008, pp. 599–600).

Based on Malerba’s discussion of sectoral innovation systems (Malerba, 2002), Markard and Truffer (2008a) make the important observation that the same network of agents can be involved in both production and innovation. While conceding that “The distinction between production systems, incremental innovation processes and radical innovation structures is mostly not very clear-cut” (Markard and Truffer, 2008, p. 610), the authors also argue that the concept of TISs should be restricted to radical innovation processes, and not used to describe and analyze neither production nor incremental change. In addition, they highlight that this implies that “a TIS begins at some point in the formative phase and ends at some point in the growth phase” (Markard and Truffer, 2008, p. 611).

Markard and Truffer (2008a) also discuss how far a TIS reaches given this system purpose and arrive at a position which adopts a narrow system boundary that only includes structural components that are closely related to, and supportive of, the innovation process. The authors argue that a broader boundary that include everything that influences the innovation process (system A) is problematic since “including ‘all important factors’ means that no distinction is made between those influences, which are closely related to the innovation process and part of potential feedback loops, and those that are not affected by the innovation process” (p. 601), and that including also negative influences would make the concept “degenerate into a merely descriptive

bracket for very different processes and structures. As a consequence, it would loose almost every explanatory power.” (Markard and Truffer, 2008, p. 610). This stands in sharp contrast to Bergek et al. (2008a) and Hekkert et al. (2007), who include most, if not all, factors that influence the innovation process. Markard and Truffer (2008) thus seem to identify TIS as a system D or E.

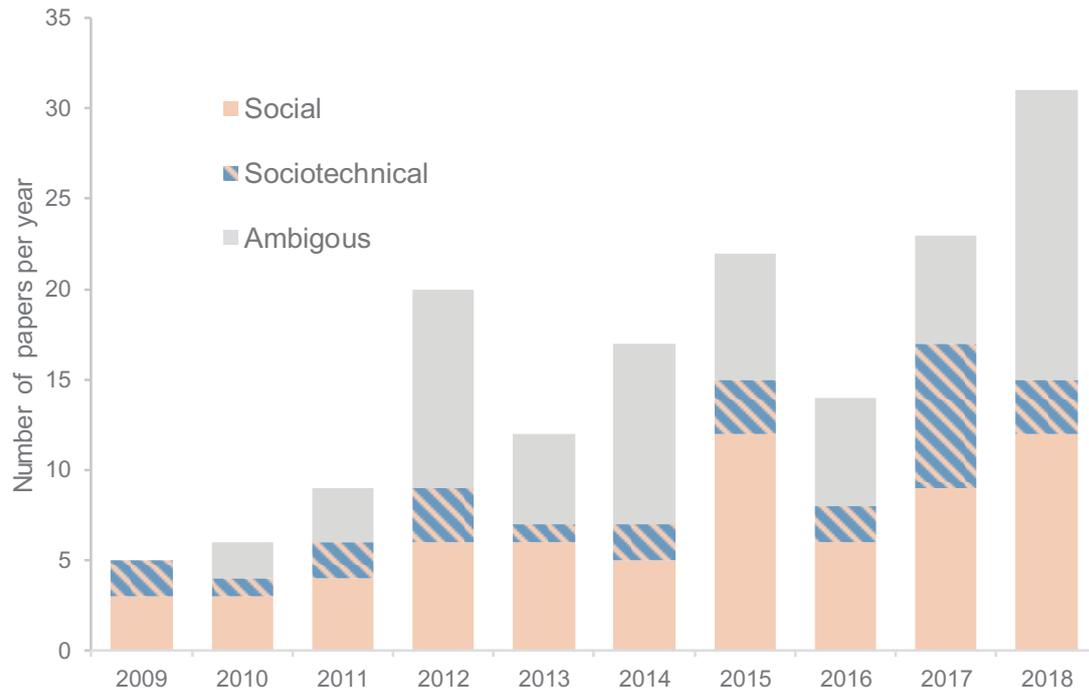
To conclude, the foundational literature is not only vague but also points in different directions when it comes to some of the basic tenets of the TIS framework (Table 1). The dominant viewpoint seems to be that TISs consist of social structures, although the idea of including technical components is introduced. Some contributions clearly state that the TIS purpose is to carry-out innovation processes, or more generally, to influence the innovation process (system A), but most are ambiguous as to whether the utilization of their results is included as well (system B). Two contributions suggests that the system boundary of the TIS is further narrowed to technology centred structures (system D or E). These differences also give rise to ambiguities when it comes to the more precise definition of functions, which is the key concept used to analyze change.

### 3.2 A growing literature and four areas in need of clarification and increased rigour

The publications by Carlsson and Stankiewicz (1991), Bergek et al. (2008b, 2008a), Hekkert et al. (2007), and Markard and Truffer (2008a), have become the foundation for a steadily growing research field that applies and advances the TIS framework. A search in the article database Scopus in the mid 2020 using the term ‘technological innovation system’ results in well over 300 publications. Empirical studies have investigated the dynamics of innovation processes related to technologies in sectors such as energy (Dewald and Truffer, 2011; Foxon et al., 2010; Jacobsson and Karltorp, 2013; van Alphen et al., 2009; Wieczorek et al., 2013), transport (Hillman and Sandén, 2008; Kivimaa and Virkamäki, 2014; Markard et al., 2009; Suurs et al., 2010), wastewater treatment (Bichai et al., 2018; Binz et al., 2014, 2012) and agriculture (König et al., 2018; Sixt et al., 2018), to mention a few. The TIS framework has not only come to occupy a central position in the sustainability transitions community (Köhler et al., 2019; Markard et al., 2012), but also been tested and applied by government agencies that develop and implement national technology policies (The Swedish Energy Agency, 2014).

Since the foundational publications, many aspect of the TIS framework have been further developed. Particular attention has been given to the role of geography, the influence of contextual structures, and the micro-level foundation. Scholars have also refined the understanding of the empirical characteristics of several functions, explored their influence on innovation dynamics, suggested new processes to complemented existing typologies (Binz et al., 2015; Kivimaa and Kern, 2016; Perez Vico, 2014). However, the basic tenets of the framework have remained intact and consequently a number of fundamental ambiguities and contradictions have been left largely unresolved.

First, the literature is contradictory with regards to whether TISs are social or sociotechnical systems. While some scholars include technology or physical artifacts as structural components (Mäkitie et al., 2018; Sandén and Hillman, 2011; Stephan et al., 2017; Suurs and Hekkert, 2009; Wieczorek and Hekkert, 2012), as suggested by Bergek et al. (2008b), others maintain a social perspective (Binz et al., 2014; Coenen et al., 2012; Dewald and Truffer, 2011; Gosens et al., 2015; Musiolik et al., 2012; Quitzow, 2015). In fact, some researchers even switch between the social and sociotechnical perspectives in different publications, which suggests that the TIS community considers the inclusion of technical structures to be an analytical choice rather than a fundamental part of the analytical framework. However, a fair share of all publications are unclear, ambiguous or even contradictory, describing the system as social and sociotechnical in the same paper. Figure 3 provides an account of to what extent it is possible to discern if 159 TIS papers published between 2009 and 2018 define a TIS as a social or sociotechnical system. With an increasing number of papers, there is no concensus and the level of clarity in not increasing.



**Figure 3. A quantitative assessment of how TISs are defined in terms of the included types of structural components.**

Second, there is considerable ambiguity when it comes to the purpose of a TIS. After the foundational publications, clarifications have been made along two opposite lines of reasoning.<sup>5</sup> On the one hand, Sandén and Hillman (2011)<sup>6</sup> propose that the purpose of TISs is to create a new production and consumption system for a specified focal product (which is in fact how they define technology), and also suggest that a TIS can be understood as a model of change rather than as a real-world system. While the latter part of their proposition has not received much attention, a number of scholars seem to agree that TISs create production and consumption systems (TIS as system A). On the other hand, several contributions describe TISs as systems that involve both innovation, production and consumption, even though this choice is rarely motivated and fully explained. Examples include Mäkitie et al. (2018), who describe a TIS as “a nascent industry” (p. 814) (i.e. system B), as well as numerous contributions that structure TISs as value chains and thus indicate a similar view (Andersson et al., 2018; Stephan et al., 2017) See Table 3 for a few typical examples from both categories.

Besides these clarifications, our review of 159 papers published between 2009 and 2018 reveal that the vast majority of TIS studies refrain from specifying the system purpose beyond references to the foundational literature (which is ambiguous as discussed in the previous section). This means that we cannot know what function scholars actually imagine that a TIS fulfills in its broader context. Nevertheless, much of the literature seems to identify TIS with an emerging production and consumption system (that also involved in innovation and its own growth). To begin with, the way conceptual development related to context is carried-out offers some insights. For example, the contribution by Bergek et al. (2015) describe a range of structures that influence the innovation process are localized to the context of the TIS, not within the TIS. This clearly disqualify TIS from being a system A, making it either a system B, D or E. In addition, it seems that the term TIS can in many empirical studies be exchanged for industry or sector, without any apparent loss of meaning, and arguably with a clearer exposition as a result.

**Table 3. Examples of TIS interpretations that are in line with System A and System B defined in Section 2.1.**

<sup>5</sup> In addition, we note that the proposition that TIS should be reserved for radical innovations seems to have been abandoned by its proponents, since Markard et al. states that “The TIS concept covers both emerging and mature technologies.” (2016, p. 332)

<sup>6</sup> This publication in fact draws upon ideas presented in a report published already in 2005 (Sandén and Jonasson, 2005).

<b>System A: A TIS is a system of structures that influence innovation activities – it creates, expands and transforms an industry</b>	<b>System B: A TIS is a system of structures that perform production and consumption activities – it constitutes an emerging industry</b>
<p>"This means that the innovation process takes place within a system comprised of different actors who contribute to the overall goal of the innovation system: the development and diffusion of the innovation in question." (Rojon and Dieperink, 2014, p. 395)</p>	<p>"Van de Ven and Garud (1989, p. 203) and de Fontenay and Carmel (2001, p. 26) appropriately describe the formative stage as one where accumulation of many small changes begins to form a new entity, industry or TIS." (Jacobsson, 2008, p. 1494)</p>
<p>"Recent insights suggest that TIS facilitates the creation of markets and the development of entrepreneurial activities around technologies by fulfilling key activities and processes.... It follows that diffusion of technologies would be enabled by improved functional performance of the relevant TIS." (Tigabu et al., 2015, p. 332)</p>	<p>"[...] we apply a value-chain perspective to TISs. We include all (vertically and horizontally) related parts of the value chain into our conceptualization of a TIS, which represents an integrated approach. This approach proposes a clear definition of the boundaries of a TIS that considers the fact that many technologies are developed, produced and used across sectors, and allows TIS to be delineated from sectoral systems of innovation." (Stephan et al., 2017, p. 710)</p>
<p>"The TIS is the systemic description of how [a production system] emerge, develop and expand." (Andersson et al., 2017, p. 143)</p>	<p>"Recent studies have shown that established sectors can indeed exercise significant influence on an emerging TIS, understood here as a nascent industry." (Mäkitie et al., 2018, p. 814)</p>
<p>"The expected results of technological innovations systems are an improvement of or a new product, process development activities, and market development or service improvement activities." (Sambo and Alexander, 2018, p. 3)</p>	

Third, the system purpose is rarely translated to boundaries that clearly define the technology in focus. As the foundational literature made clear, it is not sufficient to specify a focal product or knowledge field, without also determining the breadth of included applications (Bergek et al., 2008a; Markard and Truffer, 2008). This argument is extended and generalized by Sandén and Hillman (2011), who show that defining a technology implies specifying a bundle of alternative value chains that describe the production and use of a focal product. Nevertheless, the literature most often employs quite vague technology definitions. Most scholars seem to find it sufficiently clear to set boundaries by referring to a product, such as wind power, without specifying which production techniques and applications, as well as what parts of their value chains, that are included in the object of study. This is of course problematic since it is very different to analyze the emergence of an industry that produces wind power plants, an industry that produces wind power (i.e. electricity), and a market that uses electricity. In addition, it has implied that the literature tends to portray innovation as a one-dimensional diffusion process, while largely neglecting the multi-dimensional characteristics of its results (Yap and Truffer, 2018).

Fourth, even though the concept of functions has proven useful in empirical studies, it is unclear how it relates to other parts of the TIS framework. Functions are often described as sub-processes to the overarching innovation process, and seen as a way to decompose the system purpose (i.e. function) into a typology that enables analyzing system dynamics and contextual influence. Some also suggest that functions influence the build-up of system structure. But since the purpose and boundaries of TISs are ambiguous, it remains unclear whether the change process captured by functions occurs within the system, among structures in its context or between context and system. Furthermore, it is rarely made clear whether functions should be understood and measured as causes or effects of structural change.<sup>7</sup> This has led to confusion about how to classify data and consequently

<sup>7</sup> Even if causality is circular, i.e. structures and processes are linked in loops of causality, it matters if a type of process and theoretical construct such as 'function' is defined based on a well-defined effect, that may have many causes, on a well-defined cause, that may have many effects, or are only labels of ill-defined processes with many causes and effects. In the worst case, different (implicit) definitions of what a function represents exist in the same text.

about the meaning of different functions. For example, the function “market formation” is often indicated by regulative rules that stimulate demand (cause), and more seldom by the sales transactions themselves or the entry of users (effect). On the other hand, “knowledge development” is typically captured by patent or paper publications (effect) rather than R&D funding (cause), which instead is captured by “resource mobilization”. In addition, most functions typologies used in the literature, including the ones presented in foundational contributions, are derived inductively from a broad literature, rather than deductively from a coherent model, and therefore arguably have considerable overlaps and fail to show that categories are exhaustive (in the sense that the functions together describe all aspects of the innovation process).

In fact, we would even argue that there is no convincing conceptual distinction between structure and functions. It has not been made clear why a system attribute such as networks is treated as a structural component, while markets are discussed as the result of a functional process. A possible distinction could be based on how stable different attributes are over time, but it seems difficult to motivate why actors should be regarded as more enduring than the physical infrastructure that results from resource mobilization. Functions may also be understood as more emergent properties of the system, but there are no clear reasons to view markets as more emergent than networks. To us, this suggests that the functions concept has been used to add categories and corresponding datasets that were not established in lists of structural components often used in the innovation systems literature. Another possible explanation is that functions initially were intended to be a link between the structure of an innovation system categorized as a system A and the change they produce in a different system (System B). But due to the real world overlaps between these systems and the lack of clear systemic expositions in foundational papers, this got lost already at the outset.

#### 4 (Re)introducing technological systems as sociotechnical and technology-oriented objects of study

The previous section highlighted considerable ambiguities and contradictions in how systems concepts are used to study emerging technologies in the sustainability transitions community. It is apparent that investigations can depart from system definitions that include social or sociotechnical structures, unified by different purposes or functions. While these are all valid analytical approaches that are likely to highlight different aspects, we believe that they are sufficiently different to warrant conceptual distinction. Moreover, we see reasons for transition scholars to adopt a specific perspective for studies of emerging technologies.

To begin with, we argue that the inclusion of technical structural components is important. One reason is that physical artifacts are highly involved in interactions that govern both innovation, production and consumption. Just like social institutions, the material aspects of technology are not only created in the interaction of agents, but also constitute factors that enable and constrain their behaviour.<sup>8</sup> And even though we acknowledge that some aspects of this interaction can be captured through the immaterial aspects of technology, as suggested by Jacobsson and Bergek (2011), we believe that important perspectives on the innovation process may pass unnoticed if physical artifacts are not included as structural components in the object of study.<sup>9</sup> It is also difficult to incorporate a comprehensive conceptualization of the results and consequences of the innovation process without adopting a sociotechnical perspective. In particular, the impact of technological knowledge on the natural environment is clearly mediated through physical artifacts.<sup>10</sup>

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<sup>8</sup> We thus deviate from the ontological foundation of the MLP (Geels, 2002), which focuses on institutional structures, and agree with recent criticism against its neglect of material structures (Svensson and Nikoleris, 2018). At a more fundamental level, it can be noted that we reject Giddens (Giddens, 1984) structuration theory, in favor of a transformational model inspired by critical realist thinking.

<sup>9</sup> As noted by Edquist (2004), actors are the players and institutions are the rules of innovation systems. The question is what corresponds to the equipment. Consider the game of ice hockey – only knowing about the players and the rules will not allow you to understand, reconstruct or predict what will happen in the game. To do that, you have to know about the equipment and its characteristics. After all, the game would be very different if the players wore sandals instead of skates, held rackets rather sticks, and ran around on gravel instead of effortlessly gliding on well polished ice.

<sup>10</sup> This of course raises the question of whether the natural environment should be represented by, for example, ecological structural components (see Ahlborg et al. (2019) for an exploration of this socio-techno-ecological perspectives). Although conceptual development in this direction may be a fruitful topic for future research, we maintain that it is less problematic to exclude ecological structures than it is to adopt a purely social perspective.

Furthermore, when it comes to the purpose or function which unite the sociotechnical components included in the system, we believe that there are strong reasons to adopt a perspective centered on the purpose of the technology in focus, while including all structures that can be considered “specific” to this technology. This implies that the system ought to include structures that perform production and consumption activities as well as structures that both influence and are influenced by innovation activities. To begin with, delineating the object of study in this way shifts the focus from the creating to the created, which complements the scrutiny of innovation dynamics with attention to its consequences. This is arguably more in line with the overarching ambition of sustainability transitions research, whose interest lies not in blindly stimulating technological innovation, but in shaping change processes to promote specific outcomes. In this respect, a technology-oriented perspective highlights the multidimensional nature of sociotechnical change by including emerging industries and markets in the system, rather than treating them as an outcome of a system that only captures structures that perform innovation activities. This in turn enables a closer link to the equally multidimensional objectives that policymakers and other actors aim to achieve. A technology-oriented perspective also constitutes an important step away from the outdated emphasis on growth and expansion, and embraces an attitude that highlights directions, configurations and shapes as well as their consequences for society and the natural environment. In addition, it may, as we will see in the next section, facilitate efforts to build more rigorous conceptual models of sociotechnical change.

To operationalize this sociotechnical and technology-oriented perspective, we propose that sustainability transitions research on emerging technologies should adopt what we refer to as *technological systems* as objects of study.<sup>11</sup> Importantly, this concept should not be confused with the way Carlsson and Stankiewicz (1991) use the term. But as we will see, our definition of technological systems is quite in line with how it is used by scholars such as Hughes (Hughes, 1987). If the term “technological innovation system” is used in parallel, to avoid confusion we suggest that it should exclusively refer to the theoretical model that describes the emergence, development and transformation of a technological system (and not the technological system itself).<sup>12</sup> In the following, we will define and elaborate on the characteristics of technological systems, propose methodological guidelines for applying this construct to empirical investigations, and show how it can be used to analyze change.

#### 4.1 System definition and purpose

A sociotechnical and technology-oriented perspective on technological innovation calls for a system definition that includes both social and technical structural components, which are unified by a purpose related to the technology of interest. We therefore define technological systems as follows:

*A technological system is as a set of social and technical structures, that perform the function of a specific technology, and that exist in a given spatial region and time period.*

The purpose of a technological system is accordingly to perform the function of a specific technology. In our conception, this function has two elements. On the one hand, it includes the production and consumption of a focal product, which in fact defines the technology. On the other hand, it includes an autopoietic element that sustains and develops the system’s ability to create and use the focal product. This latter element corresponds to activities carried-out by technology-specific structures that both influence and are influenced by the innovation

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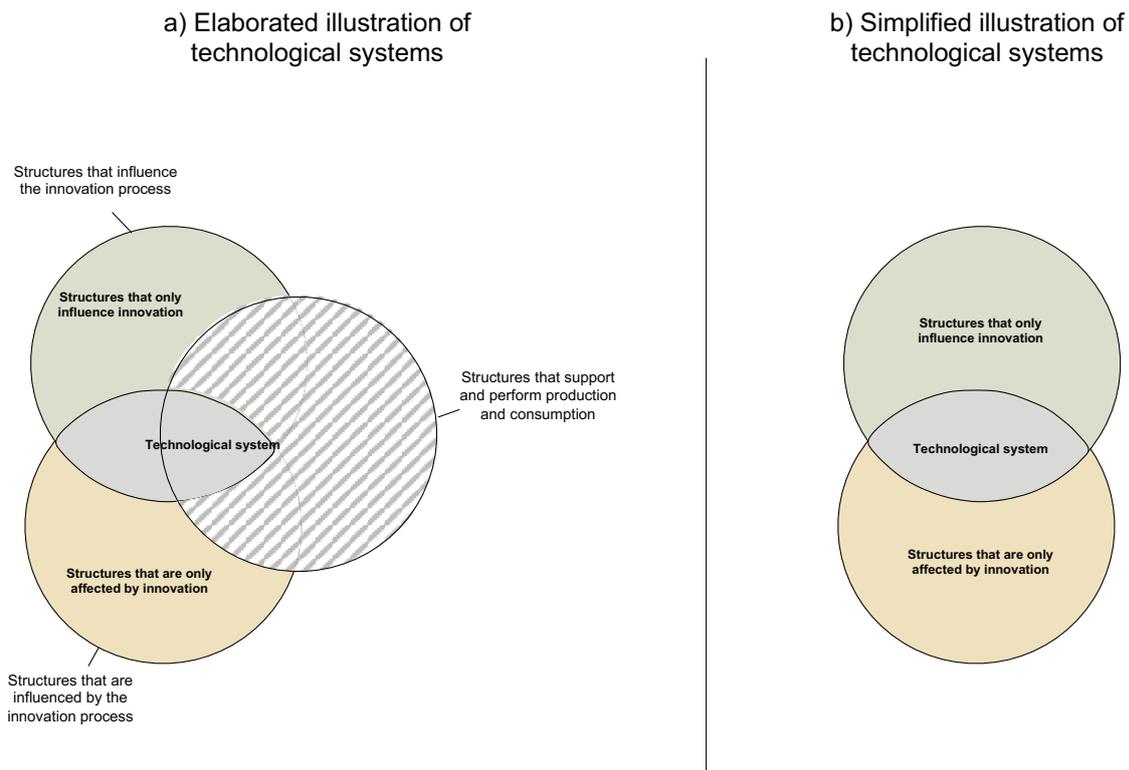
This is because ecological structures can, to a large extent, be conceptually transformed into physical artifacts as they are brought into sociotechnical interactions.

<sup>11</sup> The reason for choosing the term technological systems rather than sociotechnical systems, which probably has a similar meaning for many scholars, is threefold. First, it highlights that the starting-point when defining the system is a technology – that is, a process – rather than a set of sociotechnical structures, even though the system certainly consists of the latter. Second, it suggests that the focus is on a specific technology, rather than an industry or economic sector. That said, the latter can certainly be defined as a single rather than a collection of technologies, but this is uncommon in the literature. And third, it indicates that the delimitation to social and technical structures is an analytical choice and also paves the way for an extension of the construct towards including the natural world as well.

<sup>12</sup> One might, however, want to abstain from discussing two different types of “systems” in fear of confusing a broader audience.

process. These structures may engage in production and consumption activities as well, but also play a role that is limited to how such activities develop over time (i.e. innovation).<sup>13</sup>

Returning to the framework presented in Section 2.1, the purpose of technological systems thus corresponds to the shaded segments in Figure 4a. It should be reiterated, however, that the striped segments may in fact not exist, or at least be irrelevant in practice. If this is accepted, the system definition we propose is in fact the same as the System E defined in Section 2.1, which allows for the more simplified illustration presented in Figure 4b. The simplified illustration highlights two important aspects of technological systems. First, it shows that it is a construct that explicitly links the innovation process to its outcomes. Second, it may serve as a starting-point for efforts to build more rigorous models of sociotechnical change. This is because the different segments can be linked to attributes of such models; structures that only influence innovation are independent variables, structures in the technological system are state-variables of the model, and structures that are only affected by innovation are dependent variables.



**Figure 4. Technological systems as constructs that capture structures that support and perform production and consumption as well as structures that both influence and are affected by the innovation process. Figure 4a presents an elaborated version while Figure 4b presents a simplified version. Based on Figure 2.**

It should be emphasized, however, that the fact that technological systems have a purpose does neither mean that actors in the system necessarily share or are even aware of this purpose, nor that they, and other system structures, play a supporting role with respect to the technology in focus. On the contrary, some actors can have different objectives or be ignorant about their role in the system, while a wide range of system structures may hinder its functionality. Nevertheless, what makes the structures in a technological system form a unified whole is that their interaction, together with structures in the system context, results in the performance of a given technological function.

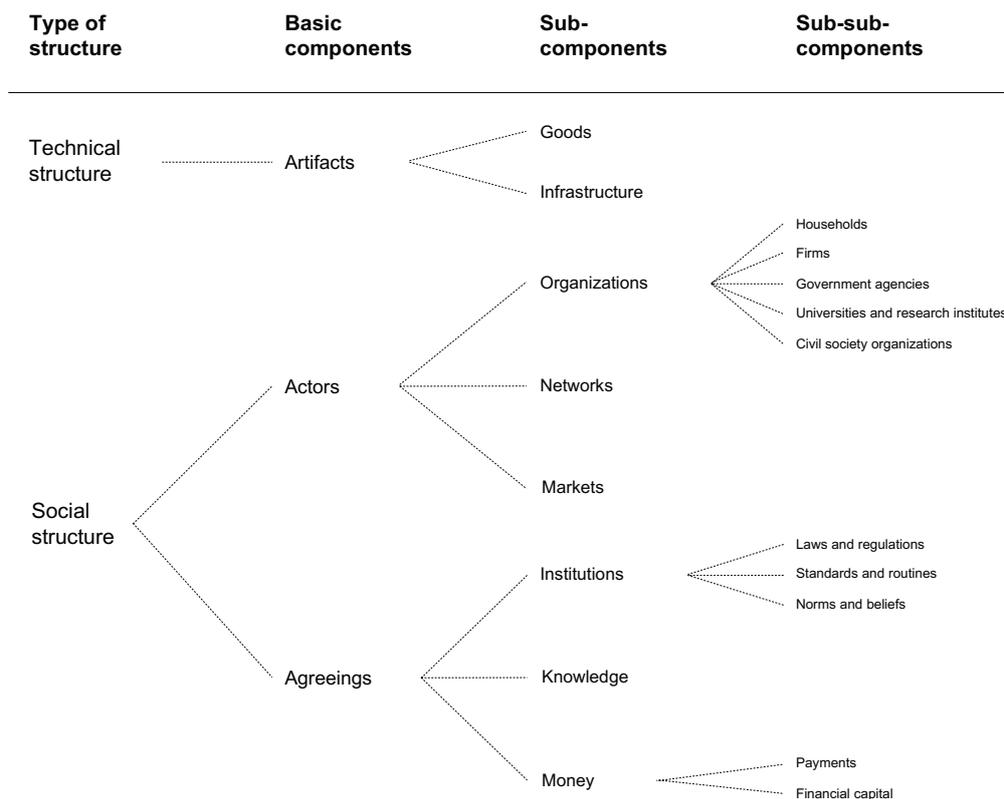
Finally, it should be noted that even though the purpose of a technological system is to perform a technological function, this does not necessarily have to occur in the real world. In contrast, the system structure may be limited to a fleeting thought or an idea scribbled down on a piece of paper, albeit one that may eventually develop into production and consumption activities that permeate major parts of the economy. The purpose of a

<sup>13</sup> Our understanding of technological systems is accordingly similar to how we tend to perceive organisms. Take a tree as an example. As a system, this organism includes cells that perform photosynthesis, cells that support this function, and cells that sustain and develop the tree’s ability to perform this function in the future.

technological system should accordingly be understood conceptually; it is used to analytically define a particular slice of reality, not to describe the real characteristics of structural interaction.

## 4.2 Structural components

As stated in their definition, technological systems consist of social and technical structures. To support description and analysis, these broad categories have to be unpacked in a way that provides a more fine grained understanding of structural components. While using slightly different sub-categories, various strands of the sustainability transitions literature seem to agree on a limited number of distinguishable components that together constitute social and technical structure (Bergek et al., 2008b; Geels, 2004; Hughes, 1987; Rip and Kemp, 1998; Sandén and Hillman, 2011; Wiczorek and Hekkert, 2012). Building on these publications, we will here propose that technological systems consist of three basic structural components – artifacts, actors, and agreeings – and also suggest a way to further decompose these into sub-components and sub-sub-components.<sup>14</sup>



**Figure 5. The basic structural components of technological systems and a possible way to decompose these into sub-components and sub-sub-components.**

To begin with, physical *artifacts* make up the technical part of technological systems. All artifacts are combinations of less complicated artifacts, and they may also be combined in different ways to form more complicated artifacts (Arthur, 2009). A possible way to decompose artifacts into sub-categories is to distinguish between *goods* and *infrastructures*, which differ in how they relate to the system function. Goods include components, sub-systems and physical products that flow through value chain process. In contrast, infrastructures include tools and equipment that support these processes as well as facilities for research, test and demonstration that rather sustain and develop their future performance. However, a given artifact can be seen as both a good and an infrastructure, depending on the technology in focus. For example, a road that gives access to remote areas is an important infrastructure for wind power technology, but rather a good for a technology focused on the production and consumption of the road as such. Note also that artifacts can be combined either

<sup>14</sup> Admittedly, the terms artifacts, actors and agreeing are quite far from the language used by the general public, policymakers and many researchers when talking about technological innovation. They may, however, be popularly translated to things, people and culture, which are concepts that can be interpreted in a reasonably similar way.

through physical links (which connect components in a machine) or flexible interfaces (such as fueling stations and cars).

The social part of technological systems fundamentally consists of human beings, either as individuals or organized in larger collectives such as organizations, networks and markets. We will refer to these as *actors*, to highlight that they are the only source of agency in sociotechnical systems. This is in line with most of the literature, even though the term agent is sometimes used either interchangeably or to refer to an individual rather than a collective. Actors can be further decomposed into the sub-categories *organizations, networks and markets*, which constitute different ways to organize human beings (Powell, 1990). In turn, it may be useful to further decompose organizations into households, firms, government agencies, universities and research institutes, civil society organizations and households. Notably, this implies that individual human beings only appear as parts of organizations.

Apart from human beings, the social part of technological systems includes agreements and shared meanings, which we will for simplicity shorten to *agreeings*. This is a formational structural component that is created as a result of the actions and interactions of actors, while also exerting a strong influence on their behavior (Giddens, 1984). While agreeings largely correspond to what is sometimes referred to as the intersubjective domain of reality, they can be embedded in the minds of actors, materialised in the structure of artifacts, and stored and transferred via symbolic systems. In other words, they have an objective and subjective representation. One way to decompose agreeings is to distinguish between *institutions, knowledge and money*. Institutions shape what actors perceive as permitted, desirable and expected, and thus exert a regulative, normative and cognitive influence on their behaviour. To increase the resolution, institutions can be further decomposed into formal laws and regulations, semi-formal standards and routines, as well as informal norms and beliefs. Knowledge is basically a justified belief or expectation about what is or will be, which makes it similar to cognitive institutions. However, a distinction can be made between the two by viewing knowledge as a higher-level fact based on cognitive institutions as lower-level building-blocks.<sup>15</sup> Money, is in its essence an agreed upon relational property between actors; a dept that has become storable and transferrable both as a physical and immaterial resource (Graeber, 2011).<sup>16</sup> It may be further decomposed into payments, that are made as goods flow through processes of production and consumption, and accumulated financial capital.

### 4.3 Applying and specifying technological systems for analytical purposes

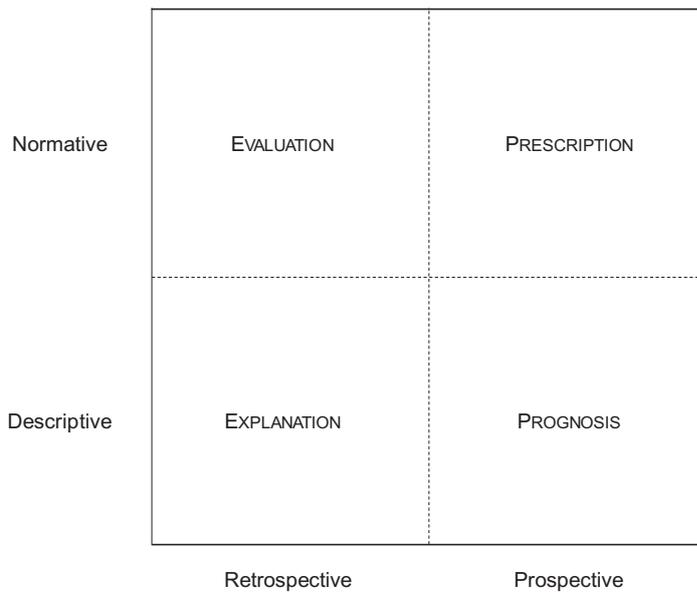
When applying the technological systems concept to empirical investigations of sociotechnical change, a necessary first step is to specify the analytical goal and scope of the study. Unfortunately, this is often lacking in the sustainability transitions literature, which at times makes it difficult to interpret and compare empirical findings.

The specification of research goal should clarify whether the study is retrospective or prospective and whether it has a descriptive or normative ambition, see Figure 6. Although there are certainly possible combinations of these types, they may serve as a useful framework when reflecting upon and describing the intention of an empirical analysis.

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<sup>15</sup> For example, while knowledge about offshore wind power describes how technical and social components can be organized to produce electricity by harnessing flows of air, cognitive institutions rather determine what meaning an actor associates with basic terms such as offshore, wind and power.

<sup>16</sup> Notably, the financial dimension has been largely absent from theoretical accounts in the TIS literature.



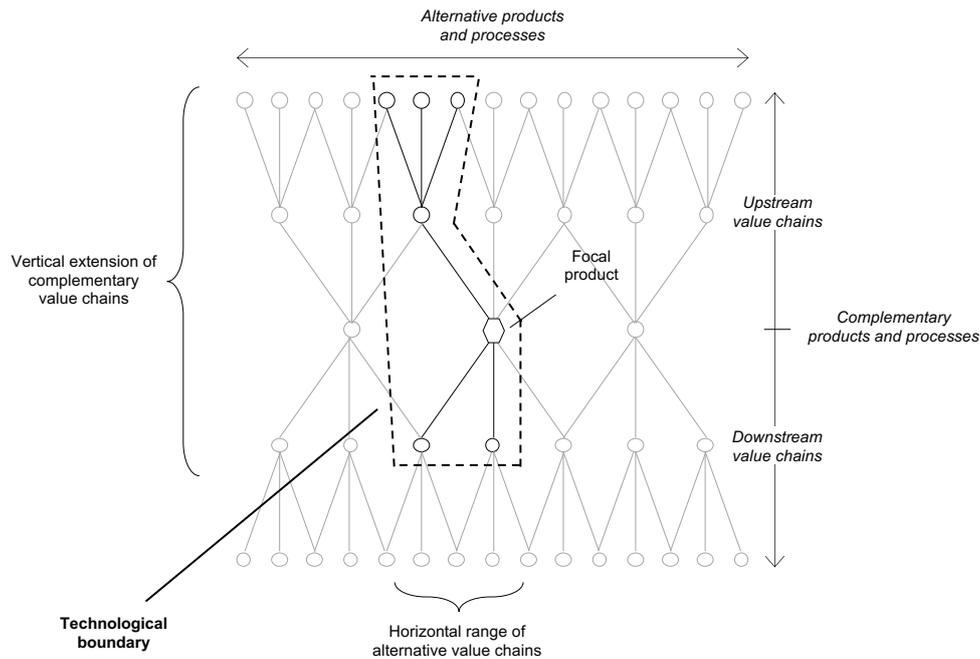
**Figure 6. Explanation, prognosis, evaluation and prescription as different research goals.**

The specification of research scope corresponds to setting system boundaries that specify a particular technological system that constitutes the object of study. This system should not only capture the technology of interest, but also be in line with the breadth and spatio-temporal focus of the study. In addition, it may be necessary to specify which parts of the system context that are taken into account, if the analysis is concerned with the dynamics of change or its broader effects. This is because many factors that influence or are affected by the innovation process are found outside the system boundary of the technological system.

#### 4.3.1 *Setting system boundaries*

System boundaries are set in technological, structural, spatial and temporal dimensions. First, a technological boundary specifies the technology in focus. Following Arthur (2009), we fundamentally understand technology broadly as a means to an end. It includes physical items like cars and pens, social constructs such as firms and organizations, and broader combinations that may include entire industries. What these things have in common is that they perform a function by organizing structures in ways that harnesses natural phenomena. In fact, this broad definition implies that nearly everything that serves a human purpose can be thought of as a technology. However, in the sustainability transitions community, the term technology is rarely used to refer to neither technical components nor entire economic sectors. Common technological domains such as offshore wind power, electric vehicles and photovoltaics rather occupy a middle-ground. At this level of abstraction, technology can be understood as the creation and use of a specific product. A first step in setting the technological boundary is therefore to specify a focal product, which may be expressed either as a good or a service.<sup>17</sup> Furthermore, since any product can be created and used in many different ways, there is a need to specify which alternative production methods and user applications that are included by the technological boundary. For example, a technological system focused on renewable electricity can include all possible ways to produce this product, or be limited to alternatives that use wind mills. In addition, since any alternative way to create and use a product involves a large, if not infinite, number of interlinked production and consumption activities, there is a need to specify which of these complementary processes that are included by the technological boundary. For example, a technological system focused on renewable electricity using wind mills may be limited to highly specific processes, such as production and assembly of towers, generators and blades, but also include less specific processes that provide general inputs such as nuts and bolts. What the technological boundary does is accordingly to specify a bundle of value chains around a focal product (Sandén and Hillman, 2011), which is illustrated in Figure 7.

<sup>17</sup> To increase the precision of this core part of the system specification, it is possible to adopt the concept of functional unit from the literature on life-cycle assessment.



**Figure 7. A technological boundary that specifies a bundle of value chains around a focal product.**

Second, a structural boundary specifies criteria for the inclusion of structural components. At one level, this boundary is given by the definition of technological systems, which limits the structure to social and technical components that perform the function of the technology in focus. As mentioned above, this implies that the included structures are specific to the technology in focus. It should be acknowledged, though, that the interconnected nature of reality implies that nothing is neither entirely specific nor completely unrelated – everything influences everything, at least over sufficiently long time scales. Consequently, the criteria for determining which structures that are sufficiently specific to warrant inclusion in the system have to be specified by the analyst.

Third, a spatial boundary restricts the system to specific region, which may be a city, county, country or even continent. Although it is possible to imagine a system that covers the entire world, spatial delimitation is unavoidable in practice. The boundary may, however, be broad and cover the entire Earth or even the part of cosmos that we have the capability to imagine.

Fourth, and lastly, a temporal boundary restricts the system to a specific time period, by defining a beginning and an ending in time. This is a choice that relates to whether analyses aim to describe and explain historical developments retrospectively or examine potential future developments prospectively. While the time period can be extensive, this delineation is also unavoidable in practice, since few observers are interested in the entire history and complete future of a technological system.

A part from these technological, structural, spatial and temporal boundaries, an additional specification determines the resolution at which the system is observed. This corresponds to setting what may be referred to as inner boundaries. While a technological system is specified by both outer and inner boundaries, the former tend to be more visible and perhaps relevant in practice since they define the reach of the object of study. In contrast, inner boundaries often appear implicitly in the choice of analytical detail.

Since technological systems interact with their context, everything in principle plays a part in how they fulfil their purpose, at least over sufficiently long time scales. This implies that system boundaries cannot be derived solely from the system purpose. There are accordingly no “correct” system boundaries, only more or less relevant and efficient ones.<sup>18</sup> In other words, the boundaries which specify technological systems are analytical choices rather than real entities.

There are two main ways to set system boundaries. On the one hand, an inductive approach derives boundaries from empirical observations. For example, if social-technical structures with some relevance for the technology in focus are confined to a particular alternative value chain, it could for some analyses make sense to restrict the

<sup>18</sup> While expanding the system boundary will always increase the understanding of a phenomenon, it requires more work both from the analyst and the receiver and interpreter of results.

system accordingly in the technological dimension. Inductive approaches to boundary-setting often aim for delineations that result in clear differences in the type of interaction that takes part *within* the system and *between* the system and its context. Although this results in boundaries that can be discovered and tested empirically, it always requires some pre-defined criteria that can be used to determine just how different characteristics of interactions have to be to merit a distinction between system and context.<sup>19</sup> While system boundaries based on inductive reasoning are informed by the empirical phenomenon under investigation, they thus remain dependent on analytical choices.

On the other hand, system boundaries can be derived deductively from logical reasoning about what is interesting and possible given the aims and resources of an investigation, without relying on empirical observations related to the technology of interest. For example, a system boundary that highlights a particular nation could be applied if an investigation aims to inform national policymaking, even if cross-country interactions are as intense as intra-country interactions. This deductive approach to boundary-setting is often motivated by time and resource constraints. Any scientific study can only investigate a small fraction of reality, and sometimes a boundary is needed only to limit the scope, even if there are no solid arguments for any particular choice at the outset of the study.<sup>20</sup>

Notably, the boundaries of a given technological system can be based on both deductive and inductive reasoning. For example, the temporal boundary can have a real character that highlights a time period of intense and interesting interaction, while the spatial boundary may be analytically defined to foreground a particular policy perspective. In fact, a single system boundary may even be based on a combination of inductive and deductive reasoning. An illustrative example is a spatial boundary derived by identifying a region with intense interactions within an analytically pre-defined country.

It is also possible to adopt multiple system boundaries, which corresponds to specifying sub-systems that cover different parts of the overarching technological system. On the one hand, this allows an analyst to distinguish different parts of a technological system for comparative purposes. On the other hand, specifying sub-systems allows an analyst to view a system on multiple levels simultaneously. This can be useful for investigations that for some reason need to cover a broad domain and yet have a particular interest in a more narrow phenomenon. In their textbook on systems science, Flood and Carson (1993) suggest that a system of interest (SOI) can be divided into a narrower system of interest (NSOI) and a wider system of interest (WSOI). For example, if a study starts with boundaries based on a particular system purpose, the analyst may find that the system is highly intertwined in a larger system and choose to split the system in a narrower and wider system of interest.

Finally, it is worth emphasizing that the boundaries which specify technological systems are not necessarily aligned with the real expanse of their structural components. For example, a technological system may in the spatial dimension be specified to cover the entire world and yet have a structure that is confined to a single country. Importantly, this also implies that the boundaries of technological systems do not necessarily change as they accumulate structural components. However, this may certainly warrant an evaluation and possible modification of system boundaries that are at least partly based on inductive reasoning. One reason to set analytical boundaries that are not aligned with the characteristics of system structure at a given point in time is that we are often interested in system growth. This implies an analytical focus on what system structure could become, rather than what it currently is. Another reason is that we may not be interested in, or lack the capacity to investigate, all structures that could be relevant for a given technology, and therefore choose to set more narrow boundaries.

#### 4.3.2 *Specifying included parts of the system context*

Since open systems interact with their context, any analysis that aims for more than static description has to take the links between structural components in the system and its context into account. Specifications of the technological systems may therefore have to be complemented by a description of contextual structures, how they influence the system, and how the system influences them in return. This creates an implicit boundary between contextual structures that are acknowledged as influential (or influenced) and the rest of the world.

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<sup>19</sup> This is why results- and process-oriented system definitions in studies of technological innovation will never be fully overlapping – although inclusion criteria may be consistent, it will be evaluated based on different purposes.

<sup>20</sup> We disagree with scholars that argue for one approach over the other, which has been the case with regards to spatial boundary setting in the TIS literature (Coenen, 2015). Our position is rather that deductive and inductive approaches to boundary-setting can, and should, be combined to fit the perspective and aim of the investigation at hand, as long as the method used is clearly described and motivated.

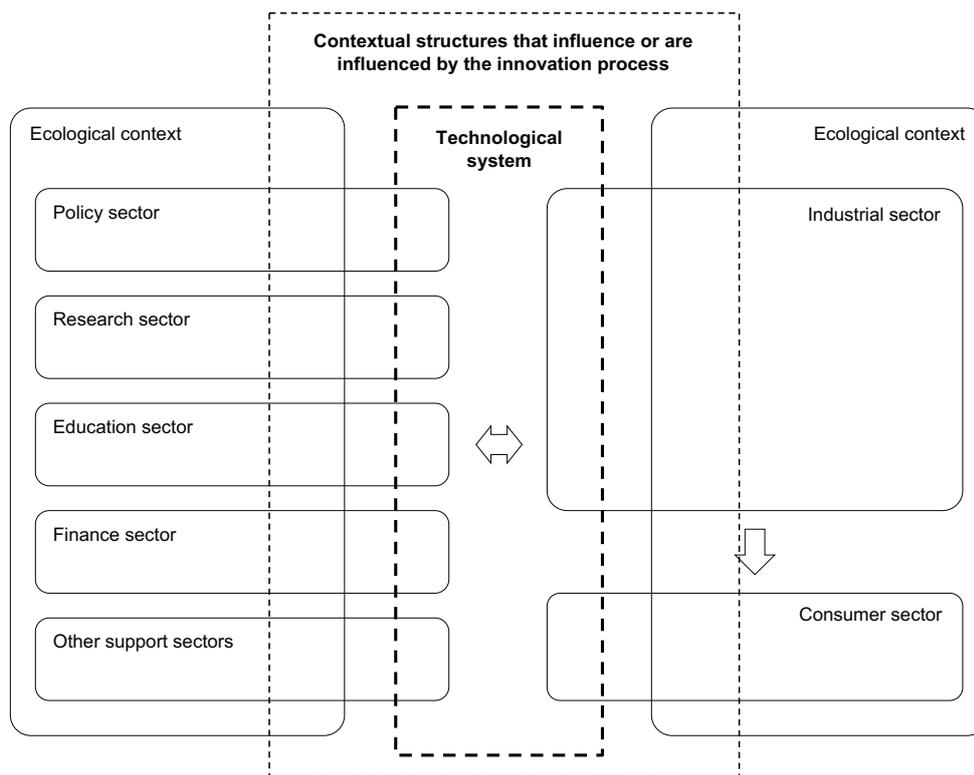
Another way to put this is that the distinction between NSOI and WSOI, discussed in Section 4.2, is always present.

Technological systems are embedded in a context that essentially consists of everything that is not included in their specification. The context thus includes structures that only influence the innovation process, structures that are only affected by the innovation process, and a more passive domain which makes up the rest of the world. To make this context more tangible, a first step is to acknowledge that contextual structures may be described as a collection of interrelated and overlapping technological systems. In fact, this was suggested in Section 4.2, where we highlighted the hierarchical nature technological systems; any technological system can both be decomposed into sub-systems and seen as a sub-system in a higher level system.<sup>21</sup>

On a high level of abstraction, it is possible to define contextual technological systems that describe the overarching sectors which are often discussed in popular language. First, there is an industrial sector, which consists of interlinked firms that produce products of different kinds. Second, there is a consumer sector where individuals and households consume products that originate in the industrial sector. Third, there are a numerous sectors that fulfill more general societal functions and thereby support (or hinder) industrial and consumer sectors. They include, but are certainly not limited to, domains such as policy, research, education, finance and media. In addition, there is a broader context of ecological structures.

Importantly, technological systems include technology-specific parts of industrial, consumer and support sectors (depending on the vertical extension of complementary value chains included by the technological boundary, a technological system may, however, exclude the consumer sector). This also highlights how the diffusion of a technology implies more than the emergence of a new product or industry; it may also restructure large parts of society.

Figure 8 illustrates how the specification of a technological system can be complemented by an additional boundary that highlights which contextual structures that are included in a particular study, either because they exert an important influence on the innovation process or because they are affected by its outcomes.



**Figure 8. A technological system that includes industrial, consumer and support sectors, together with a specification of contextual structures that influence or are influenced by the innovation process.**

<sup>21</sup> This raises the question of what, if anything, that lies beyond technological systems. One possible answer on a more philosophical note is that this domain is occupied by natural phenomena that are purely disconnected from human purposes and thus cannot be described as technological systems.

#### 4.4 Analyzing change

Whereas the previous sections have painted a quite static picture of technological systems, we will now focus on their dynamics – that is, how they changes over time.<sup>22</sup> To begin with, it is important to distinguish between two types of system dynamics. The first one is embedded in the function of technological systems and refers to the structural change which occurs as the focal product is produced and consumed.<sup>23</sup> This can be described as goods and payments that flow through the system, while other structures are maintained to continuously support this process. In contrast, the second type of system dynamics is related to how the system function changes over time. While the former is the defining feature of technological systems, this paper thesis mainly engages with the latter, since it constitutes the innovation dynamics that govern how new technologies are developed and diffused.

When conceptually explaining the characteristics of innovation dynamics, an appropriate point of departure is to acknowledge that there is a beginning. At some point, a technology first appears as an idea in a subjective mind, it is then shared, further improved and combined with other insights, and may in the end restructure reality at a planetary scale.<sup>24</sup> This corresponds to the expansion of structure in a technological system with an appropriate analytical specification. But as one technology is developed and diffused, others are often abandoned. This rather corresponds to the contraction of structure in another technological system. In addition, since technological systems are hierarchical, it is possible that one sub-system grows and another declines. In other words, technological systems may change their configuration. This can for example involve the rise and fall of alternative value chains and redistribution of activity among spatial regions. For a given technological system, growth, decline and reconfiguration of structure constitute three different aspects of their innovation dynamics. To capture all three, we will use the term structural transformation.

To describe and analyze the innovation dynamics of technological systems, the structural transformation process must be decomposed into its constituent parts.<sup>25</sup> Preferably, this should be done in a way that results in categories that are non-overlapping (i.e. mutually exclusive), while covering all aspects the process (i.e. collectively exhaustive). One approach to developing such a typology is to identify sub-processes based on their effect on different types of system structure, which is analogous to decomposing structural components into sub-categories, as was done in Section 4.4. While different typologies are likely to suit different analytical tasks, it seems appropriate at this point to move beyond the basic distinction between artifacts, actors and agreements, and rather focus on sub-categories that capture more nuance. The sub-categories are also more in line with the resolution at which different parts of the innovation process are usually discussed in the sustainability transitions literature.

In Table 4, we propose a typology of nine structural transformation processes. It is based on the sub-categories in Figure 5, except for money which is decomposed into financial capital and payments. The reason is to highlight the difference between payments that flow through the system as it performs its function, and financial capital that has a stronger link to its innovation dynamics. In fact, the mobilization of payments mirrors the flow of products across the system boundary at the end of downstream value chains, and may accordingly be seen as a form of demand. Similarly, the mobilization of goods corresponds to the supply of products to the system from its context.

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<sup>22</sup> Dynamics is a concept that describes how something changes over time, which means that the discussion in this and upcoming sections is carried-out from the perspective of the temporal dimension of technological systems. Paradoxically, this means that the dimension itself becomes implicit since it is hidden in the very notion of dynamics and change.

<sup>23</sup> In fact, this could be referred to as functional dynamics. For a TIS, which at least originally had a purpose related to innovation, functional dynamics thus describe the development and diffusion of new technology. But for a technological system, functional dynamics rather describe the use of technology.

<sup>24</sup> An obvious but useful analogy is the growth of a plant.

<sup>25</sup> One of the reasons behind the widespread use of the TIS framework in the sustainability transitions community is that it offers a set of such sub-processes, commonly referred to as functions. However, functions have been developed inductively based on literature reviews and their conceptual links to both causes and effects of technological innovation are obscure.

**Table 4. A typology of structural transformation processes.**

The transformation of...	Describes the transformation of...
...goods	...components, sub-systems and physical products, which flow through the processes of production and consumption that make up concrete product chains.
...infrastructures	...tools and equipment that support processes of production and consumption as well as facilities for research, test and demonstration.
...organizations	...households and firms that participate in production and consumption activities as well as government agencies, universities and research institutes, and civil society organizations that play a supporting role.
...networks	...settings in which organizations (and individuals) engage in different types of collaborations.
...markets	...settings in which commercial exchange of products and payments occur throughout the product chain.
...institutions	...laws and regulations, standards and routines, and informal norms and beliefs.
...knowledge	...justified beliefs or expectations about what is or what will be.
...financial capital	...accumulated dept that can be used to mobilize different types of resources and achieve various kinds of change.
...payments	...monetary flows throughout the product chain.

Although developing, testing and validating this typology is a task left for future research, it is worth noting that the processes it suggests can be aggregated to a higher level of abstraction in different ways. This may be valuable for studies that want to focus on particular aspects of the innovation process. In Table 5, we show three alternative ways to categorize sub-processes; one that corresponds to the basic categories from which they were first derived; another that seeks to align with a trichotomy of actors, resources and rules (Giddens, 1984); and a third that strives to arrive at the distinction between technology, actors, networks and institutions commonly used in the extent TIS literature. However, to the latter we have to add the financial dimension, which is difficult to associate with a specific category.

**Table 5. Three ways to categorize structural transformation processes.**

The transformation of...		
<b>...artifacts</b>	<b>...actors</b>	<b>...technology</b>
<ul style="list-style-type: none"> <li>• ...goods</li> <li>• ...infrastructure</li> </ul>	<ul style="list-style-type: none"> <li>• ...organizations</li> <li>• ...networks</li> <li>• ...markets</li> </ul>	<ul style="list-style-type: none"> <li>• ...goods</li> <li>• ...infrastructure</li> <li>• ...knowledge</li> </ul>
<b>...actors</b>	<b>...resources</b>	<b>...actors</b>
<ul style="list-style-type: none"> <li>• ...organizations</li> <li>• ...networks</li> <li>• ...markets</li> </ul>	<ul style="list-style-type: none"> <li>• ...goods</li> <li>• ...infrastructure</li> <li>• ...knowledge</li> <li>• ...financial capital</li> <li>• ...payments</li> </ul>	<ul style="list-style-type: none"> <li>• ...organizations</li> </ul>
<b>...agreeings</b>	<b>...rules</b>	<b>...networks</b>
<ul style="list-style-type: none"> <li>• ...institutions</li> <li>• ...knowledge</li> <li>• ...financial capital</li> <li>• ...payments</li> </ul>	<ul style="list-style-type: none"> <li>• ...institutions</li> </ul>	<ul style="list-style-type: none"> <li>• ...networks</li> <li>• ...markets</li> </ul>
		<b>...institutions</b>
		<ul style="list-style-type: none"> <li>• ...institutions</li> </ul>
		<b>(...money)</b>
		<ul style="list-style-type: none"> <li>• ...financial capital</li> <li>• ...payments</li> </ul>

While it is beyond the scope of this paper to develop a micro-level foundation that explains causality, it is important to highlight that the determinants of structural transformation processes are multidimensional. To

begin with, structural transformation may result from both internal creation and external mobilization. This basic distinction between endogenous and exogenous factors is central to the TIS literature, since it provides a conceptual foundation for identifying and analyzing positive and negative feedbacks in the innovation process. However, neither endogenous nor exogenous factors are evenly distributed in technological, structural and spatial dimensions. For example, the accumulation of financial capital may result from investments from various types of actors, active in different parts of the bundle of value chains, and located in different regions. As a matter of fact, this multi-dimensionality also concerns the outcomes of structural transformation processes, since it may result in different configurations. This highlights the importance of accounting for the technological, structural and spatial characteristics of structural transformation processes, both with respect to their determinants and results.

## 5 Discussion and conclusions

This paper set out to clarify the focus and improve the rigour of sustainability transitions research on emerging technologies. We first reviewed the TIS literature by using core concepts from systems thinking and showed that there are considerable ambiguities in many fundamental parts of the system definition. We then argued that the sustainability transitions community should adopt a sociotechnical and technology-oriented perspective when analyzing emerging technologies, and suggested technological systems as suitable objects of study. In the end, we elaborated on the system definition, purpose and structural components of technological systems, provided guidelines for applying the construct to empirical investigations, and showed how it can be used to analyze change.

It should be emphasized that many ideas put forward when elaborating on the technological systems concept are not uncommon in the sustainability transitions literature. In fact, our understanding of technological systems is likely to be in line with how some scholars think about TISs. However, introducing technological systems as a well-defined object of study increases clarity and creates an important conceptual distinction between innovation and technology-oriented approaches to studying sociotechnical change. This not only enables us to argue for the latter as more suitable for sustainability transitions research, but may actually benefit conceptual development and empirical investigations building on both approaches. It is, quite simply, easier to build cumulative knowledge if scholars understand and use key concepts in a similar way.

While it is beyond the scope of this paper to develop an explanatory model of how technological system change over time, we present a typology of structural transformation processes derived by decomposing structural components. By categorizing these in different ways, it is clear that they cover more or less the same aspects of sociotechnical change as common lists of functions in the TIS literature. Nevertheless, there are differences. On the one hand, our framework is slightly broader, in the sense that it covers aspects that are absent or hidden in most functions typologies. For example, we emphasize the entry, formation and development of different types of actors, which is only partly, and implicitly, covered by the function “guidance of the direction of search”. On the other hand, the function “development of positive externalities” is not covered by our typology. In our understanding, positive externalities appear when structural components are available to many actors (i.e. when resources are pooled). We choose to view this as a higher level structure that emerges from the basic structural components, which makes it similar to properties such as the extent to which processes are specialized or shared and competing or complementary. A potential development of our framework is to introduce complementary meta-processes that describe how these high-level structures emerge.

What is perhaps most important about the introduction of structural transformation processes, however, is that they establish a clear link between structures and processes involved in technological innovation. This in turn paves the way for conceptual development that may eventually result in a theory, or at least a rigorous model of sociotechnical change.

To conclude, we hope that the ideas presented in this paper will contribute to clarifying the focus and improving the rigour of sustainability transitions research on emerging technologies and open a number of interesting avenues for continued conceptual development.

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