THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Shape it until you make it

A conceptual foundation for efforts to analyze and shape technological innovation

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Cover by Linn Schildt:

The drawing illustrates three plants that can be found in the author's (and artist's) kitchen. They originate from the same seed. And they show that change is not only about growth and expansion, but also about directions and configurations.

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To all the beautiful forgotten souls

That remain hidden in shadows

Cast by the glowing giants

On whose shoulders

they tell us

we stand

ABSTRACT

These are times of accelerating climate change and mass extinction of species on planet Earth. We are in the midst of an ecological crisis that will have profound consequences for human society and its natural environment. While the conditions for life have changed abruptly in the past, the current situation is characterized by the increasing power of a single species. Human beings are not only to blame for the unsustainable practices that brought us here, but also capable of harnessing their combined ingenuity to develop technology that may reduce environmental impacts and provide additional benefits for society.

At the same time, the answer to the ecological crisis and other grand challenges is not found in the blind expansion of new technologies. Our success in accomplishing social and environmental objectives rather depends on how, where and when innovation influences patterns of production and consumption. This calls into question the focus of academics and policymakers on stimulating technological innovation. And it highlights the need for analytical tools that can be used to explore how policymakers and other actors may shape the direction of change.

The research presented in this thesis therefore aims to develop a conceptual foundation for analyzing and shaping technological innovation. This effort draws on three qualitative case studies that investigate emerging renewable energy technologies from a Swedish perspective. The thesis is situated in the sustainability transitions research community and takes the literature on technological innovation systems as a theoretical point of departure. However, the research adopts a critical perspective and gradually departs from the core concepts used in this literature, over the course of a learning process that unfolds in five appended research papers.

In the end, the thesis proposes the *technological systems framework* as a set of concepts that offers a multidimensional perspective on the dynamics and outcomes of technological innovation. It also presents empirical findings that demonstrate different development trajectories, reveal some of their underlying dynamics and highlight policy implications. This will hopefully contribute to an ongoing shift in academia and politics – from stimulating the expansion of new technologies, to shaping the direction of change.

Keywords: Technological systems; Sociotechnical systems; Technological innovation systems; Sustainability Transitions; Sociotechnical change; Technological innovation; Sustainable innovation; Technology Assessment; Innovation policy

LIST OF APPENDED PAPERS

The thesis is based on the work presented in the following appended papers:

I Andersson, J., Perez Vico, E., Hammar, L., Sandén, B.A., 2017. The critical role of informed political direction for advancing technology: The case of Swedish marine energy. Energy Policy 101, 52–64.

II Andersson, J., Hellsmark, H., Sandén, B.A., 2018. Shaping factors in the emergence of technological innovations: The case of tidal kite technology. Technological Forecasting and Social Change 132, 191–208.

III Andersson, J., Hellsmark, H., Sandén, B.A., 2020. Photovoltaics in Sweden – a failed innovation system? Under review in Renewable and Sustainable Energy Reviews.

IV Andersson, J., Hojckova, K., Sandén, B.A., 2020. Clarifying the focus and improving the rigour of sustainability transitions research on emerging technologies, in: Proceedings to the 11^{th} International Sustainability Transitions Conference 2020 in Vienna, Austria.

V Andersson, J., Hellsmark, H., Sandén, B.A., 2020. Unpacking the directionality of technological innovation. Submitted to Environmental Innovation and Societal Transitions.

The thesis author has made the following contributions to the appended papers:

In Paper I, Andersson designed and performed the empirical investigation in close collaboration with Perez Vico, and with support from Hammar, for the purposes of a book chapter. The study was then elaborated and used as a basis for a research paper written by Andersson, with support from Perez Vico, Hammar and Sandén. In Paper II and Paper III, Andersson designed and performed the empirical investigations, reviewed literature, developed conceptual frameworks, performed data analysis and wrote manuscripts. Hellsmark and Sandén supported the research process in continuous discussions and commented on draft manuscripts. In Paper IV, Andersson, Hojckova and Sandén collaboratively reviewed literature and developed conceptual ideas, drawing on preliminary versions of this thesis as well as unpublished work by Sandén. Andersson wrote the final manuscript with support from Hojckova and Sandén. In Paper V, Andersson reviewed literature, developed conceptual ideas and wrote the final manuscript. Hellsmark and Sandén supported the research process in continuous discussions, commented on draft manuscripts and wrote two of the illustrating empirical examples.

OTHER PUBLICATIONS BY THE AUTHOR

Andersson, J., 2017. On national technology policy in global energy transitions: The case of Swedish marine energy. Licentiate thesis. L2017:089. Department of Technology of Management and Economics, Chalmers University of Technology, Gothenburg, Sweden.

Andersson, J., Hellsmark, H., Sandén, B.A., 2016. Aligning innovation policy with the spatial nature of socioeconomic benefits: An analysis of the tidal kite technology innovation system from a Swedish policy perspective, in: Proceedings to the 7th International Sustainability Transitions Conference in Wuppertal, Germany.

Perez Vico, E., Andersson, J., Hammar, L., 2015. The importance of political direction: An analysis of the Swedish marine energy innovation system, in: Proceedings to the 6th International Sustainability Transitions Conference in Brighton, UK.

Perez Vico, E., Andersson, J., Hammar, L., 2014. Marin energi, in: Hellsmark, H., et al. (Eds.), Teknologiska innovationssystem inom energiområdet: En praktisk vägledning till identifiering av systemsvagheter som motiverar särskilda politiska åtaganden. ER 2014:23. Swedish Energy Agency, Eskilstuna, Sweden.

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When I look back at the five years of research that resulted in this thesis, I am pretty sure that it will not be the hardship, anxiety and doubt that comes to my mind. What I will remember is the warm, welcoming, dedicated and intelligent research environment that I was privileged to be a part of. You are all amazing people. And I will miss you dearly. Many of you have been important for me during these years. Too many to mention. Too many to give the personal recognition they deserve. But a select few have taught, inspired and influenced me in a very special way.

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But at the end of the day, there is only one person who really understands what lies beneath these pages.

Linn – I love you from the very bottom of my heart! You endured the hardship, the anxiety, the anger, the frustration, and the panic. You stayed strong, when I was weak. You were a light that kept me sane, when my mind pulled me into darkness. I may have written this thesis, but you gave me the strength to do it. I am leaving this ridiculous world of abstractions now. I am coming back to you. And I want us to write new chapters, about real things, together...

PREFACE

I have always been drawn to heights.

As a child, I used to run away from kindergarten to a nearby hill, lay down on a perfectly shaped rock, and absorb the city at my feet. It made me calm in an almost spiritual sense.

As I grew older, the hill became a remote mountain. I climbed it as much as I could. Because it gave me perspective. And the weightless feeling of surrendering to gravity on the way down showed me the secret to happiness. It still does.

As I embarked on my doctoral studies, the mountain transformed. But the journey remained remarkably similar. Because research is also about reaching new heights and gaining perspective. It is about looking far into the distance and seeing what no one has seen before. It is about turning around in time and enjoying the journey back to another reality. And it is about telling the world about the experience.

When I started doing research, I had a rough map that showed me the way towards a summit that promised a new perspective and yet seemed to be within reach. But as I set out towards it, my eyes kept wandering in another direction. I saw a different summit that could make me see further. And even though it was less chartered, much higher and covered in mist, I could simply not resist its allure.

I never made it to the summit. But at least I turned around in time to tell you what I saw from its sidelines. It is not much. Because the descent took its toll. Still, I hope that I can guide the next person in line – towards a better route than the one I attempted, or towards a different summit altogether.

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CHAPTER 1 – INTRODUCTION

These are times of accelerating climate change and mass extinction of species on planet Earth (IPBES, 2019; IPCC, 2018, 2014). This is the context in which this thesis is written and the reason it strives to support efforts to shape the direction of change towards a future where human society thrives within the limits set by our one and only planet.

In this introductory chapter, I will first present the background of this research by describing its context, motivation, theoretical point of departure and empirical focus. I then introduce the precise purpose and aim of the thesis as well as a set of questions that have guided the underlying research. In the end, I summarize the contributions of the five appended research papers and present an outline of the following chapters.

1.1 Background

Human society has always had an impact on its natural environment (Grübler, 1998; Ponting, 2007). In our search for food, shelter, pleasure and meaning, we protect, support, harness, change, pollute and even destroy nature. This was true when humans lived as hunters and gatherers in small groups, and it remains true in the industrialized and globalized world of today. But while human society used to play a small role with respect to the global environment, our ecological footprint has gradually increased (IPBES, 2019; IPCC, 2014; WWF, 2018). Drawing on a unique ingenuity and imagination, we have been able to think and act as a collective, build upon previous achievements, and engage in ever more complex ways of reaching our goals (Harari, 2014). This process of technological innovation has not only enabled us to take advantage of nature in new ways, but also propelled a massive expansion of human society. As we enter the Anthropocene, human civilization is a dominant force of environmental change on planet Earth (Steffen et al., 2007; Waters et al., 2016).

Sadly, the great powers of human society have not been matched with a similar degree of responsibility. Throughout history, we have time and again destroyed ecosystems, driven species extinct and depleted natural resources (Grübler, 1998; Ponting, 2007). This systematic degradation of the environment has forced us to expand the human enterprise further. And when this has been out of reach, ecological and societal collapse have often gone hand in hand. What makes current times extraordinary, however, is that environmental degradation is a global phenomenon that cannot be escaped through continued expansion. We cannot move away from warmer temperatures, rising sea levels and more extreme weather events (IPCC, 2018, 2014). And we cannot leave the ongoing mass extinction of species behind and expand into pristine lands (IPBES, 2019). Instead, we have to find a way to thrive within the limits set by our one and only planet (Jenner et al., 2012; Rockström et al., 2009).

To avert the ecological crisis and move towards this harmonious state of sustainability, human society has to leave many extractive and polluting technologies behind (IPCC, 2018, 2014; Rockström et al., 2017; Sachs et al., 2019). While this is likely to involve new goals, changed priorities and reduced consumption, we also need to develop and diffuse new technologies that can meet the needs of a growing population with an acceptable environmental impact. Achieving sustainability is accordingly not about stopping technological innovation, but rather shaping the direction of change towards a purpose that goes beyond the expansion of human society.

While it is an indisputable fact that the development of human society, its technologies and their impact on nature can unfold in many directions, innovation has ever since the advent of the scientific and industrial revolutions often been investigated and promoted as a tool for achieving economic growth – an objective that used to be largely uncontested among mainstream economists, industrialists and policymakers (Stirling, 2009). But with the emergence of a global discourse around the limits to economic growth (Meadows et al., 1972) and the need to achieve a more sustainable development (WCED, 1987), and later in relation to increasingly urgent grand challenges such as climate change (IPCC, 2018, 2014) and biodiversity loss (IPBES, 2019), a different paradigm has slowly gained momentum. Researchers and policymakers around the world are gradually adopting a more pluralistic conception of innovation, which acknowledges the existence of different development trajectories and highlights their consequences for a multitude of commonly shared, and contested, objectives in social and environmental domains. This ongoing paradigm shift is demonstrated by the establishment of global sustainable development goals (UN, 2015), the emergence of innovation policy approaches that aim for more specific directions of change (Diercks et al., 2018; European Commission, 2020; Mazzucato, 2018; Vinnova, 2019), and the development of new theoretical frames through which to describe and analyze the dynamics of innovation (Van Den Bergh et al., 2011).

In this context, the literature on sustainability transitions has gained prominence as a source of conceptual frameworks, empirical insight and policy advice. Transitions scholars are interested in fundamental shifts towards more sustainable patterns of production and consumption in society (Köhler et al., 2019). The literature emphasizes that this requires changes in intertwined and interdependent sociotechnical structures, including technology, organizations, policies and culture, and therefore conceptualizes transitions as the emergence, reconfiguration and decline of sociotechnical systems (Bergek et al., 2008a, 2008b; Geels, 2002; Hekkert et al., 2007; Köhler et al., 2019; Markard et al., 2012; Markard and Truffer, 2008a; Rip and Kemp, 1998). It is also based on the assumption that specific directions of change are not only desirable, but also possible to achieve through deliberate interventions by policymakers and other actors.

One of the main strands of sustainability transitions research focuses on sociotechnical change associated with specific technologies that may bring social and environmental benefits. Scholars in this tradition often draw on the technological innovation systems framework, which offers a useful approach to analyzing the processes which govern successful development and diffusion of new technologies (Bergek et al., 2008a; Hekkert et al., 2007; Markard and Truffer, 2008a). This has resulted in a growing literature that provides a rich understanding of innovation dynamics and brings practical advice to policymakers (Bergek, 2019).

But even though the literature on technological innovation systems emphasizes a specific direction of change by focusing on technologies that are considered 'clean', 'green' or 'sustainable', it fails to fully capture the multidimensional characteristics of sociotechnical change (Yap and Truffer, 2018). Indeed, any technology can develop along vastly different trajectories. These not only differ in the level of diffusion with respect to the product, process or knowledge field in focus, but also result in sociotechnical structures with different configurations. For example, industries and markets that emerge as a result of successful innovation in solar photovoltaics technology may focus on a variety of module designs and applications, involve a few large or many small producers, be governed by different types of policies, and exist in different countries.

While there is certainly an urgent need to diffuse 'clean', 'green' or 'sustainable' technologies, it is clear that the more specific characteristics of sociotechnical change remain important. Accomplishing many, if not most, social and environmental objectives not only depends on whether a technology is developed and diffused, but also on how much, in what way, where and when it is utilized. This is perhaps most evident from a regional perspective. For example, a government that funds research and development in solar photovoltaics technology is likely to be interested in creating domestic rather than foreign industries (Hansen and Coenen, 2015; Joas et al., 2016). This is an objective that represents a specific spatial configuration of sociotechnical structures, which is not necessarily realized even though the technology develops successfully and diffuses widely. After all, domestic markets may be, and often are, supplied by foreign industries. But also from a global perspective, it is quite clear that commonly shared objectives are related to the multidimensional characteristics of sociotechnical change, rather than one-dimensional diffusion of technology.[1] At the end of the day, any imaginable technology can have an environmental impact that exceeds the carrying capacity of planet Earth if it is used too much or in the wrong way. What is ultimately called for, it seems, are efforts to shape sociotechnical change, rather than stimulate technological innovation; even if the technology in focus is desirable, and no matter whether the perspective is national or global.

This suggests that there is a need to advance the analytical approach used by transitions scholars that focus on specific technologies, in order to better support policymakers and other actors that aim to shape the direction of change towards specific outcomes. An interesting empirical context for such endeavors is renewable energy technology in comparatively small and wealthy countries such as Sweden. Here, policy support to research, development, demonstration and deployment often aims to mitigate climate change, increase the share of renewables in the domestic energy system and drive domestic industrialization (Swedish Government, 2016). These sometimes conflicting objectives clearly imply an ambition to achieve a particular configuration of sociotechnical structures, particularly in the spatial dimension. At the same time, however, innovation processes in small countries are particularly intertwined with and dependent on international developments. This is likely to magnify the challenge of shaping sociotechnical change, which makes the empirical context suitable for developing and illustrating new analytical approaches.

To conclude, the research I present in this thesis belongs to an intellectual tradition that opposes the idea that economic growth and innovation are desirable per se, and engages with the policy challenge of directing the development and diffusion of new technologies towards social and environmental objectives. But where many researchers settle for shifting the focus from promoting the growth of general economies to stimulating the expansion of specific technologies, I move further by concentrating on how sociotechnical change can be shaped towards desirable outcomes.

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[1] One may also argue that rapid global diffusion of technology may depend upon, or at least be facilitated by, the achievement of more specific directions of sociotechnical change. For example, the legitimacy of climate policies that stimulate the diffusion of renewable energy technologies is dependent on the creation of local job opportunities (Vona, 2019).

1.2 Purpose and aim

Against the background presented in the previous section, the purpose of this thesis is to support efforts to shape sociotechnical change towards desirable outcomes. It is situated in the sustainability transitions community and adopts the technological innovation systems literature as a theoretical point of departure. The aim is to develop a conceptual framework that (i) captures the characteristics and dynamics of sociotechnical structures associated with specific technologies, (ii) explains the role of policymakers and other actors in shaping the transformation of these structures, and (iii) establishes links to their social and environmental consequences. The conceptual development required to reach this aim draws on three empirical case studies of innovation in renewable energy technology, set in a predominantly Swedish context. The case studies describe historical developments, identify innovation dynamics and derive policy implications, and their empirical findings add to the contribution of this thesis.

There is accordingly a conceptual and an empirical dimension to this research. In the former, I develop new ways of describing and analyzing technological innovation. This involves adopting and reinterpreting ideas from the extant literature, developing new concepts that correspond to identified research gaps, and assembling the different parts into a cohesive conceptual framework. In the empirical dimension, I develop knowledge about the nature of technological innovation and derive policy implications. This not only results in empirical findings that complement previous research, but also supports conceptual development by revealing weaknesses in existing theories and enabling test and illustration of new ideas.

The conceptual development and empirical investigation carried-out as parts of this research are guided by slightly different questions, which feed into an overarching question that relates to the thesis purpose. These research questions are presented in Table 1.1.

Table 1.1. Guiding research questions.

Overarching research question	
How can technological innovation be described and analyzed in a way that supports efforts to shape sociotechnical change towards desirable outcomes?	
Conceptual research questions	**Empirical research questions**
1. How can the characteristics of sociotechnical structures associated with specific technologies be described and demarcated? 2. How can the dynamics of these structures be described and decomposed into a typology of transformation processes? 3. How can the role of policymakers and other actors in shaping the transformation of these structures be described and analyzed? 4. How can the social and environmental consequences of these structures be described and analyzed?	1. What characterizes the emergence of solar photovoltaics and marine energy technology in Sweden? 2. What innovation dynamics underlie the development trajectories for these technologies? 3. What are the implications of these cases for policymaking?

It should be noted, however, that the conceptual development effort presented in this thesis puts a stronger emphasis on the first two conceptual research questions. In a sense, the point of departure is a thorough investigation of the characteristics and dynamics of sociotechnical structures associated with specific technologies, which then reaches out in two directions; one towards the role of policymakers and other actors, and another towards social and environmental consequences. Although these perspectives, which are represented by the last two conceptual research questions, are not explored in much detail, they remain important to contextualize the conceptual contribution and illustrate its potential role as an analytical bridge between the dynamics and consequences of technological innovation.

1.3 Contribution of appended papers

This thesis consists of five original research papers. While they all make important contributions to the general purpose of this research, they engage with the conceptual and empirical dimensions in different ways and to varying degrees.

Paper I analyzes the development and diffusion of marine energy technology in Sweden until 2014, employing an analytical approach based on the technological innovation systems framework. It focuses on identifying and analyzing problems in the innovation process and discusses their implications for Swedish policymakers. While the main engagement is with the empirical dimension, the analysis highlights that policy aims are related to directions rather than growth and thereby suggests a need for conceptual development.

Paper II analyzes the global emergence of tidal kite technology, a specific marine energy technology concept developed by Swedish actors, until the beginning of 2016. It focuses on how resources provided by domestic and foreign regions have influenced the localization of key activities and discusses policy implications from a Swedish perspective. In addition, a new analytical approach based on the technological innovation systems frameworks developed and demonstrated. The paper thus engages with both the empirical and conceptual dimensions.

Paper III analyzes the development and diffusion of solar energy technology in Sweden until 2018. It presents a historical review of the innovation process, identifies development trajectories and underlying dynamics, and discusses policy implications. An analytical approach based on the technological innovation systems framework is used, but some conceptual extensions and modifications are made. Although the paper mainly engages with the empirical dimension, it accordingly involves some conceptual development as well.

Paper IV presents a detailed review of the literature on technological innovation systems and identifies a number of ambiguities and contradictions in the use of basic systems concepts. It also proposes 'technological systems' as an alternative systems construct, 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. The paper has a conceptual character and limits its engagement with the empirical dimension to brief illustrative examples.

Paper V argues that efforts to investigate and promote specific directions of change call for new analytical frameworks that capture both the dynamics and consequences of technological innovation. It also develops an elaborated conceptualization of the directionality of technological innovation, based on the technological systems concept. Although the proposed conceptual ideas are illustrated through empirical cases, one of which is based on Paper III, the paper has a strong focus on the conceptual dimension.

This introductory essay summarizes empirical findings for each case study and presents cumulative contributions made in the conceptual dimension as a new conceptual framework that may support policy efforts to shape the emergence of specific technologies. It should be emphasized, however, that Papers I-III do not fully align with this novel conceptual framework. And while Papers IV-V describe its main features, some additions and elaborations are made in this introductory essay, which also provides deeper reasoning and more thorough justification. The papers should accordingly be viewed as parts of a learning process that culminates with this thesis.

1.4 Thesis outline

In this introduction, I have set the scene for a thesis that unfolds in nine additional chapters. To lay a firm foundation for the research endeavor, Chapter 2 discusses metatheoretical ideas and assumptions about science, ontology and epistemology. Thereafter, Chapter 3 presents an analytical perspective based on systems thinking and elaborates on how it can be applied to technological innovation. With this analytical perspective as a point of departure, Chapter 4 provides an overview of the field of sustainability transitions research, positions the thesis in relation to the strand which focuses on technological innovation systems, and identifies the conceptual research problem through a detailed review of this literature. Chapter 5 then discusses methodology in relation to the research endeavor, while Chapter 6 describes the research design used to fulfill its purpose. The focus then shifts towards the results of the research presented in the thesis. Chapter 7 summarizes empirical findings from the three case studies and discusses their implications for policymaking and conceptual development. Thereafter, Chapter 8 introduces and elaborates on the technological systems framework, which constitutes the conceptual contribution of the thesis. In the end, Chapter 9 offers an extensive and critical discussion about the merits of the thesis, before Chapter 10 provides a brief summary of its main conclusions.

CHAPTER 2 – METATHEORETICAL FOUNDATION

As described in the previous chapter, this thesis focuses on developing a conceptual framework that may be used to describe, analyze and shape sociotechnical change. But before engaging with this challenge, I will take a step back and present the metatheoretical foundation upon which my pursuit of knowledge rests. This involves discussing the nature of science and addressing difficult questions of ontology and epistemology. However, it should be made clear already at the outset that I will not provide a comprehensive philosophy, but rather attempt to declare the ideas and assumptions that underpin this research. This will hopefully provide justification and clarification to the conceptual and empirical reasoning that follows in subsequent chapters.

In the following sections, I will first discuss how science can be understood as a set of social norms. Then I establish design and description as distinct but interlinked modes of scientific inquiry. In the end, I elaborate on my ontological assumptions and their epistemological implications.

2.1 Science as a set of social norms

If the human experience is about anything, it is about pursuing knowledge. Through our senses, we perceive a reality that presumably exists beyond our subjective minds. Using our analytical capabilities, we observe patterns and regularities that form the basis for categorization and prediction. And by the means of language, we produce representations that enable the codification, modification and exchange of meaning and understanding. Conceived of in these broad terms, the pursuit of knowledge is both a personal and collective endeavor, which may involve very different questions, and very different ways of answering them – imagine a toddler who explores their immediate environment by crawling around on the kitchen floor, a teenager passively listening to a dull mathematics lecture, a group of adolescents discussing which university to apply for, and a network of thousands of prominent researchers collaboratively assessing the risks brought by global warming. While these are all examples of pursuits of knowledge, only the latter is commonly understood as science. This is not because of the questions asked or the type of answer sought. After all, it is easy to imagine both scientific and non-scientific ways of answering most questions. Nor is it sufficient to distinguish science by referring to the characteristics of activities carried-out in its name. The multiplicity of methods used to scientifically pursue knowledge are so different that it hardly makes sense to group them under the same label without looking for something beyond immediate practice. Consider, for example, the difference between a chemist that develops and tests hypotheses about the characteristics of molecular compounds, an anthropologist that describes and interprets cultural behavior, and a journalist that reports newsworthy events in a foreign country. In terms of their practice, the anthropologist and the journalist may be more similar than the chemist and the anthropologist, even though it is the latter two who engage in what is commonly thought of as science.[2]

To distinguish science from other human and social activities, we rather have to look for a deeper set of values and norms that govern the scientific enterprise. In a seminal essay first published in 1942, Merton (1973) describes this ethos of science by pointing to four institutional imperatives, which have since then been developed and refined to include a fifth category and allow for the eloquent acronym CUDOS (Anderson et al., 2010; Ziman, 2000). The first imperative, *communalism*, captures the collective ownership of results and the practice of giving up intellectual property rights in exchange for recognition and esteem. Second, *universalism* postulates that claims should not be evaluated on the basis of race, class, gender, religion, or nationality, but rather in terms of impersonal criteria. Third, *disinterestedness* promotes selfless action that serves noble objectives, rather than personal gain. Fourth, *originality* encourages creative activities that lead to novel claims, rather than mere replication of existing results. And fifth, *skepticism* points to the fundamental idea that all claims and results produced by science are subject to rigorous and systematic scrutiny. Adherence to these norms means adopting a particular attitude to the pursuit of knowledge, which makes the endeavor scientific.

As a researcher, I strive to nurture this scientific attitude, but I also recognize my limits as a human being. Properly deserving kudos for staying true to the CUDOS of science implies, among other things, acting selflessly and without prejudice, an ideal which is as laudable as it is unattainable for mere mortals. However, this does not imply that the scientific enterprise may never adhere to norms such as disinterestedness and universalism, but rather emphasizes that they should be seen as desirable attributes of a scientific community that consists of both human

[2] I use the term science in a broad sense that includes the humanities and social sciences, thus approaching the meaning of the German term 'Wissenschaft' and the Swedish term 'vetenskap'.

agents and social institutions. Put differently, the virtues that define science, such as the quest for objectivity, are woven into its fabric and not traits of individual researchers (Longino, 1990).

2.2 Design and description as distinct but interlinked modes of scientific inquiry

Scientific knowledge in the form of theoretical propositions can be valuable for different reasons.[3] A broad distinction can be made between epistemic values, that refer to the extent to which theories are true and justified, and pragmatic values, that refer to their utility in relation to objectives beyond the immediate pursuit of knowledge (Nola and Sankey, 2007).[4] Epistemic values thus highlight that theories may be regarded as ends in themselves, while pragmatic values rather emphasize that they can be used as means to achieve a certain outcome.

Although epistemic and pragmatic aspects of theoretical valuation are deeply intertwined, they serve as a useful point of departure when considering different types of science. A distinction is commonly made between basic science and applied science, and, as pointed out by Niiniluoto (1993), the difference has an axiological character; where basic science emphasizes epistemic values, applied science seeks to combine epistemic and pragmatic values.

A perhaps more categorically distinct typology of science can be found by shifting the focus from the epistemic and pragmatic qualities of theoretical propositions to the fundamental questions they address. In particular, an important dividing line can be drawn between descriptive science and design science. The former addresses questions about the world as it was, is or will be, while the latter is concerned with prescribing what ought to be done in order to achieve a certain outcome (Niiniluoto, 1993; Simon, 1968). A fundamental and important distinction is thus made between the pursuit of descriptive knowledge about phenomena that lie beyond the notion of value, and the pursuit of prescriptive knowledge about phenomena that cannot be separated

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[3] In fact, this discussion is in principle valid for any type of knowledge and not merely for the scientific kind.

[4] Pragmatic values are normally derived from theoretical utilities in relation to social objectives beyond science, but may arguably also refer to theoretical utilities in relation to epistemic objectives (i.e. whether a theory can be useful to advance science).

from the notion of value.[5][6] But however distinct the two modes of scientific inquiry may be, they are at the same time highly interdependent. On the one hand, design science inherently draws on descriptive knowledge. It is, for example, impossible to prescribe a course of action that results in boiling water without knowing that this state is associated with a rising temperature or decreasing pressure. On the other hand, descriptive science is enabled and driven by design knowledge. The latter is not only essential for the development of methods, instruments and laboratories with which to advance scientific inquiry, but it is also common that questions and ideas emerge from practical application (Price, 1984). As noted by Nelson (1994), Sadi Carnot actually launched the field of thermodynamics because he wanted to understand what was happening in steam engines.

Additional depth can be added to the distinction between descriptive science and design science by invoking their relation to technology and natural phenomena. As will be further elaborated in Chapter 3, this thesis understands technology as a way to convert means, fundamentally derived from natural phenomena, to an end. This reveals an enlightening link to the distinction between descriptive science and design science, as illustrated in Figure 2.1.

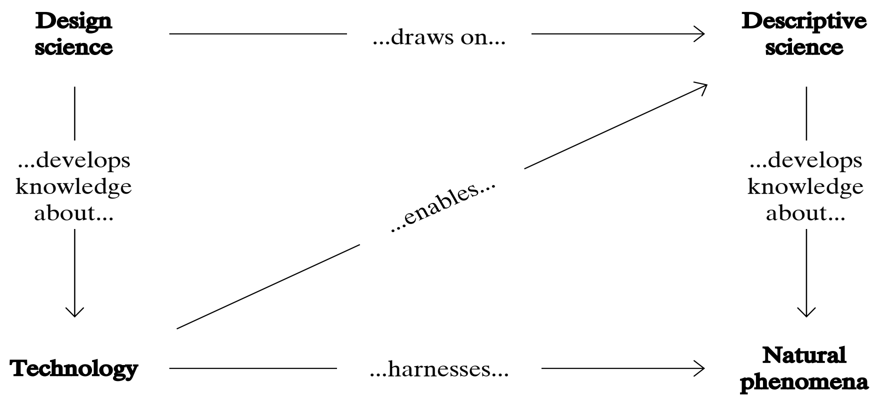

Figure 2.1. Linkages between design science, descriptive science, technology and natural phenomena.

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[5] It should be noted that Romme (2003) distinguishes between science, design and humanities as different modes of inquiry in organization research. While the first two domains correspond to the descriptive-design distinction promoted here, Romme frames the humanities mode as the study of human experience in relation to normative aspects of organizations. Although the study of human experience is fundamentally different from the study of the objective domains of reality, I maintain that it should be viewed as a type of descriptive research.

[6] It can be objected from certain epistemological positions that descriptive theoretical propositions are fundamentally normative since they propose how we *ought to* describe reality.

It has been noted that the border between descriptive science and design science splits many scientific fields (Niiniluoto, 1993). In fact, many if not most researchers engage in both descriptive and design-oriented research activity, and I am no exception to this rule. As I examine technological innovation, my interest lies in what was, is and will be as well as what ought to be done. The former line of inquiry results in empirical findings that describe particular instances of technological innovation, but in principle also involves reviews of existing literature. The generated descriptive knowledge then feeds into the development of prescriptive knowledge in the form of conceptual frameworks and policy recommendations, which may serve as means to further our collective understanding of technological innovation and capacity to shape it towards desirable outcomes. This is also what makes my research inherently normative, since such prescriptive knowledge cannot be formulated without reference to a value statement of some kind.

2.3 Ontological assumptions

All science, no matter whether it is oriented towards description or design, is based on philosophical ideas about the nature of reality and our ability to perceive and learn about its features. What makes them philosophical is that we cannot know whether anything beyond our immediate experiences exist (metaphysical skepticism), and there is no guarantee that what we perceive as causes and effects are linked in any meaningful way (inductive skepticism) (Glymour, 1992). These and other philosophical problems imply that matters of ontology and epistemology are fundamentally about assumptions and beliefs. However, this does not leave them irrelevant or unimportant to the scientific endeavor. On the contrary, declaring the assumptions and beliefs on which theoretical propositions rest is essential for cumulative knowledge development. If we cannot agree upon a shared metatheoretical foundation, or at least understand our different points of departure, it is simply not possible to engage in sophisticated debate about the meaning, relation and value of different ideas.

A fundamental ontological assumption on which the research presented in this thesis builds is that an objective physical reality exists. Importantly, I make this assumption entirely based on belief, intuition and perhaps hope. To the extent that I doubt, I am reminded that a realist position appears to have instrumental value, both for me as an individual and for human society at large; I find comfort and community in drawing my experiences from the same universe as my fellow human beings; and I think it serves us well to assume that we live in the same world, even though we certainly perceive it very differently.

Physical reality is made up of matter and energy that are situated in, move through and seemingly interact in temporal and spatial dimensions. This gives rise to an ever changing topology of interlinked objects, which I will refer to as objective structures. Notably, I use the term structures simply to capture aggregates of components (in this case physical objects), rather than as way to describe enduring and reoccurring patterns of organization.

Objective structures have various characteristics that can be perceived and used a basis for classification: some are blue, others are red; some are stable over time, others are quickly transformed beyond recognition; some are large, others small; and so forth. A particularly important characteristic of some objects is that they seem to have conscious minds and senses through which they experience reality, and a select few even possess the power of reason and purposive action. I refer to the latter as agents with agency, and for the purposes of this thesis they can be thought of as human beings. That said, there is no reason to assume a principal difference between human and non-human agency – we are animals, albeit particularly thoughtful and industrious. I do, however, draw a firm line between living beings and non-living machines; although the latter can certainly engage in purposive action, I view consciousness and experience beyond their reach.

The existence of consciousness and experience opens up a non-physical dimension of reality. One part of this dimension consists of thoughts, emotions and perceptions that appear inside individual minds, which I will refer to as subjective structures. While these are unique and inaccessible to anyone but the subject in question, they are as real as their objective counterparts in the physical dimension. Another part of the non-physical dimension consists of agreements and shared meanings that exist in the interaction of individual minds, which I will refer to as intersubjective structures. These are unique and inaccessible to anyone but the subjects involved in creating and recreating the meanings they entail. Intersubjective structures can thus rightly be referred to as socially constructed, which is not the case for neither objective nor subjective structures. Furthermore, while both intersubjective and subjective structures are non-physical, they cannot be separated from the physical bodies of living agents and may thus be situated in time and space. However, this is different from the imprints individual and shared experience make on the physical dimension. For example, although a political message could be written on enduring concrete walls all over the world, it would as an intersubjective structure be situated in the time and space occupied by the agents that are aware of its meaning.

Figure 2.2 illustrates how reality can be decomposed into objective, intersubjective and subjective structures. I will, however, refrain from discussing the origins of the temporal and spatial dimensions in which they are situated.

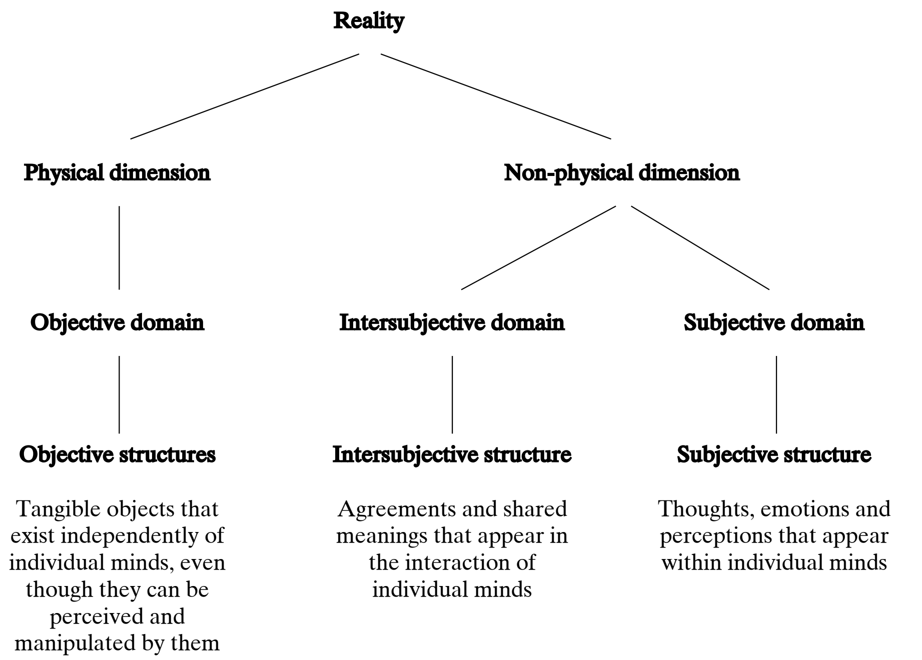

Figure 2.2. Objective, intersubjective and subjective structures as the constituent parts of reality.

Objective, intersubjective and subjective structures not only exist, interact and move through time and space, but may also influence the course of development. In the physical dimension, the fundamental properties of objective structures create a tendency for things to fall towards the ground, while certain objects such as tables and chairs may give rise to counteracting mechanisms. In the non-physical dimension, intersubjective structures in the form of shared ideas of what is permissible and desirable have a strong influence on the behavior of individual agents. An important question that follows is what ontological status these causal powers have and how they relate to their constituent parts.

Following critical realist ideas (Bhaskar, 1998), I adopt the view that reality has depth: it includes the objects and events we observe; what passes unnoticed due to our ignorance or incapability; as well as underlying mechanisms and causal powers, even though they may not be actualized in terms of effects in objective, intersubjective and subjective domains. For example, my ability to type this sentence is as real as the sentence itself, no matter whether I type it or not. This also implies that when we propose a course of action to achieve a certain outcome – such as a carbon tax to stimulate the diffusion of renewable energy technology – we actually argue for (i) the existence of a (real) mechanism that would lead to the desired outcome, and (ii) the possibility of actualizing this mechanism through the proposed course of action.

Another important feature of reality is stratification. This means that causal powers may emerge at aggregate levels of organization, without being reducible to the properties of constituent parts.

Coming back to the previous example, my ability to type this sentence is not only due to the individual properties of the cells in my body, but also their relational organization.

The emergent nature of structural properties also holds for the particularly important causal power we refer to as agency. In fact, human agency can be understood as an emergent property of the individual properties and relational organization of human cells, or even their smaller constituent parts, even though I believe that there is more to consciousness than this view suggests.[7] More importantly for the purposes of this thesis, agency can emerge at higher levels of organization than individual agents. For example, a collective, such as family or a firm, has powers of reason and purposive action that cannot be reduced to the agency of its constituent agents. Following widespread conventions, I will refer to such collectives as actors. This is to distinguish them from agents that are the lowest level of organization at which agency appears, and also the only level at which consciousness exists.

Although agents by definition have agency, its role in explaining their behavior is not trivial. Some adopt a voluntarist view that emphasizes free will and autonomy, while others take a determinist position that highlights the influence of external structures (Burrell and Morgan, 1979). An often cited middle ground is Giddens' (1984) structuration theory, which suggests a reciprocal link between agency and structure; the actions of agents create and re-create structures that in turn constrain and enable further actions. However, structuration theory emphasizes intersubjective structures, and thus views agency and structure as inseparable (Porpora, 1998; Svensson and Nikoleris, 2018). It thereby fails to highlight the influence of objective structures, even though these clearly partake in the reciprocity of agency and structure.[8] In addition, whereas intersubjective structures are re-produced in their interaction with agents, objective structures may pre-exist independently from such interaction.

To capture these features, I again follow critical realist thinking and adopt a transformational perspective that acknowledges this multiplicity of structures (Bhaskar, 1998). This also implies broadening the focus from human agency as a specific driver of structural change to the

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[7] I reject the idea that consciousness can be explained by the individual properties and relational organization of the constituent parts of conscious beings on spiritual grounds. Although I do belive in an entity that unifies all existence – call it energy, vibrations, or god – my intuition is that it stretches far beyond what we have the ability to imagine.

[8] The influence of subjective structures is mediated by the objective and intersubjective domains, since agents cannot know about the subjective thoughts, emotions and experiences of other agents unless they make an imprint on the objective and intersubjective parts of reality.

reciprocal influence of a wide range of causal powers. After all, given that all structures interact over sufficiently long time scales, and that causal powers not only influence, but also emerge from these structures, feedbacks between causes and effects are a general feature of reality. And as we will see in the next section, this has consequences for the possibility of finding universally applicable laws. The transformational perspective on structural change adopted in this thesis is illustrated in Figure 2.3.

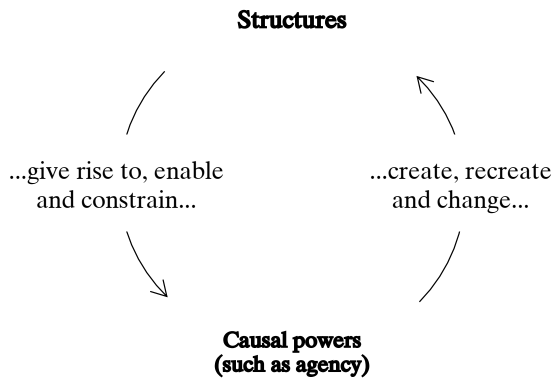

Figure 2.3. A transformational perspective on structural change.

It should be highlighted at this point that the structures which constitute reality have a dual nature. On the one hand, they are entities that can be categorized based on their static characteristics; an objective structure is objective not because of what it does, but because of what it is. On the other hand, structures are involved in transformation processes, which implies that they can also be categorized based on their dynamic characteristics. The question is what ontological status these perspectives should be granted. In my view, it seems likely that the fundamental fabric of reality is change – vibrations of energy, if you will – while stability is an illusion. But nevertheless, we perceive static qualities of the structures that surround us since we cannot, or perhaps do not want to, observe the dynamics which give them their stability. In the end, I would argue that seeing the world as both static and dynamic at the same time is a fundamental part of the human experience. And this is why my ontology acknowledges that we can observe, evaluate and categorize what we perceive from both structural and transformational perspectives.

Finally, not much has been said to this point about the ontological difference between human society and the natural environment. And the reason is that I cannot see one. The objective, intersubjective and subjective domains, the depth and stratification of reality, the reciprocity of structure and agency, and feedbacks among causes and effects, which together constitute the ontological foundation upon which this thesis rests, cut through what is commonly thought of as society and nature. Nevertheless, it sure seems plausible to assume a quite major difference in the powers of reason and purposive action of human and non-human conscious agents. This may warrant a methodological and conceptual distinction that classifies structures based on their relation to human as opposed to non-human agency. For subjective structures, this is most often trivial since we can easily distinguish humans from other conscious beings. Also for intersubjective structures, the distinction is reasonably straight-forward since communication barriers limit the extent to which shared meanings appear in the interaction of human and non-human beings.[9] However, separating objective structures that belong to human society from ones that are a part of the natural environment makes the matter more intricate. What link between human agency and an object is necessary to associate the object with society? While I will not attempt to answer this question fully, it should be noted that objective structures associated with society are most often designed with a human purpose in mind. As we will see in Section 3.2, they may in fact be referred to as technologies.

2.4 Epistemological implications

When it comes to questions of epistemology, the ontological framework described above has certain consequences. To begin with, it establishes that there is an objective and intersubjective reality beyond our own subjective experiences, which we can strive to describe and explain. However, such efforts are fundamentally based on our perceptions, which not necessarily represent reality in a way that is true to its objective and intersubjective qualities. We do, for instance, most often perceive the Earth as flat due to our limited senses and perspective of observation. Moreover, the ideas that form the building-blocks of description and explanation are not just the result of our fallible perceptions, but also influenced by our preconceptions. In particular, we seem biased towards confirming our existing beliefs. These features cause problems of under-determination and theory-ladenness; we form ideas that are not necessarily supported by empirical observations, and the empirical observations we make are influenced by the ideas we already have (Glymour, 1992). In addition, any attempt to describe and explain reality will change the structures we attempt to capture. As human agents, we cannot escape our causal powers, which means that whatever reality we knew will necessarily have disappeared as a result of our attempts to know it.

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[9] That said, inter-species culture certainly exists – just look into the eyes of a schimpansee and you will know.

Another epistemological consequence is that structural change is not understood as governed by laws, but rather as an emergent property of a complex interplay of causal powers that emerge from existing structures in the objective, intersubjective and subjective domains. Explaining structural change is thus not about relating it to laws that apply everywhere, but rather about identifying which mechanisms that were actualized in the particular instance as well as the conditions that were required for this to occur. This means that generalization and prediction is beyond reach except for closed settings where mechanisms and conditions repeat themselves. Although such settings are rare in a constantly changing reality, it is clear that the scientific method allows for theoretical development that reveals patterns and regularities. These in turn enable us to predict and influence the course of events with a level of accuracy that serves many human purposes.

The epistemological position of this thesis thus occupies a middle ground between nomothetic and ideographic approaches. This is to large extent because of an ontology that acknowledges both objective and subjective features of reality, while understanding change as the result of reciprocal interaction between a plethora of mechanisms and causal powers, including agency, and the existing structure from which they emerge.

To summarize this chapter, I first discussed my understanding of science and suggested that it can be understood as a set of social norms. I then established design and description as distinct but interlinked modes of scientific inquiry. In the end, I elaborated on my ontological assumptions and their epistemological implications. This forms the metatheoretical foundation of this thesis. In the next chapter, I will describe an analytical perspective based on systems thinking and define the phenomenon of interest for this research.

CHAPTER 3 – ANALYTICAL PERSPECTIVE

As the metatheoretical foundation established in the previous chapter suggests, the world we inhabit is not only vast, but also extraordinarily complex. We cannot reflect upon, observe or even imagine the dynamic interplay of all structures that span the objective, intersubjective and subjective domains. To engage in meaningful pursuits of knowledge, we therefore have to focus on a specific slice of reality at the time, while paying less attention to the wider context in which it exists. This slice of reality can be formally delineated as a system, which is the core concept used in this thesis to capture technology and how it changes over time. The focus of this chapter is to elaborate on this analytical perspective and discuss my understanding of technological innovation as a phenomenon of interest.

In the following sections, I will first elaborate on the conceptual meaning I attach to the notion of systems. Then I describe how I choose to define the terms technology and innovation, which together describe the phenomenon of interest in this thesis. In the end, I discuss different ways to apply the systems concept when investigating this phenomenon. This forms a point of departure for the next chapter, in which I review the literature and further specify the conceptual research problem addressed by this thesis.

3.1 Systems as analytical constructs that demarcate a part of reality

What is today referred to as 'systems thinking' is based on ideas brought forward from the 1950's and onwards by a diverse array of scholars (Bertalanffy, 1950; Boulding, 1956; Churchman, 1968; Foerster, 1960; Forrester, 1961; Simon, 1962; Wiener, 1948). In this section, I will focus on how I use the systems construct to demarcate a particular slice of reality from the wider context in which it exists, while I revisit the historical background to this line of thinking in Section 4.1.1.

A system is commonly defined as "a regularly interacting or interdependent group of items forming a unified whole" (see for example the Merriam-Webster dictionary (2020)). Already at the outset, two important points have to be made about this definition: first, everything real is interacting and interdependent, at least over sufficiently long time scales; and second, an infinite number of unified wholes can be imagined by a sufficiently creative observer. This implies that everything can be conceived of as a system, which from an ontological perspective, I would argue, renders them social constructs in the intersubjective domain. In other words, systems do not exist as objective entities in the world but are created by agents to make sense of and discuss their subjective experiences. As put by Meadows: "There are no separate systems. The world is a continuum. Where to draw a boundary around a system depends on the purpose of the discussion – the questions we want to ask." (2009, p. 97).

In my view, a system is accordingly a construct that demarcates a part of reality from its context. Since the structures which make up reality can be evaluated and categorized from different perspectives, boundaries that specify a particular system are normally set in several dimensions. To begin with, spatial and temporal boundaries can be used to specify a domain in the four fundamental dimensions of space-time, and thus limit the system to structures within this domain. These may be implicit but are always there in practice, since few analytical endeavors would claim to cover all imaginable, and unimaginable, spatial regions and time periods (Sandén et al., 2017). For many investigations it is also appropriate to collapse the three dimensions of space into one dimension and employ a single spatial boundary that distinguishes geographical areas. This is the approach adopted in this thesis.

Since many, if not all, systems studies are only concerned with some of the many structures that exist in a given spatial region and time period, there is a need for additional boundaries that specify which structural components that are included in the system. One such boundary can be derived from the notion of a unified whole that unifies the items and interconnections in the system. This unified whole is often expressed as a purpose or function that the system fulfills (Meadows, 2009). Importantly, the idea of a system purpose neither implies that the system is "conscious" and has a "will", nor that its components must share or even be aware of this purpose (Sandén et al., 2017). It simply means that for something to be viewed as a system by an observer, it needs to have one or several functions in its wider context. Or put differently, it needs to perform a set of processes or activities that result in some particular type of structural change.

To highlight that specifying the system purpose is basically about defining a set of processes that constitutes its function, I use the notion of a functional boundary. This boundary creates a rationale for including some structures and excluding others, depending on their relation to the processes which constitute its function; structural components that are involved in these processes are seen as a part of the system, while ones that are not belong to its context. However, due to the interconnected nature of reality, everything is in principle involved in everything. This means that the functional boundary should not only specify a set of processes that constitute the system function, but also define criteria for determining which structural components that are sufficiently involved in the processes captured by the functional boundary to warrant inclusion in the system.

In addition, many systems studies limit their scope to a particular type of structural components, without making reference to their relation to the system function. For example, some systems constructs only include structural components that have a social character, even though the processes included by the functional boundary are strongly dependent on other types of structures as well (Ingelstam, 2012). I will refer to the boundary that determines which type of structural components that are included in a system as its structural boundary.

It should be highlighted that whereas the structural boundary delimits the system to a specific type of structures, the functional boundary delimits the system to a set of processes that constitute its function. When determining what is included in a system, the structural boundary thus evaluates structures based on their static characteristics, while the functional boundary evaluates structures based on what they do with respect to dynamic processes of change. The two boundaries thus depart from the ontological perspectives of structure and transformation respectively, which as noted in the previous chapter constitute distinct but intertwined perspectives on reality.

Although both functional and structural boundaries are arguably needed to specify a system, one of them always constitutes the starting-point. On the one hand, an analysis can start with a structural boundary that includes a particular set of structures and then derive the functional boundary (i.e. the system purpose) by observing what processes these structures are involved in. Within sustainability transitions research, this could for example involve focusing on a set of firms in an industry (structural boundary) and then identifying the technological processes they develop and use (functional boundary). On the other hand, an analysis can start with a functional boundary that focuses on a set of processes and then derive the structural boundary by observing the structural components they involve. Coming back to the previous example, this would involve focusing on a set of technological processes and then identifying the firms involved in their development and use.

When it comes to delineating functional, structural, spatial and temporal boundaries for a particular investigation, the underlying reasoning can be inductive or deductive (Ingelstam, 2012). In the former case, system boundaries are derived from empirical observations. This approach often seeks to establish differences in the type of structural interaction that takes place *within* the system and *between* the system and its context. For example, processes within the human body are qualitatively different from those between the human body and its context. To describe a human being as a system it thus makes sense to use the skin as system boundary. But although inductively derived system boundaries can be discovered and tested empirically, it always requires some analytically 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. There are accordingly no "correct" system boundaries, only more or less relevant and efficient ones.[10]

When system boundaries are based on deductive reasoning, the delineation is instead based on analytical preferences, which in turn depend on the interests, capabilities and preconceptions of the analyst. 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. A deductively derived system boundary can also be motivated by time and resource limitations. Any investigation can only cover a small fraction of reality and sometimes a boundary needs to be set only to limit the scope, even if there are no solid arguments for any particular choice (Sandén et al., 2017).

System boundaries in different dimensions may also follow different rationales. For example, the temporal boundary can have an inductive character that highlights a time period of intense and interesting interaction, while the spatial boundary may be deductively derived to foreground a particular analytical 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 a pre-defined country.

Note also that it is possible to adopt multiple system boundaries in functional, structural, spatial and/or temporal dimensions. This enables an analyst to distinguish between systems that are either separate or overlapping, or to specify sub-systems of different kinds.

While system boundaries are often associated with the outside of a system, they are for analytical purposes present on its inside as well. Any structural component in a system can in itself be viewed as a sub-system (at least to the extent that its constituent parts can meaningfully be identified and disentangled), and any system can be viewed as a component in a higher-level system. This implies that specifying a system not only highlights interactions among its structural components at the expense of phenomena in the outer context, but also involves black-boxing (i.e. hiding or disregarding) the inside of its components. This inner context is mainly associated with an inner structural boundary, which black-boxes lower-level structures such as individual

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[10] 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.

staff in an organization. But in principle, there are inner contexts associated with functional, spatial and temporal boundaries as well. These can be thought of as the system resolution with respect to function, space and time.

Since 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 system in focus therefore have to be complemented by a description of contextual structures, how they influence system structure, as well as the influence by the system on its context. In fact, this creates an implicit boundary between contextual structures that are acknowledged as influential (or influenced) and the rest of the world. It is also worth noting that I use the term system context rather than system environment since the latter term could be confused with the natural environment. The latter is a particular type of context, which should not be confused with the idea of a context.

Given these general ideas, it is hard to imagine any scientific understanding of the world that does not explicitly or implicitly make use of the systems concepts. At a fundamental level, it has even been noted that systems thinking is used, implicitly or explicitly, to differentiate between scientific disciplines (Sandén et al., 2017). Most, if not all, scientific disciplines hide or disregard interactions at some level of abstraction, to enable investigations of interactions at a higher level; atoms are routinely black-boxed in chemistry, organisms in ecology, persons in sociology, and firms in economics. Other disciplines make their task to open these boxes; atoms are complicated systems in physics, organisms in physiology, persons in psychology, and firms in management studies.

It even seems as if systems thinking is in fact applied to most analytical endeavors, within science and beyond. In this sense, the systems concept can be viewed as a metatheoretical construct that clarifies which part of reality that a particular investigation is mainly concerned with as well as its relation to the wider context in which it is embedded (Bertalanffy, 1968; Boulding, 1956).

3.2 Technology as a means to an end

Although most people have an intuitive idea about what technology is, the concept is rarely defined in a precise and uniform manner. Commonly used dictionaries point to multiple meanings that include knowledge, the application of knowledge as well as the capabilities, equipment and machinery this brings. This suggests that technology has both material and immaterial characteristics, or put differently, that it transcends the physical and non-physical dimensions of reality.

A prominent scholar that has explored the nature of technology further is the evolutionary economist Brian Arthur (2009). Searching for a rigorous way to explain what technology actually is, he concludes that technology "is a means to fulfill a purpose: a device, or method, or process. A technology does something. It executes a purpose." (Arthur, 2009, p. 33). This is also similar to how Heidegger describes technology as "an ordering of the world to make it available as a "standing reserve" poised for problem solving and, therefore, as a means to an end" (Heidegger, 1977, p. 19).

In this thesis, I follow this line of thinking as I define technology as 'a means to an end'. In relation to the ontological assumptions presented in Section 2.3, this implies that technology harnesses structures in the physical and non-physical dimensions of reality, to achieve a change process that results in a new structural configuration which corresponds to a function or purpose conceived by an agent.

While this is not the place to present a thorough philosophy of technology, I want to highlight five important points about this definition. First, it implies that a broad range of phenomena can be classified as technologies. Technology is not confined to physical tools or machines, but also includes immaterial means such as organizations and language. It can be as simple as a sharpened stone or as complicated as an entire industry. In essence, anything that is designed to achieve something can be thought of as a technology.

Second, and as pointed out by Arthur (2009), technology is a compound and hierarchical phenomenon. While some very basic technologies only harness structures that have not been designed by an agent, most draw upon pre-existing technologies. This means that any technology can both serve as a means for a more complex technology and be decomposed into constituent sub-technologies, at least to the point where the only means that remain are natural phenomena that can be purely disentangled from a human purpose.

Third, the term technology can refer both to an idea of how to convert means to an end and to the structures involved in the actual conversion of means to an end. To illustrate this, imagine the first person in the world to envision a bicycle. While this idea, albeit crude and restricted to an individual mind, is a technology, so is the bicycle that brought you to work this morning.

Fourth, technology is inseparable from consciousness. Without the capability of imagining a purpose, it is reduced to a change process that cannot be distinguished from what we commonly think of as natural phenomena. As a result, technology would in fact disappear if consciousness were to disappear.

Fifth, technology is not necessarily a human phenomenon. It can achieve many purposes that relate to the natural environment rather than human society (i.e. stabilizing climate change).

And while such purposes are often imagined and valued by human beings (i.e. stabilizing climate change to safeguard human civilization from disruption and potential extinction), there are several examples of technological development and use that only involve non-human agents. For example, New Caledonian crows are known to manufacture and use hook tools to catch insects and larvae (Hunt, 1996).

Sixth, and lastly, technology can be perceived from the perspective of both structure and transformation. A structural configuration that converts means to an end can be seen as a technology, but so can the process of converting means to an end. However, when defining, specifying and distinguishing technologies, the starting-point is always the transformational perspective; a structural configuration is a technology because of what it does, not because of what it is. I would even argue that we cannot conceive of technology without thinking in terms of processes of structural change. This is also why specifying systems that capture specific technologies have to start with the functional boundary – an argument that will be developed further in Chapter 8.

In addition, it should be noted that my understanding of technology implies that their emergence in principle have a starting-point. A technology is first conceived when a new idea of how to achieve a purpose appears in a subjective mind. It then enters the intersubjective domain of reality where it propels structural change through exchanges of meaning between agents that together develop the idea, combine it with other ideas or transform it into something entirely different. As this process progresses, the technology may appear in the objective domain, where it propels structural change through the actions of agents. And if allowed to advance, it may even reshape reality at a planetary scale. Technology can thus be described as a malleable force of transformation – a causal power, if you will – that propels structural change and simultaneously changes its own characteristics. The emergence of new technologies can accordingly be described as a process of cumulative causation (Myrdal, 1957), characterized by feedback between technological development and diffusion, and its results. As we will see in the next section, it is this transformation process that I refer to as technological innovation.

Finally, this view of how technologies change over time also suggests that a given technology is difficult to demarcate from the rest of reality. As put by Rip and Kemp, who describe technology in terms of configurations that work, these "cannot be demarcated from the rest of society in a simple and obvious way. Things and skills are part of routines, of patterns of behavior, of organizations. They work only because they are embedded in this way. Furthermore, their work is not limited to serving the need implied by their official function." (Rip and Kemp, 1998, p. 331). How to precisely specify a particular technology, and describe how far it stretches into to objective, intersubjective and subjective structures that constitute reality, will be further elaborated when the conceptual contribution of this thesis is presented in Chapter 8. Indeed, developing the broad definition of technology provided in this section, into a conceptual framework that captures core tenets of technology and how it changes over time, is one of the core challenges addressed by this thesis.

3.3 Innovation as the development and diffusion of novelty

Innovation is a term that is used increasingly in academic, political and societal discourses. Some would even argue that it has in fact turned into a buzzword used to convey connotations such as positivity, modernity and creativity, rather than a precise meaning (Berkun, 2006; O'Bryan, 2020). It is therefore in order to specify how I understand this concept.

For starters, it should be noted that two quite different meanings are commonly attached to innovation. On the one hand, the term is used to refer to novelties, which may be ideas, products, practices, methods or technologies. In this sense, an innovation is a tangible or intangible thing (i.e. a structural configuration) that may be developed, diffused and used in society. On the other hand, the term is used to refer to the development and diffusion of novelties. This means that innovation is viewed not as a thing, but rather as an action or process (i.e. a structural transformation).

In this thesis, I will attempt to reserve the term innovation for the latter meaning. When referring to technological innovation, I thus mean the development and diffusion of new technologies, not new technologies as such or their utilization in the production and consumption of goods and services. This is in line with Nelson and Winter, who uses the term innovation "...as a portmanteau to cover the wide range of variegated processes by which man's technologies evolve over time." (Nelson and Winter, 1977, p. 37).

It is also worth highlighting that I do not make a Schumpeterian distinction between invention (as the creation and development of novelty) and innovation (as the introduction and diffusion of novelty). This is because the two are today intertwined to the extent that they cannot be disentangled in a meaningful way.[11]

[11] These days novelties are continuously developed and refined, sometimes beyond recognition, after their initial market introduction. The creation, development, introduction and diffusion of novelties are also processes that transcend organizational boundaries. As pointed out by Nelson and Winter (1977), Schumpeter wrote at a time when independent inventors often relied on separate firms to market their inventions, which made the distinction between invention and innovation more appropriate.

An attentive reader may here object that innovation and utilization with respect to a given technology are also intertwined and difficult to disentangle. In fact, testing, demonstrating and applying a new technology is an integrated part of its continuous development and diffusion. But although I certainly acknowledge the existence and importance of feedbacks between innovation and utilization, I maintain a conceptual distinction and view them as separate but intertwined processes. As we will see throughout this thesis, this is necessary to enable the development of conceptual frameworks that capture key aspects of technological innovation.

3.4 Applying the systems construct to technological innovation

When applying the systems construct to technological innovation, in order to create conceptual frameworks that support description and analysis, it is possible to focus on different kinds of structural components and depart from various functional perspectives. Put differently, analytical approaches may differ in how the structural and functional boundaries of the system in focus are delineated conceptually in relation to technological innovation as the phenomenon of interest.

To begin with, it is possible to develop conceptual frameworks that differ in the type of structures included by the structural boundary. Although technological innovation is a phenomenon that involves objective, intersubjective and subjective structures, this does not necessarily mean that all these types are included in a given conceptual framework. On the contrary, it is possible to apply structural boundaries that focus on any combination of structures and thereby capture different aspects of the innovation process.[12] As we will see in Chapter 4, conceptual frameworks used in the sustainability transitions literature in fact highlight systems that apply different structural boundaries in this respect.

To highlight these differences, it is worthwhile to already at this point establish a distinction between ecological, technical and social structures. This is a slightly different categorization than the distinction between objective, intersubjective and subjective structures, which forms a part of the metatheoretical foundation presented in Chapter 2. First, ecological structures refer to non-human life and its natural environment. Although some of these are geological and even cosmological, rather than ecological in a strict sense, I use the word ecological for simplicity. Note also that ecological structures transcend the objective, intersubjective and subjective domains of reality, since my ontological position acknowledges the existence of non-human

[12] A similar argument is provided by Rip and Kemp (1998) when they discuss a concentric view of technology as a phenomenon that involves hardware, software, orgware and socware.

consciousness and intersubjective communication. Second, technical structures refer to physical artifacts that have been designed with a human purpose in mind. They accordingly occupy a sub-set of the objective domain of reality. And third, social structures refer to human agents and their experiences as well as the agreements and shared meanings that govern their interaction. This means that they primarily occupy a sub-set of the intersubjective and subjective domains of reality, even though they are strongly associated with their objective manifestations (e.g. human bodies). It should be emphasized that ecological, technical and social structures are clearly intertwined and difficult, if not impossible to disentangle empirically. They are, however, mutually exclusive and collectively exhaustive from a conceptual perspective.

Depending on which of these structures the structural boundary includes, we may distinguish between different types of systems. Ecological systems include ecological structures, technical systems include technical structures, and so forth. In addition, there are systems that combine these basic types, such as socio-technical and socio-techno-ecological systems (Ahlborg et al., 2019). A comprehensive typology that highlights the seven possibilities this gives rise to is illustrated in Figure 3.1.

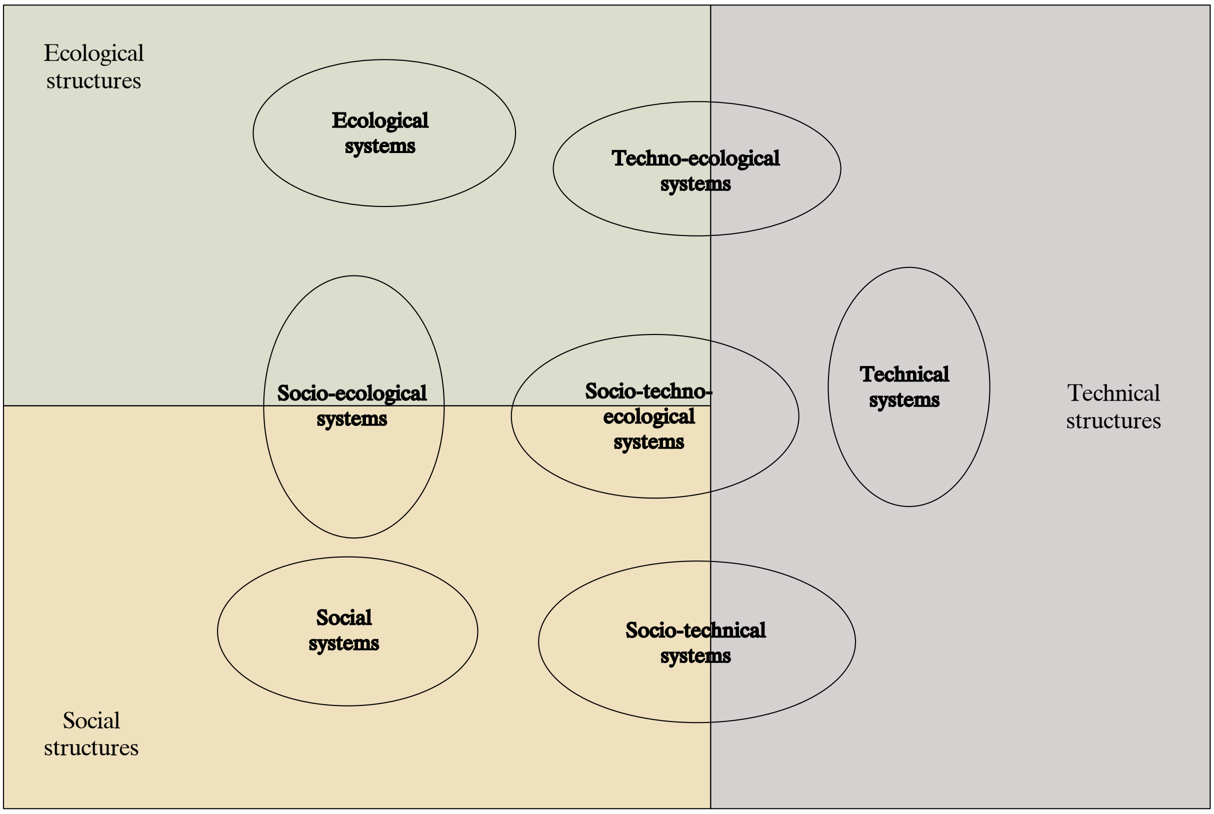

Figure 3.1. A typology of systems based on the type of structural components included by the structural boundary.

Furthermore, it is possible to develop conceptual frameworks that highlight different system purposes. In other words, they differ in the processes included by the functional boundary. As we will see in Chapter 4, conceptual frameworks used in the sustainability transitions literature are different in this respect as well. To enable a constructive discussion about these differences and pave the way for the conceptual contribution of this thesis, I here highlight three different ways in which structures can relate to technological innovation. First, there is a set of structures that utilize the technology in focus. The utilization of technology can be seen as production-consumption activities, organized in value chains of interlinked processes that together describe how different means are converted to a specific end. This end can be conceptualized as a focal product, which together with the associated value chains may, in layman terms, be viewed as an industry, or a part of an industry centered on a technology, and its related market. As will be further elaborated in Chapter 8, a technology can in fact be defined by specifying a focal product and a bundle of value chains. Second, there is a set of structures that develop and diffuse the technology in focus. They accordingly perform innovation activities that influence how technology is utilized by changing the characteristics of production-consumption activities. Notably, this may not only imply that technology is utilized more or less, but also in a different way. And third, there is a set of structures that are influenced by the utilization of technology, which implies that they are also influenced by its development and diffusion.

The three sets of structures are different with respect to what they do from a functional perspective. But in contrast to the domains which capture ecological, technical and social structures, the sets partially overlap from a structural perspective, since many structural components have multiple relationships with the innovation process. For example, firms in an industry are often involved in both production-consumption and innovation activities, while being affected by their outcomes. Conversely, there may exist structures that influence the development and diffusion of a technology, without taking part in its utilization. Possible examples include a research department at a university, a tax law or a generic infrastructure. In addition, there are structures that are only influenced by production-consumption activities, while neither being involved in them, nor influencing their characteristics. Examples include humans and animals harmed by pollution from increased production of some product, or parts of society indirectly benefitting from a stronger economy resulting from such growth.

In Figure 3.2, I 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, which accordingly have different functional boundaries.

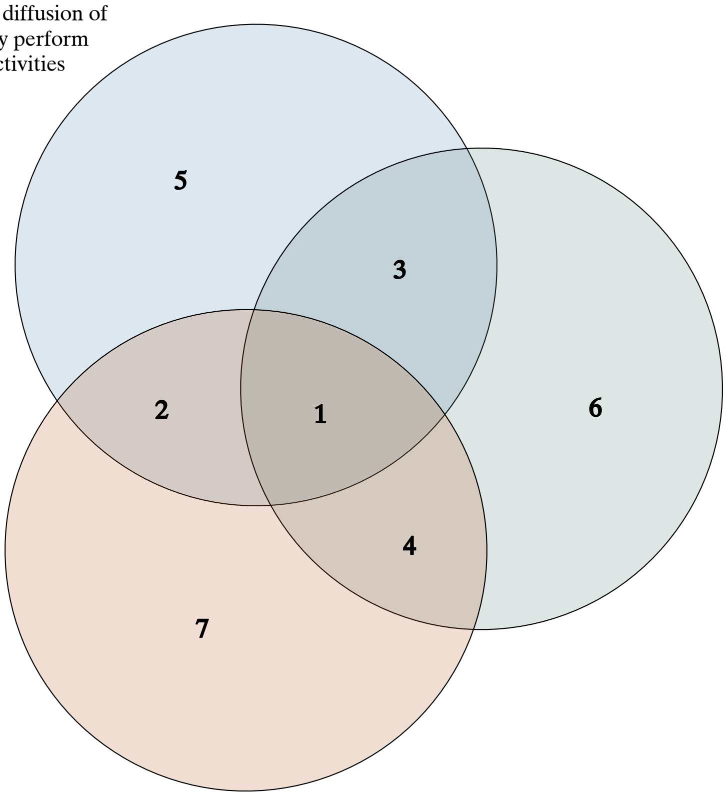

Figure 3.2. Three overlapping sets of structures that, respectively, perform innovation activities, perform production-consumption activities, and are influenced by innovation and production-consumption activities. The overlapping sets result in seven segments (1-7) of structures with similar relation to the technological innovation process.

It is, however, possible to argue that some of the segments in Figure 3.2 are non-existing in practice, or at least less interesting from an innovation perspective. To begin with, structures in both Segment 3 and 6 perform production-consumption activities, without being influence by their outcomes. This is arguably a situation that is difficult to imagine. Furthermore, structures in Segment 4 perform production-consumption activities and are also influenced by their outcomes, but do not engage in innovation activities. This suggests that they can be seen as a passive part of the industry subject to change. But we may also argue that such passive parts do not exist, at least not over longer time scales. After all, if an actor, or other structural component, is involved in production-consumption activities, they are likely to at least exert some influence on how these activities develop over time.

If it is accepted, or assumed, that structures in Segment 3, 4 and 6 are non-existing in practice, we may simplify Figure 3.2. This is illustrated in Figure 3.3, which also defines four types of systems (A-D), based on the functional characteristics of the structures they capture.

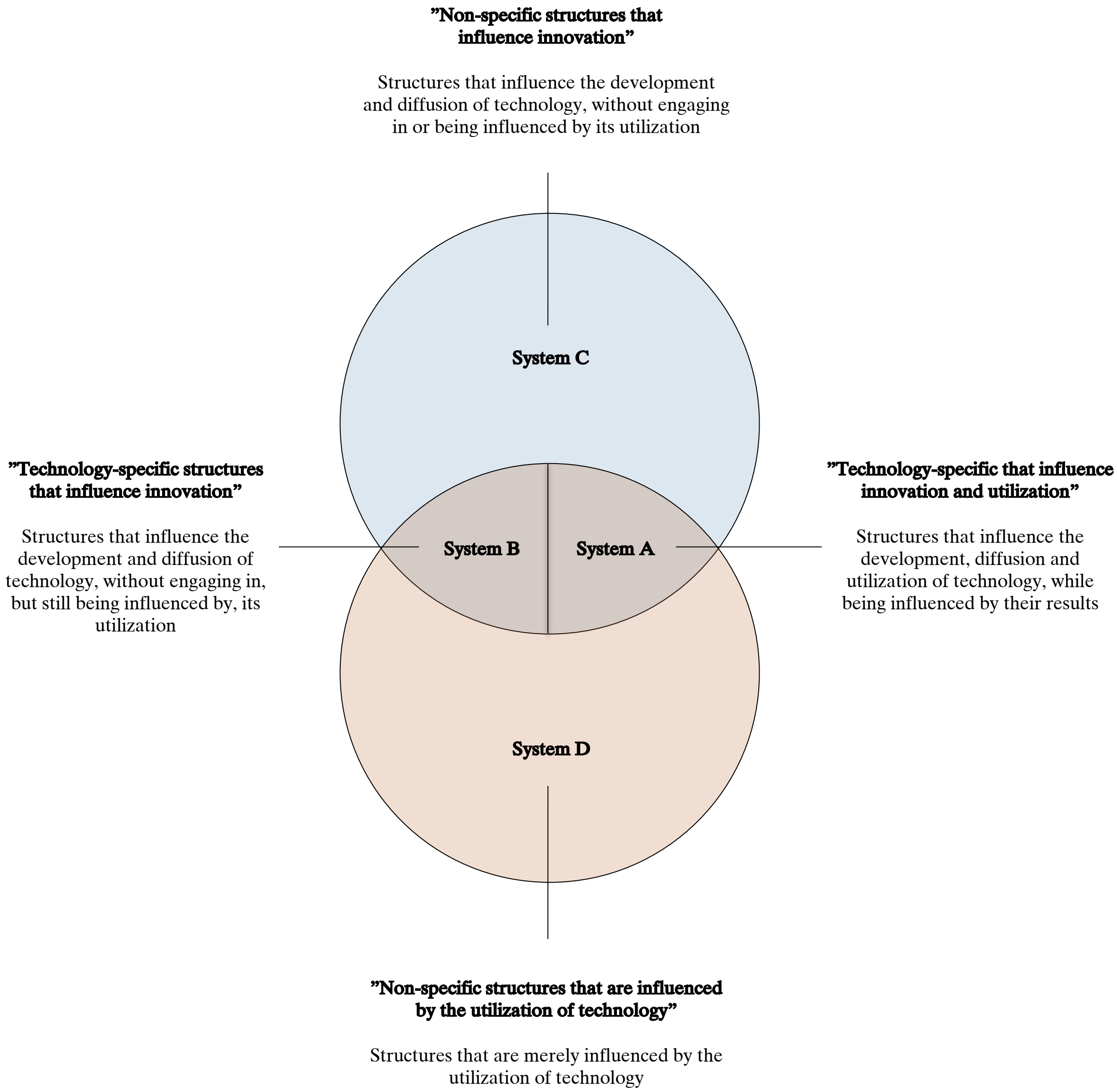

Figure 3.3. A simplification of Figure 3.2, which also defines four types of systems (A-D) based on the functional characteristics of the structures they capture.

The four types of systems defined in Figure 3.3 will be used as an analytical lens when reviewing the literature in the next chapter and also form the foundation for the conceptual contribution presented in Chapter 8.[13] They therefore deserve some elaboration. First, System A captures structures that influence the development, diffusion and utilization of technology. They perform

[13] Note that a slightly different definition of system types is employed in Paper IV. The underlying reasoning is identical, but the exposition in this introductory essay has (hopefully) made the arguments more accessible for the reader.

both production-consumption and innovation activities, while also being influenced by their outcomes. System A can accordingly be thought of as an industry, or a part of an industry centered on a specific technology, together with its related market. Second, System B captures structures that influence the development and diffusion of technology. They perform innovation activities and are influenced by their outcomes, but do not engage in production-consumption activities. System B include a range of more general structures supporting or inhibiting innovation. While not being directly involved in production-consumption activities, they would often not exist, or at least have a very different form, if it were not for the technology in focus. One example is a university research group focused on wind power development, which would not exist without wind power technology. Like structures in System A, the components of System B can therefore be understood as technology-specific. Third, System C captures structures that influence the development and diffusion of technology, without being influenced by the outcomes of this process or partaking in production-consumption activities. This type of structure can, for example, consist of a general tax law that influences the development and diffusion of a technology, without changing as a result of its utilization. Structures in System C may therefore be understood as non-specific to the technology in focus. Fourth, and lastly, System D captures structures that are merely influenced by the utilization of technology. Since these structures are not involved in the development, diffusion and utilization of technology, they can also be seen as non-specific. Notably, System D 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, B and C).[14] It should also be noted that the purpose of both System B and C is to *achieve change* of System A, System A is *subject to the change* caused by System B and C, and System D is *influenced by* System A (and, indirectly, by the change caused by System B and C).

To summarize this chapter, I first elaborated on the conceptual meaning I attach to the notion of systems and described how I choose to define technological innovation as the phenomenon of interest in this thesis. I then discussed different ways to apply the systems concept when investigating this phenomenon, by highlighting different ways to delineate structural and functional boundaries. These ideas will be used in the next chapter, where I position my work in relation to the sustainability transitions literature and further specify the conceptual research problem addressed by this thesis.

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[14] This means that one can question whether these structures should be referred to as a system. Nevertheless, I do so for the purpose of simplicity.

CHAPTER 4 – LITERATURE REVIEW AND RESEARCH PROBLEM

The research presented in this thesis is situated in the vibrant, diverse and growing field of sustainability transitions research.[15] What unifies scholars in this tradition is an interest in understanding and promoting sociotechnical change processes that lead towards more sustainable modes of production and consumption in society (Köhler et al., 2019). Such transitions are fundamentally about what I refer to as the shaping of technological innovation, which makes this field an appropriate point of departure for this research. The focus of this chapter is to position my work in relation to this literature and elaborate on the conceptual research problem addressed by this thesis.

In the following sections, I will first trace the historical roots of sustainability transitions research in four streams of ideas and literature. Then I describe the emergence of two approaches to studying transitions and identify the technological innovation systems framework as a suitable conceptual starting-point for this research. Based on a detailed review of the literature that engages with this framework, carried-out from the analytical perspective presented in the previous chapter, I proceed to identify areas that call for conceptual development. In the end, I argue that these constitute knowledge gaps that should be addressed by conceptual development and empirical investigation.

4.1 Historical roots

What is today thought of as sustainability transitions research has its intellectual roots in a broad range of social, cultural, political, technological and scientific developments. Although I will

[15] For simplicity, I will at times refer to “transitions” rather than “sustainability transitions”.

refrain from even attempting to review these in a comprehensive manner, four particularly important streams of ideas and literature, brought forward in the second half of the 20th century, can be identified: the emergence of systems thinking, evolutionary economic theorizing, sociological and historical perspectives on technology, and the environmental movement. Below, I will review these briefly to provide a historical context for subsequent developments.

4.1.1 Systems thinking[16]

The first stream is the emergence of what is today commonly referred to as systems thinking, which is based on ideas brought forward from the 1950's and onwards, by scholars from different backgrounds. In particular, the works of the mathematician Norbert Wiener (Wiener, 1948) and the biologist Ludwig von Bertalanffy (Bertalanffy, 1950) are considered important starting-points. Weiner was interested in how machines, organisms and organizations control their behavior, and described the dynamics of feedback mechanisms and their balancing and reinforcing effects (Wiener, 1948). Although he mainly referred to machines, and also coined the term cybernetics to describe his theory of communication and control, these terms are widely understood as largely analogous to what other scholars called systems and systems theory (Ingelstam, 2012). Bertalanffy had a slightly different objective as he described and promoted the idea of a more general systems theory (Bertalanffy, 1950). In his work as a biologist, he had observed principles that seemed applicable to any system and that could be brought together in a metatheory with the potential to strengthen the rigor of individual scientific disciplines and improve interdisciplinary communication. These ideas quickly attracted scholars from different fields, and in 1954, Bertalanffy founded The Society for the Advancement of General Systems Theory, together with the economist Kenneth Boulding and the biomathematician Anatol Rapoport (Ingelstam, 2012). This network would play an important role in the development of general systems thinking until its activities faded towards the end of the 1980's.

Although there are certainly differences in the approaches adopted by the early scholars in this tradition, they share a common ambition to understand the attributes and behaviors of wholes, which makes them deviate from the reductionist strife to decompose phenomena into basic components and find elementary laws. This leads them to develop and define the different concepts and ideas that we today use to describe and analyze systems (Bertalanffy, 1950; Boulding, 1956; Churchman, 1968; Foerster, 1960; Forrester, 1961; Simon, 1962; Wiener, 1948). For example: wholes are conceptualized as systems that consist of interdependent components

[16] In this section, I am greatly indepted to Lars Ingelstam's (2012) comprehensive and eloquent summary of the key lines of research that constitute the emergence of systems thinking.

and their interconnections; any component can be understood as a lower level system, and any system can viewed as a component in a higher level system; different systems can be identified based on the characteristics of their components; systems are separated from their environment by system boundaries, but there is most often interaction across these boundaries; system boundaries are commonly derived from the idea of a purpose or function that the system fulfills in its wider environment; system dynamics are governed by feedback mechanisms that may suppress or reinforce a particular behavior; and so forth. Moreover, they realize that these ideas are widely applicable and in fact built into most, if not all, scientific disciplines. This leads some leading thinkers, notably Bertalanffy (Bertalanffy, 1968) and Boulding (Boulding, 1956), to argue that systems thinking should be advanced towards a general metatheory.

In the early days of systems thinking, the focus of application was on technical artifacts and organisms. This should not come as a surprise given the disciplinary backgrounds of scholars like Bertalanffy and Weiner. There is, however, an increasing interest in applying systems thinking to matters that involve social phenomena such as organizations and whole societies. This is encouraged by Bertalanffy who opens up for systems that are purely conceptual and difficult to describe mathematically, while Weiner maintains that his theories are a part of the mathematical sciences (Ingelstam, 2012). However, the study of social systems not only make it challenging to use formal analytical methods based on quantitative measurements. It also implies that the system which is observed has the ability to observe itself. This is noted by Heinz von Foerster, who made a sharp distinction between systems that are observed and systems that are observing, by referring to the latter as second order cybernetics (Foerster, 1960).

For the purposes of this thesis, a particularly important line of development focused on social systems starts with dynamic models of firms and industries, developed by scholars such as Jay Forrester (Forrester, 1961) and Stafford Beer (Beer, 1972). As we will see, these models not only provided insights with important implications for subsequent theorizing about technological innovation, but also served as the intellectual foundation for the research which led to the influential publication Limits to Growth (Meadows et al., 1972).

Finally, it should be noted that while systems concepts can be used for both descriptive and design purposes (Simon, 1962), an orientation towards solving problems has from the start been strong among many systems theorists. One prominent figure in this context is C West Churchman (Churchman, 1968), who brings forward many familiar insights about the potential and limitations of systems analysis as a problem-solving tool. In fact, he introduced the concept of wicked problems, which is ever more relevant and important in the current era of ecological crisis (Churchman, 1967).

4.1.2 Evolutionary economic theorizing

The second stream consists of mounting critique against neoclassical economic theories that had come to dominate economic thinking. These theories make far-reaching assumptions about the rationality and capability of economic agents, and view the supply of capital and labor as the key determinants of economic development. The economy is portrayed as a system dominated by negative feedback mechanisms due to decreasing returns, which make it gravitate towards an equilibrium that represents an efficient allocation of resources. This idea of an economy that by nature strives towards an optimal state of affairs is commonly highlighted with reference to Adam Smith's notion of 'the invisible hand'.

What is perhaps most striking about neoclassical models is that they largely neglect the role of knowledge as an intangible resource and thus fail to see the crucial importance of learning in explanations of firm performance and economic growth. As put by Lundvall, it was as late as "the beginning of the 1980s [...] a standard assumption among economists and policy makers that reducing national nominal wages or devaluing the national currency was the most effective—and perhaps the only—way to enhance international competitiveness of domestic firms" (Lundvall, 2007, p. 97). The limitations brought by this limited view was of course debated and recognized. It was shown that changes in the supply of labor and capital could only explain a minor part of observed economic growth, and it was acknowledged that the residual was due to improved technologies (Solow, 1957). However, the common response to this key insight was to treat technology as a production factor that was determined by investments in research and development.[17] This linear conception of technological innovation not only came to dominate among economists and policymakers, but was also institutionalized through systems of reporting and measuring innovation related statistics (Freeman, 1995). And the fact that technology was still treated as an exogenous factor meant that basic economic models, and the limited understanding of economic realities they brought, remained largely intact.

At the same time, however, evolutionary economists realized that technological innovation has characteristics that are incompatible with the very core of neoclassical economic models. To begin with, it is a collective process. Technological innovation is not restricted to research and development departments within producing firms, but rather involves managers and workers as well as customers, collaborating firms and research organizations (Freeman, 1995; Mowery and

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[17] As noted by Freeman (1995), this has to be seen against a background of hugely influential science-driven technological break-throughs in the beginning of the 20th century, which surely made it seem as if new technologies were pushed towards consumer markets by the means of science.

Rosenberg, 1979). Furthermore, technological innovation is cumulative. New technologies are often combinations of existing technologies, and any improvement or advancement, no matter whether it concerns equipment, products, processes or practices, is intimately bound to previous achievements (Nelson, 1994). In addition, technological innovation involves competition among alternatives. When a new technology comes into existence many alternative designs compete for resources and recognition, but as the innovation process continues, the number of alternatives is gradually reduced and eventually a dominant design emerges (Abernathy and Utterback, 1978). This process of selection also seems to follow certain natural trajectories, which are formed within broader technological paradigms (Dosi, 1982; Nelson and Winter, 1977).

It was accordingly argued that technological innovation is an evolutionary phenomenon, characterized by processes of generation, competition and selection. Moreover, it was emphasized that throughout these processes, minor events may have major consequences (Arthur, 1989; Nelson, 1994). For example, if a technology gains an advantage over its competitors, it will be seen as a more viable candidate, its proponents will find it easier to mobilize resources for further development, and so forth. And since an advantage can come about in ways that have little to do with the long-term potential of the technology, ranging from lobbying by interested parties to pure chance events, this means that inferior technologies may get locked-in at the expense of more desirable alternatives.

In contrast to neoclassical thinking, the evolutionary economists thus highlight that the economy is a system characterized by positive feedback mechanisms due to increasing returns (Arthur, 1994, 1989; Dosi and Nelson, 1994).[18] This turns the idea of an invisible hand that guides developments towards an optimal state of affairs upside down. Although there are negative feedback mechanisms that may lead to temporary stabilization around local equilibria, the economy is constantly pulled in different directions through technological innovation, and any movement along a particular path is reinforced through processes of cumulative causation. Technological innovation is accordingly more than a factor – it is the fundamental driver and shaper of economic change.

These insights were not only interesting, but also come with important implications for policymakers interested in stimulating economic growth. In contrast to the prevailing idea that policymakers should limit their interventions to correcting for so-called market failures, the evolutionary perspective implies that they may go further by enhancing learning processes in the

[18] This had also been noted by scholars in the systems tradition (Wiener, 1948) and early economists such as Alfred Marshall (Marshall, 1890).

economy (Metcalfe, 1995). It also means that choices with regards to technological and economic developments cannot conveniently be left to market forces, but rather have to be resolved through the political process.

4.1.3 Sociological and historical perspectives on technology

The third stream originated from sociologists and historians with an interest in science, technology and society as interlinked phenomena. These scholars investigated how the social construction and interpretation of meaning shapes technological innovation, and thus went beyond the predominant focus on technical and economic aspects. Within this tradition, three perspectives emerged as rather distinct ways of conveying the intertwined nature of technology and society: social construction of technology, large technological systems and actor network theory (Bijker et al., 1987).

The social construction of technology perspective is mainly associated with the sociologists Wiebe Bijker and Trevor Pinch (Pinch and Bijker, 1984). Focusing on the development of technical artifacts, these scholars realized that the identification and formulation of design problems, as well as the generation, development and eventual selection of solutions, is laden with what is referred to as interpretative flexibility. This means that the innovation process is shaped by socially constructed ideas, rather than objective facts. In addition, Pinch and Bijker (1984) acknowledge that a wide range of actors are involved in defining and solving problems. It is argued that groups of actors with shared attitudes towards a technical artifact may influence how other actors think about and value its characteristics, which in turn shapes the innovation process.

There are clearly parallels between these ideas and evolutionary perspectives on technological innovation. But where the economists tend to describe the evolutionary characteristics of higher level processes involved in developing the set of technologies used in the economy, Pinch and Bijker (1984) focus on the micro-processes involved in developing a specific technology. In other words, the black box of technology is opened as ideas, rather than technologies, are adopted as the units subject to evolution.

The concept of large technological systems was introduced by the historian Thomas P. Hughes in a famous empirical study of electrification in western society (Hughes, 1983), and was subsequently used in a number of empirical studies (see the edited volume by Jane Summerton (Summerton, 1994)). The concept highlights how physical artifacts, organizations, laws and regulations, and natural resources, are interlinked in a seamless web. Through their interaction, these social and technical components solve problems and fulfill goals, which revolve around changing the physical world in useful or desirable ways. The components are also highly interdependent; if one of them is modified or removed, the others change accordingly. Not surprisingly given these characteristics, Hughes (1987) chose to adopt the notion of a (large) technological system. On the one hand, this system shapes society as the seamless web of social and technical components expands and increasingly incorporates structures in its context. But on the other hand, it is socially constructed, since the seamless web is woven by actors that actively build the system by mobilizing and developing its components, in an evolutionary process where different systems compete for dominance.

These ideas accordingly combine evolutionary, organic and systems perspectives on technological innovation. With regards to the latter, it should be noted that while Hughes (1987) is quite clear about the components and purpose of technological systems, he neither discusses their boundaries nor offers a formal model of how they change over time. He does, however, propose that technological systems have two kinds of environments; one that influences the system, and another that is influenced by the system. This not only suggest a certain degree of sophistication in his use of the systems concept, but also indicates that he has an inductive approach to boundary setting.

Actor network theory is mainly associated with sociologists such as Michel Callon, Bruno Latour and Steve Woolgar (Callon, 1987; Latour and Woolgar, 1979). They highlight the interlinked characteristics of society and technology by referring to a socially constructed actor network, which consists of interdependent components. These components have a complex nature and can in fact be seen as networks in themselves. Notably, all components are called actors, or actants, even though they have both social and technical characteristics. The concept of an actor is thus expanded to include inanimate entities, which is a hallmark of actor network theory.

Despite the parallels that can be drawn between the idea of an actor network and a technological system, proponents of the former theory strongly reject the notion of a system. In the words of Callon: “The systems concept presupposes that a distinction can be made between the system itself and its environment. In particular, certain changes can, and sometimes must, be imputed to outside factors. The actor-network concept has the advantage of avoiding this type of problem and the many difficult questions of methodology it raises.” (Callon, 1987, p. 100).[19]

Finally, it should be noted that even though both social construction of technology and actor network theory are quite often interpreted as based on an idealist ontology, nothing prevents the two perspectives to be employed by scholars that assume the existence of an objective reality

[19] The attentive reader may notice that the reality portrayed by actor network theory lies close to my ontological assumptions, although the terminology differs. What actor network theoreists seem to reject, however, is my way of using the systems concept as a metatheoretical construct.

(Bijker, 2010). In my opinion, it is likely that the confusion boils down to the way key concepts span the physical and non-physical domains of reality. For example, the terms technology and artifact often refer to both material objects and immaterial knowledge, which implies that they are both objective and intersubjective (i.e. social constructs) at the same time.

4.1.4 The environmental movement

The fourth and final stream of ideas and literature can be described as the increased awareness about environmental degradation and the rise of a global movement that promotes global sustainable development. This environmentalism has a different character than the developments discussed above, since it is not merely a field of research, but rather transcends scholarly work, politics and civil society (Dauvergne, 2009).

Although efforts to reduce human impacts on the natural environment dates back thousands of years, and also intensified as resource extraction and pollution grew in the wake of the industrialization, it was not until the mid 20th century that a global environmental movement emerged. Rachel Carson's influential book Silent Spring (Carson, 1962), in which she documents the ecological problems caused by the use of pesticides and shows that the chemical industry spreads disinformation and manipulates public officials, is often seen as an igniting spark that raised public awareness about the adverse environmental effects of the modern economy. A decade later, the global perspective was highlighted by Donella Meadows and colleagues (Meadows et al., 1972) in their much debated book Limits To Growth. Using ground-breaking computer simulations, based on ideas from the emerging field of system dynamics (Forrester, 1961), they argued that the carrying-capacity of the natural environment sets limits to economic expansion, which was of course highly controversial at the time.

These and many other important scholarly works inspired, and was perhaps inspired by, civil society developments. Non-governmental organizations such as WWF, Friends of the Earth and Greenpeace, which had roots in 19th century environmental conservation movements, were founded, grew rapidly and had by the 1980's established an international presence (Dauvergne, 2009). Throughout the post-war period, environmental activism was also intertwined with the peace movement and coupled with concerns about the proliferation of nuclear weapons.

After the 1960's, the environmental movement also started to influence governments around the world. These not only established environmental agencies and introduced national legislation, but also sought international collaboration to face an issue that was increasingly seen as global. In 1972, the first UN Conference on the Human Environment was held in Stockholm, Sweden. This became the starting-point for intensified international negotiations that resulted in a number of environmental treaties. However, these were most often focused on a specific problem such as the trading of endangered species and dumping of waste in oceans.

It was not until the end of the 1980's that the policy perspective broadened to cover what we now refer to as sustainability and sustainable development. These terms were popularized through the publication of Our Common Future (WCED, 1987) – the so-called Brundtland-report – which was based on a UN mandate to examine environmental and development issues. Importantly, the report established a firm link between environmental degradation and poverty, arguing that sustainable development had to balance objectives in the environmental, social and economic domains. Around the same time, a consensus had also formed among scientists that carbon emissions from human activities were increasingly driving global warming. In 1988, the Intergovernmental Panel on Climate Change was established in order to continuously provide scientific assessments of the current state and knowledge about this issue (IPCC, 2020).

Finally, in 1992, world leaders gathered for a UN sponsored Earth Summit in Rio de Janeiro, Brazil. This meeting clearly illustrates the momentum which characterized the environmental movement in the 1980's and early 1990's. But even though two major treaties on biodiversity and climate change were negotiated, the political climate was about to change (Dauvergne, 2009). Other issues called for attention and it had become increasingly clear that mitigating global environmental problems might threaten economic growth in western society. But nevertheless, the environmental movement since the 1960's had made its mark. Not least in academia where an increasing number of researchers were drawn to investigating sustainability issues from various perspectives.

4.2 The emergence of two approaches to sustainability transitions

In the 1990's, two different approaches to studying what would later be called sustainability transitions emerged from the streams of ideas and literature reviewed in the previous section – technological innovation systems and technological transitions. These have in common that they draw on insights from systems thinking, evolutionary economic theorizing and sociological perspectives on technology, while focusing on and explicitly promoting technological innovation processes related to the environmental movement. But at the same time, they choose to observe transitions from slightly different perspectives. Where the technological innovation systems approach focuses on the emergence of specific new technologies in early development stages, the technological transitions approach is more concerned with how established economic sectors are challenged by and interact with innovative niches (Markard and Truffer, 2008a). In the following, I will review the emergence and core features of these approaches.

4.2.1 The technological transitions approach

The technological transitions approach was developed by Arie Rip, René Kemp and colleagues in the 1990's (Kemp, 1994; Kemp et al., 1998; Rip and Kemp, 1998). These scholars were interested in sustainability-driven and fundamental shifts in sociotechnical systems of production and consumption. In particular, they sought to explain why the emergence of environmentally benign technologies is a slow and difficult process, even though it would bring substantial benefits.

Building on the ideas from evolutionary economic theorizing (Dosi, 1982; Nelson and Winter, 1977) and sociological perspectives on technology (Hughes, 1987; Pinch and Bijker, 1987), the early transitions scholars furthered the concept of technological regimes (Kemp, 1994; Rip and Kemp, 1998). In their version, technological regimes not only describe the search heuristics of researchers and engineers, which had been the focus of previous literature (Dosi, 1982; Nelson and Winter, 1977), but rather "the whole complex of scientific knowledges, engineering practices, production process technologies, product characteristics, skills and procedures, and institutions and infrastructures that make up the totality of a technology" (Kemp et al., 1998, p. 182). On the one hand, these structures constitute the existing technologies that any novel alternative must compete with. On the other hand, they stretch into the selection environment in which novelties emerge by providing a set of rules that guide actors involved in innovation processes.[20] From an evolutionary perspective, this means that there are coupled dynamics between processes of variation and selection.

As a result of these coupled dynamics, technological trajectories that favor novelties in line with the technological regime tend to form, while the outcomes of innovation along these trajectories in turn strengthen the regime further. This process of cumulative causation leads to stability and inertia, which hinders the emergence of radically different alternatives. Put differently, the development and diffusion of environmentally benign technologies may require shifts from unsustainable to sustainable technological regimes – in fact, these shifts constitute what is commonly called sustainability transitions.

The early transitions scholars also noted that successful technologies tend to develop in specialized niches (Kemp, 1994; Kemp et al., 1998; Rip and Kemp, 1998). These serve as protected spaces in which processes of learning and institutional adaptation can unfold without being exposed to competition and negative pressure from the technological regime. In particular, niches are considered crucial to build a critical mass and initiate processes of cumulative causation in early development stages. They may in fact be viewed as breeding grounds where

[20] Notably, the rule-aspect is what makes the authors use the term regime, rather than paradigm or system (Kemp et al., 1998).

new technologies are brought from early prototypes to viable alternatives that can compete with, and potentially replace, the prevailing regime.

This leads to the development of a policy approach based on the strategic management of niches. It is defined as “the creation, development and controlled phase-out of protected spaces for the development and use of promising technologies by means of experimentation, with the aim of (1) learning about the desirability of the new technology and (2) enhancing the further development and the rate of application of the new technology.” (Kemp et al., 1998, p. 186). Notably, this is an approach that not only targets research and development with respect to a specific technology, but also broader learning processes and institutional alignments necessary to eventually replace an existing technological regime.

At the same time, the reasoning behind concepts such as technological niches and regimes clearly shows that technological innovation is a highly complex and uncertain process that is difficult to shape towards desirable outcomes. In fact, the objectives of policy intervention are often contested and also change as more knowledge about technological options and their consequences is developed. To deal with this reality, transitions management is proposed as an alternative policy approach focused on learning, involvement and continuous modulation of innovation dynamics (Rotmans et al., 2001).

While combing niches, technological regimes and broader sociotechnical landscapes, to form a framework explaining the dynamics of transitions, was in fact suggested by Rip and Kemp (1998), this idea would be further developed and popularized by Frank Geels in the early 2000’s. In a number of foundational publications (Geels, 2005, 2004, 2002), he outlined a multi-level perspective on transitions, which focuses on interactions among developments on the niche, regime and landscape levels. Together with strategic niche management and transitions management, the multi-level perspective has become a key analytical framework in the technological transitions approach.

At first, the literature based on the multi-level perspective portrayed transitions as a process characterized by tensions and incompatibilities between niches and regimes; the latter is stable and difficult to change, but developments in the sociotechnical landscape may create windows of opportunity that enable niches to gain momentum, break-through and eventually replace the old regime. However, later publications have moved away from this stylized and simplistic pattern, and developed a more nuanced understanding of the ways in which transitions unfold (Markard et al., 2012). In particular, it has been emphasized that actors associated with the technological regime, such as incumbent firms, not always resist change. On the contrary, they may act as important promoters of radical alternatives and also control resources that may be decisive for successful transitions.

4.2.2 The technological innovation systems approach

The technological innovation systems approach (I will henceforth adopt the commonly used acronym TIS) has its origin in a family of systems frameworks that adopt a nation, region, sector or technology as the point of departure. These in turn emerged from the national innovation system concept, which is mainly associated with Bert-Åke Lundvall, Chris Freeman and Richard Nelson.[21] These scholars collaboratively developed and diffused this concept in a number of publications in the late 1980's and early 1990's (Freeman, 1988; Lundvall, 1992; Nelson, 1993). They drew upon evolutionary economic ideas and accumulating empirical evidence that pointed out innovation as the key driver of economic development (Nelson and Nelson, 2002). They realized that learning not only takes place within firms, but rather depends upon the interaction of a wide range of actors, including firms that produce and use new products as well as organizations dedicated to research and education (Freeman, 1995). And they acknowledged the importance of institutions that influence how firms and other organizations interact (Lundvall et al., 2002). Since these characteristics were largely neglected by neoclassical economic theories and contemporary policy approaches, the national innovation systems concept was introduced as an alternative analytical framework (Lundvall, 2007). Although this brought a focus on the broad range of factors that influence innovation processes in a specific country, a commonly accepted definition of national innovation systems was never established.

The ideas behind the national innovation systems concept were nevertheless quickly adopted by scholars that begun developing other innovation-related systems frameworks. To begin with, scholars such as Charles Edquist (Edquist, 2004, 1997) chose to focus on general innovation systems that are not necessarily confined to a specific country. Instead, the concept is discussed without setting an a priori spatial boundary and used to describe real interactions that can be found on different levels of analysis (Borrás, 2004). Furthermore, scholars such as Philip Cooke (Cooke, 2008, 1992; Cooke et al., 1997), who were interested in the economic performance of regions larger than a municipality but smaller than a nation, introduced the regional innovation systems concept. In this strand of literature, innovation systems are understood as real entities that are "discovered", which is the basis of arguments for why the national level of analysis is not appropriate (Cooke et al., 1997). However, other scholars adopt a more nuanced view, as they focus on the links between innovation systems at national and regional levels, while

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[21] As these authors often highlight, the basic ideas were inspired by the economist Friedrich List who focused on the creation of productive forces rather than allocation issues (Freeman, 1995; Lundvall, 2007). Notably, List was active in the mid 19th century, which is before neoclassical theories became the dominant paradigm.

highlighting that firms in regional clusters exploit both local and global resources (Asheim and Isaksen, 2002). In addition, scholars such as Franco Malerba (Malerba, 2005, 2002) introduced sectoral innovation systems, which create, develop and diffuse a specific set of products. Although this implies a focus on a specific type of innovation, the sociotechnical delineation is broad and includes all technologies that are involved in fulfilling an overarching function related to a set of products. It should also be noted that sectoral innovation systems are clearly distinguished from sectoral production and consumption systems. In fact, the concept emerged from the earlier and broader notion of sectoral systems of production and innovation (Malerba, 2002).

What would be most influential for the development of the TIS approach, however, is the technological systems concept developed by Carlsson and Stankiewicz (1991). While they followed other early innovation systems scholars in adopting an evolutionary perspective, important inspiration was also found in the concept of development blocks that had been introduced by the economist Eric Dahmén in the 1960's (Dahmen, 1950; Dahmén, 1988). As will be further discussed later in this chapter, Carlsson and Stankiewicz (1991) did not limit their concept to innovation. The focus on novelties and innovation-related activities was instead introduced in later publications, which also added the term innovation to the basic concept.

At first, the literature on technological (innovation) systems had little to do with sustainability. The concept was used and developed by Swedish scholars through case studies of factory automation, where the ambition was to inform policymaking that aimed to promote specific technologies in order to achieve economic growth (Carlsson, 1995). But as it were, empirical investigations increasingly came to focus on renewable energy (Johnson and Jacobsson, 2001). The TIS approach was also adopted by other scholars with an interest in studying emerging technologies that could contribute to sustainable development. In the end, it would become a complement, or perhaps competitor, to the technological transitions approach in the emerging sustainability transitions community.

As it stands today, the TIS literature focuses on technologies that may reduce environmental impacts. It provides a conceptual framework that has gained prominence as a valuable tool for identifying problems in technological innovation processes and devising intervention strategies for policymakers and other actors. In contrast to the literature on technological transitions, the focus is generally on one or several specified technologies, rather than on a broader economic sector. And even though the influence of existing sociotechnical structures is certainly taken into account, investigations focus more on innovation dynamics related to the emerging technology. Although attempts have been made to integrate the technological transitions and TIS approaches (Markard and Truffer, 2008a), they are widely considered to be distinct lines of inquiry that highlight different aspects of sustainability transitions.

In this thesis, I am mainly concerned with investigating how sociotechnical change associated with specific emerging technologies can be shaped towards desirable outcomes. This implies that the TIS approach is an appropriate point of departure for conceptual development and empirical investigation. It should be noted, however, that given my understanding of technology, nothing in principle prevents me to view an economic sector, or even the entire global economy, as a technology. Since this implies that the growth of economies and sectors can be conceptualized as the emergence of new and decline of existing technologies, the technological transitions approach, as well as other innovation systems concepts, are strongly linked to the contribution of this thesis. I will return to this issue in the discussion.

4.3 Technological innovation systems and the direction of change

A growing strand of sustainability transitions research applies the TIS framework to studies of emerging 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 literature has a strong focus on emerging technologies with lower environmental impact than established alternatives, and most analyses are oriented towards informing policymakers with an interest in promoting their development and diffusion. 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 (Swedish Energy Agency, 2014).

A prominent feature of most TIS studies is the use of so called ‘functions’ as a way to analyze the performance and dynamics of processes that govern the development and diffusion of new technologies (Bergek et al., 2008a; Hekkert et al., 2007; Hekkert and Negro, 2009). Several typologies of such processes have been proposed in the literature, but most focus on phenomena such as development and diffusion of knowledge, experimentation with new ideas, mobilization of resources, development of legitimacy, direction of search processes and the formation of markets (Bergek et al., 2008a; Hekkert et al., 2007).[22] Foregrounding processes enables a more dynamic analysis, focused on interrelatedness, cumulative causation and feedback. This creates an analytical toolbox that can be used retrospectively, to describe and learn from the historical emergence of new technologies, as well as prospectively, to identify current strengths and weaknesses that may inform policy intervention aiming to propel the system towards a future goal. Note that I will henceforth distinguish this key concept (i.e. 'functions') from other meanings of the term function by using single quotation marks.

Using the concept of 'functions' as an analytical starting-point, TIS scholars have examined how different factors stimulate or hinder innovation processes. Although much attention has been given to technology specific policies (Andersson et al., 2017; Quitzow, 2015; Reichardt et al., 2016), studies have also focused on other aspects such as the role of researchers (Perez Vico, 2014), research infrastructure (Hellsmark et al., 2016), incumbent firms (Markard and Truffer, 2008b), networks (Musiolik et al., 2012) and institutions (Wirth et al., 2013). Furthermore, scholars have increasingly explored the influence of contextual factors that exist beyond the focal TIS, by analyzing how other emerging technologies (Sandén and Hillman, 2011), established industry sectors (Wirth and Markard, 2011), the financial sector (Karltorp, 2016; Karltorp et al., 2017), the educational sector (Jacobsson and Karltorp, 2012) and the political landscape (Kivimaa and Virkamäki, 2014; Markard et al., 2016) exert a positive or negative influence on the innovation process. In addition, a number of studies have highlighted the importance of geography, showing that innovation processes are sometimes carried-out in global networks that transcend specific regions (Binz et al., 2014) and that developments in different regions may exhibit coupled dynamics that influence their performance (Binz et al., 2017).

With regards to the direction of change, the focus on a specific technology, which is inherent to the TIS approach, implies an interest in shaping innovation processes. Choosing to scholarly investigate (or by policy means support) a TIS, rather than a national or regional innovation system, suggests an analytical (or policy related) goal which points to a certain technological direction. In cases where the focal technology is limited to a specific region, the goal also involves a spatial direction. But at the same time, the literature rarely acknowledges that the dynamics of TISs can result in different configurations, both within and beyond a specified goal. The topic is raised in studies that examine spatial shifts in the emergence of industries and markets (Andersson et al., 2018; Binz et al., 2017, 2015; Dewald and Fromhold-Eisebith, 2015; Quitzow,

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[22] It should be noted that the early sets used in the literature were developed based on literature reviews (Bergek et al., 2008a), which may explain certain overlaps between categories and divergent interpretations in later publications.

2015; Zhang and Gallagher, 2016), as well as the dynamics which underlie technological trajectories (Hillman and Sandén, 2008; Hojcková et al., 2018; Markard et al., 2009; Suurs and Hekkert, 2009), but it is still argued that existing publications mainly focus on quantitative diffusion of homogenous technologies (Yap and Truffer, 2018).

When building on the TIS literature in investigations that focus on shaping rather than stimulating technological innovation, a number of conceptual ambiguities also rise to the surface. It is, for example, not obvious whether TISs should be interpreted as systems that create new industries, as systems that become new industries, or a combination of the two. Since this and other core features of the TIS framework are particularly important for studies that focus on directions rather than growth, the next section will take a closer look at the ideas brought forward in foundational publications.

4.4 A critical review of the foundational literature on technological innovation systems

Although the historical roots and more recent emergence of the TIS framework involve a large number of influences, the frame of reference used by scholars that apply and advance the framework is often limited to five widely cited foundational publications (Bergek et al., 2008a, 2008b; Carlsson and Stankiewicz, 1991; Hekkert et al., 2007; Markard and Truffer, 2008a). In this section, I will review these foundational publications in some detail, in order to shed light on the conceptual ideas on which the cumulative TIS literature builds.[23] The review adopts a systems perspective and focuses on how the components, purpose, boundaries and dynamics of TISs are described. Note also that I will at times refer to the four types of systems introduced in Section 3.4 and illustrated in Figure 3.3 (System A-D).

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. 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

[23] Numerous other publications by these and other scholars were certainly important in the early development of the TIS framework. It is beyond the scope of this introductory essay to provide a full review, which is why I focus on these widely cited papers. Notably, their extensive citation also indicates that later scholars have mainly learned about the TIS framework through these contributions, which justifies viewing them as foundational for subsequent conceptual development and empirical investigation.

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 use the term to refer to sociotechnical systems in contemporary work (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, which is in line with a System B or C, rather than a System A, as illustrated in Figure 3.3. 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, which is more in line with a System A. 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.

Lastly, while Carlsson and Stankiewicz (1991) highlight multiple factors that influence the dynamics of innovation processes, there is little reference to the multidimensional characteristics of their results. This should perhaps not come as a surprise, since the authors are mainly interested in exploring the link between technological change and economic growth. It should be noted, however, that the publication focuses on describing the concept of technological systems, rather than discussing how it can and should be used in actual analyses of technological change.

As mentioned above, the technological systems concept was further developed and used in numerous empirical studies throughout the 1990's and early 2000's, mainly by a group of Swedish scholars (Carlsson et al., 2002). In 2008, this resulted in a publication that outlines an analytical framework to studying emerging technologies from a policy perspective, building on what was now referred to as 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). While this definition highlights social structural components, which are also in focus throughout the text, they in one place explicitly identify TISs as "socio-technical systems" (Bergek et al., 2008a, p. 408). The authors 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. But while advancing the framework in many ways, ambiguities with regards to the system purpose persist.[24] It does, however, seem as if the authors view the utilization of technology as a phenomenon that is achieved by, rather than occurs within, TISs, which is in line with a System B or C.[25]

Moreover, Bergek et al. (2008a) elaborate on an analytical approach focused on functional dynamics, which had been introduced in prior publications (Jacobsson and Bergek, 2004; Johnson and Jacobsson, 2001).[26] The breakthrough insight behind the focus on functional dynamics 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

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[24] For example, the authors write that "the paper presents a framework that not only captures the structural characteristics and dynamics of an innovation system, but also the dynamics of a number of key processes, here labeled 'functions', that directly influence the development, diffusion and use of new technology and, thus, the performance of the innovation system." (Bergek et al., 2008a, p. 408). It is clearly difficult to understand the difference between structural and 'functional' dynamics unless the development, diffusion and use of technology is viewed as a system output.

[25] 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" (Bergek et al, 2008a, p. 409), which clearly categorizes a TIS as a System C. However, later in the paper 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*" (Bergek et al., 2008a, p. 420), which seems to identify a TIS with a growing industry, that is, a System A.

[26] Johnson was Anna Bergek's maiden name.

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 4.1).

Table 4.1. 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

The analytical approach proposed by Bergek et al. (2008a) describes a number of steps that start with the delineation of a focal TIS. The authors suggest that analysts first choose a product or knowledge field as a starting-point, and then further define the breadth and depth of the investigation. This refers not only to the level of aggregation, but also to the range of included applications. In addition, it is recognized that a spatial boundary is often appropriate for analytical purposes, even though innovation processes are in most cases international. The remaining steps include the identification of structural components, description and assessment of the performance and dynamics of 'functions', as well as the identification of inducement mechanisms, blocking mechanisms and key policy issues. Taken together, the concept of 'functions' and this step-wise approach constitute a policy-oriented analytical framework that would prove its practical value and be further developed in a large number of subsequent publications.

What Bergek et al. (2008a) present, however, is a framework that is still focused on growth, albeit with respect to a specific technology and spatial region. Except for a brief comment that expands the function 'influence on the direction of search' to cover mechanisms that influence how actors engage with alternative technologies, applications, markets and business models, the authors do not discuss the different configurations of sociotechnical structures that may result from technological innovation. They also fail to show how the suggested analytical approach can be used to inform interventions that aim to shape innovation processes within the pre-defined technological and spatial scope, rather than to stimulate general expansion.

Lastly, while Bergek et al. (2008a) only include social structural components, at least explicitly, a contemporary publication from the same research group introduces the idea of including technology as a structural component (Bergek et al., 2008b). Moreover, the authors clarify the system purpose by first distinguishing between a TIS and a broader technological system, which 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. They thus seem to refer to a System B, or possibly a combination of System A and B. In addition, they propose that 'functions' "influence the buildup 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, they do not offer an explanation of how this is linked to the more broadly defined technological system where production-consumption activities occur.

A few years before the two 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 understandings of 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) describe 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" (p. 416). This quite vague description of system components is later simplified to actors, networks and institutions. The authors also point out that the term technological system is also used by Hughes (1987) and other scholars 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 structures. 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). This indicates that they characterize a TIS as a system focused on innovation, rather than production and consumption, which is in line with a System B or C, or possibly a combination of the two.

But as was the case with Bergek et al. (2008a), Hekkert et al. (2007) are mainly concerned with an analytical approach based on 'functions'. However, since the authors strive to integrate findings from actor-oriented innovation scholars with a broader innovation systems approach, they focus on activities and suggest that these can be categorized by using 'functions'.[27] This stands in contrast to the understanding of 'functions' suggested by 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). Nevertheless, Hekkert et al. (2007) and Bergek et al. (2008a) derive similar list of 'functions', see Table 4.1, which indicates that their ideas are not too far apart.

Lastly, it should be noted that Hekkert et al. (2007) focus on the dynamics and performance of 'functions', while paying quite little attention to how the focal system can and should be defined by setting system boundaries. Moreover, although the authors emphasize sustainability rather than economic growth as an overarching objective, they do not highlight the fact that technological innovation may result in sociotechnical structures with different configurations.

In contrast to their Swedish and Dutch colleagues, the Swiss scholars arrive at the TIS concept 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 innovated, 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 feedback 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

[27] In fact, Hekkert et al. (2007) view activities as analogous to 'functions'.

elements except from the fact that it is the element an innovation researcher might be most interested in studying" (Markard and Truffer, 2008a, 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, 2008a, 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, 2008a, 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 supportive of the innovation process. The authors argue that a broader boundary, that includes everything that influences the innovation process, in line with a System C, 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" (Markard and Truffer, 2008a, p. 610), 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 lose almost every explanatory power." (Markard and Truffer, 2008a, 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 a TIS as a System A or System B.

When it comes to 'functions', Markard and Truffer (2008a) explicitly describes them as sub-functions to the overarching system function (which is to generate, diffuse and utilize innovations). The authors argue against interpreting 'functions' as activities or events and rather describe them as "emergent properties of the interplay between actors and institutions." (Markard and Truffer, 2008a, p. 597). However, they refrain from offering their own 'functions' typology and instead refer to the contributions by Bergek et al. (2008a) and Hekkert et al. (2007).

Lastly, although Markard and Truffer (2008a) write that structural components in TISs "share the goal of furthering at least some variant of the socio-technical configuration" (p. 611), and thus acknowledge that the results of technological innovation are multidimensional, they fail to discuss how different development trajectories can be integrated with an analytical framework based on the TIS concept.

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. This is evident when looking at Table 4.2, which summarizes systems descriptions from the reviewed publications. 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 purpose of a TIS is to carry-out innovation processes, or more generally, to influence the innovation process, which is in line with a System B or C, or a combination of the two. But most are ambiguous as to whether the utilization of technology is included as well, which would suggest an interpretation in line with a System A. Two contributions also suggest that the system boundary of the TIS is narrowed to technology-centered structures, that is, to a System A or B. In turn, these different and vague descriptions of the system purpose give rise to ambiguities when it comes to the more precise definition of 'functions', which is the key concept used to analyze change. In addition, the foundational literature is strongly focused on capturing the complex dynamics involved in technological innovation processes, but pays little attention to the multidimensional characteristics of their results.

Table 4.2. 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 *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." (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) "we focus on technological innovation systems (TIS)[...], i.e. socio-technical systems focused on the development, diffusion and use of a particular technology (in terms of knowledge, product or both)." (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) "[a TIS is restricted to] actors, institutions and networks that are supportive16 to the innovation process, i.e. that share the goal of furthering at least some variant of the socio-technical configuration" (p. 611)

4.5 Conceptual advancements in recent literature on technological innovation systems

The foundational publications reviewed in the previous section have given rise to a steadily growing body of literature that involves both empirical investigation and conceptual development.[28] With respect to the latter, particular attention has been given to topics such as

[28] A search in the article database Scopus in the year 2020 using the term 'technological innovation system' results in well over 300 publications.

geography (Binz et al., 2014), context (Bergek et al., 2015), networks (Musiolik et al., 2012; Musiolik and Markard, 2011), resources (Andersson et al., 2018; Musiolik et al., 2018), markets (Dewald and Truffer, 2011) and agency (Kern, 2015). Much effort has also been directed at refining the understanding of the empirical characteristics of several 'functions', exploring their influence on innovation dynamics, and suggesting new processes to complemented existing typologies (Binz et al., 2015; Kivimaa and Kern, 2016; Perez Vico, 2014). Although many of these contributions are interesting, and perhaps worthy of more attention, they have so far had a quite small imprint on the broader conceptual understanding of the TIS framework. This is shown by the fact that most studies still limit their frame of reference to the foundational literature and use more or less the same concepts as the ones proposed in these publications.

It is accordingly quite clear that the TIS literature has neither resolved the fundamental ambiguities and contradictions identified in the previous section, nor shifted towards more attention to the results of technological innovation processes. However, there have been some developments that are relevant for these perceived weaknesses, which will be described briefly below.

4.5.1 Characteristics of structural components (structural boundary)

While the foundational literature is largely in agreement that TISs are social systems, the idea of including technology as a structural component is proposed by Bergek et al. (2008b). This sociotechnical view was quickly adopted by some scholars (Mäkitie et al., 2018; Sandén and Hillman, 2011; Stephan et al., 2017; Suurs and Hekkert, 2009; Wieczorek and Hekkert, 2012), while others maintained that TISs are social systems (Binz et al., 2014; Coenen et al., 2012; Dewald and Truffer, 2011; Gosens et al., 2015; Musiolik et al., 2012; Quitzow, 2015). In 2015, leading scholars from the groups behind the foundational literature defined a TIS as a "set of elements, including technologies, actors, networks and institutions, which actively contribute to the development of a particular technology field" (Bergek et al., 2015, p. 2). Although the paper did not focus on, nor specifically discussed, this particular issue, it clearly indicates that the sociotechnical view had become widely established. However, this is not to say that the social view had been abandoned. Instead, both views are still common in the literature, with some leading scholars even changing their perspective back and forth in different publications. This 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.[29] This is

[29] Some publications are even ambigous and contradictory with regards to the structural boundary. Examples include: Bleda and del Rio, who define a TIS as a "dynamic socio-technical system of agents that by interacting within a particular institutional infrastructure are involved in the development,

acknowledged by Jacobsson and Bergek (2011), who also highlight that approaches that focus on social structures include technology "as knowledge embodied in actors and as outputs of the system (codified knowledge and artefacts)" (p. 45). However, a fair share of all publications is still unclear, ambiguous or even contradictory, describing the system as social and sociotechnical in the same paper. Figure 4.1 provides an account of to what extent it is possible to discern if 159 TIS papers published between 2009 and 2018 define the focal system as social or sociotechnical. With an increasing number of papers, there is no consensus and the level of clarity in not increasing.

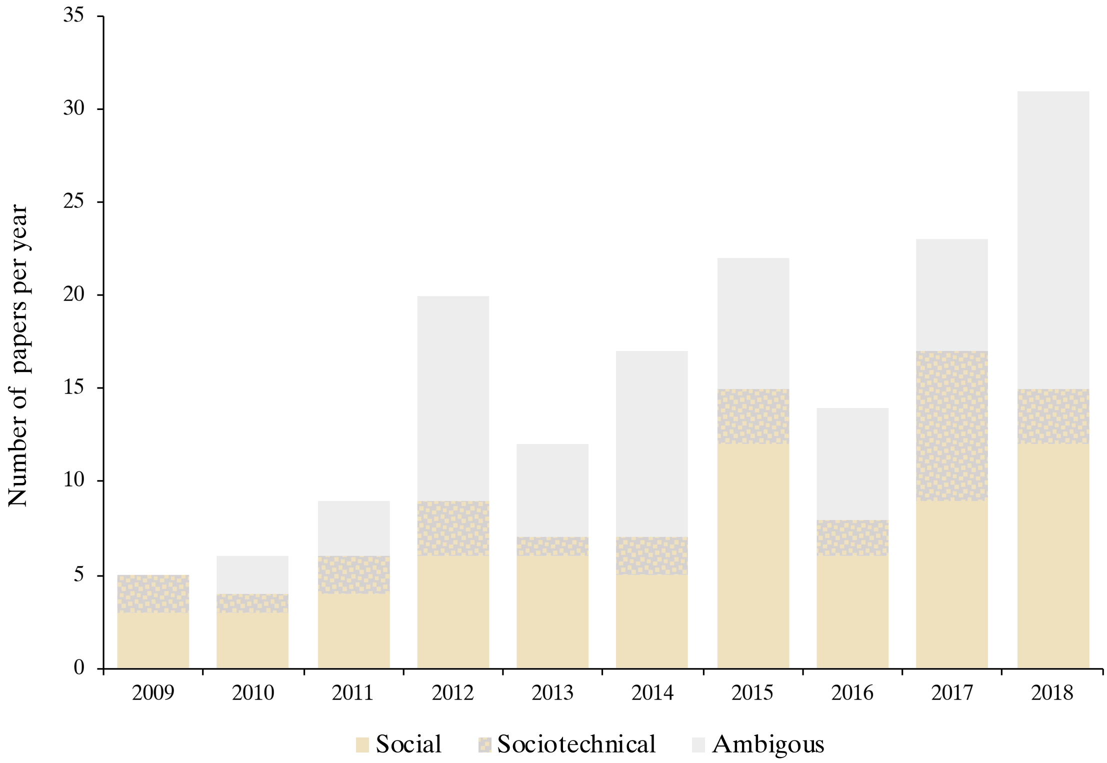

Figure 4.1. A quantitative assessment of how technological innovation systems are defined in terms of the included types of structural components.

4.5.2 Definition of system purpose (functional boundary)

With regards to the system purpose, the foundational literature points in different directions and shows considerable ambiguity as to whether TISs are systems that include structures involved in

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diffusion, and use of a specific technology" (2013, p. 1041); and Suurs and Hekkert (2009), who start by defining a TIS as a social system and then adds technology as a structural component without explanation.

innovation, production-consumption, or both. In the subsequent literature, clarifications have been made along two opposite lines of reasoning.

On the one hand, some scholars clearly exclude production-consumption activities from TISs. For example, Sandén and Hillman (2011) focus on the results of the innovation process, which they understand as the emergence of a new sociotechnical system of production and consumption.[30] In their view, the growth of this latter system can "be described by some 'innovation system functions' that relate the growth (or decline) of the elements of the system (and emergent system properties) to the system itself and to external forces" (Sandén and Hillman, 2011, p. 409), and they also argue that the TIS concept in fact refers to this system model of change. The authors thus make a sharp distinction between systems of innovation and systems of production and consumption, arguing that the former create the latter. In a similar vein, Bergek (2019) acknowledges that an analytical distinction can be made between an innovation system, a production system and a distribution-market system, and suggests that a TIS is an example of the former since its "nature and boundaries [...] should be defined in terms of problem-solving networks rather than buyer-supplier relationships" (p. 202). In the terminology introduced in Section 3.4, both Sandén and Hillman (2011) and Bergek (2019) accordingly view a TIS as a System B or C, or possibly a combination of the two.

On the other hand, several contributions describe TISs as systems that include production-consumption activities (that is, a System A), 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), 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).[31] In Table 4.3, I provide a few examples of publications that seem to interpret TISs either as a System A or as a combination of a System B and C.

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[30] This publication is in fact based on a report published already in 2005 (Sandén and Jonasson, 2005) and also draws on ideas presented in Hillman and Sandén (2008).

[31] We also note that there are other interpretations. For example Suurs et al. (2010) write that "technologies develop within the context of a Technological Innovation System (TIS)" (p. 419).

Table 4.3. Examples of interpretations of technological innovation systems that are in line with either a System A or a combination of System B and C, as illustrated in Figure 3.3.

System B/C: A TIS captures structures that influence innovation activities – it creates, expands and transforms an industry	**System A: A TIS captures structures that influence innovation and production-consumption activities – it constitutes an emerging industry**
"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)	"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)
"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) "The TIS is the systemic description of how [a production system] emerge, develop and expand." (Andersson et al., 2017, p. 143)	"[...] 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)
"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)	"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)

Besides these clarifications, a review of 159 papers published between 2009 and 2018 (presented in Paper IV) reveals 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 can most often not know what function scholars actually imagine that a TIS fulfills in its broader context.

Nevertheless, the literature indicates that the common understanding of TISs actually includes both innovation, production and consumption. To begin with, the way conceptual development related to context is carried-out offers some insights. For example, Bergek et al. (2015) offer an extensive discussion of TIS context, without making any reference to industries and markets where the focal technology is utilized. If these were not imagined to be a part of the TIS, they should be identified as important contextual structures. In fact, it is generally uncommon that the TIS construct is complemented with an additional system (or other entity) that performs production-consumption activities. It should also be added that the term TIS can in most empirical studies be exchanged for industry or sector, without any apparent loss of meaning, and arguably with a clearer exposition as a result.

This suggests that to the extent that the foundational literature views a TIS as a system focused on innovation, which is at least likely to be true for some scholars given their intellectual roots in the systems of innovation literature, this understanding has gradually shifted as the framework was adopted and used in new settings by other scholars. This can be viewed as a natural part of the scientific endeavor and is not problematic per se. What is troublesome, however, is the persistent ambiguity with regards to this core part of the TIS framework, which arguably hinders further conceptual advancements.

4.5.3 Definition of 'functions'

A question that relates very much to ambiguities in the system purpose is how the concept of 'functions' should be understood. Most publications either directly, or by reference to foundational literature, describe 'functions' as a way to decompose the overarching system purpose into a typology that enables a dynamic analysis. This idea is often expressed by referring to 'functions' as sub-processes to the wider innovation process, while some describe them as "intermediate variables between structure and system performance" (Jacobsson and Bergek, 2011, p. 46). But since the overarching system purpose is most often unclear, it remains ambiguous what 'functions' actually describe. Other publications go further and argue that 'functions' in fact contribute to the build-up of system structure. But since it is rarely stated in which system this structural build-up occurs, the ambiguity persists. An exception is Mäkitie et al. (2018) who refer to "processes that support innovation and influence the build-up of an innovation system" (p. 814), which they have previously described as a nascent industry. Given that most would probably agree that 'functions' are an attempt to describe change, which in turn can be understood in terms of structural change in some system, the unresolved question seems to be in which system structural change occurs – the TIS, another system that involves production and consumption, both, or something entirely different?

Furthermore, since 'functions' are most often referred to as processes, it is unclear whether they should be understood and measured as causes or effects of structural change.[32] This has led to

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[32] Even if causality is circular (i.e. structures and processes are linked in loops of causality) it matters if a theoretical construct such as a 'function' is (i) defined based on a well-defined effect that may have many

confusion about how to classify data and consequently 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). Moreover, "knowledge formation" is typically represented by knowledge output, while data representation for "entrepreneurial experimentation" and "guidance of the direction of search" differs widely. Since one effect can have many causes, and one process can be the cause of many effects, this makes the 'functions' notoriously ill-defined. In addition, most 'functions' typologies used in the literature, including the ones presented in foundational contributions, 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, I would even argue that there is no convincing conceptual distinction between structures 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 'function'. 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.[33] '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 me, 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' were intended to be a link between the structure of innovation systems and the change they produce in their contexts.

4.5.4 Approaches to setting system boundaries

While the characteristics of system components and the precise definitions of system purpose and 'functions' have been subject to little debate in the literature, more attention has been given to system boundaries. This has often been coupled with wider criticism concerning a perceived lack of attention to geography and an ad-hoc approach to delineating spatial boundaries

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causes, (ii) defined based on a well-defined cause that may have many effects, (iii) or merely viewed as a label of an (ill-defined) process with many causes and effects. In the worst case, different (implicit) definitions of what a function represents can in fact be found in the same text.

[33] Unless physical infrastructure is treated as a structural component, which is the case in some studies (see for example Suurs et al. (2010) and Suurs and Hekkert (2009)).

(Coenen et al., 2012; Hansen and Coenen, 2015). Scholars have questioned not only the strong empirical focus on nationally delineated TISs, most often in industrialized countries, but also the general use of analytically defined spatial boundaries, proposing that analysts should rather discover the system by "by following the network to wherever it leads, instead of setting system boundaries in an arbitrary and closed-off way" (Coenen et al., 2012, p. 977). Although the appropriateness of using analytical approaches to spatial delineation is still debated, the criticism has led to contributions that experiment with multiple system boundaries that highlight the interdependence of developments in different regions or at different spatial scales (Andersson et al., 2018; Binz et al., 2012; Binz and Truffer, 2017).

When it comes to system boundaries that define the technology in focus, it has been argued that it "remains [...] a little ambiguous how exactly the boundaries of a technological domain are set in relation to its geographical and sectoral embeddedness." (Coenen and Díaz López, 2010, p. 1152). 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, 2008a). 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 particular 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 covered by the analysis. This is of course problematic since it is very different to analyze the emergence of an industry that produces windmills, an industry that uses windmills to produce electricity, and a market that uses electricity. It has also implied that the literature tends to portray innovation as a one-dimensional diffusion process, while largely neglecting the multidimensional characteristics of its results (Yap and Truffer, 2018).

In addition, it is worth noting that the scholars involved in developing the TIS framework also discussed the possibility of defining technologies based on empirical observations (such as science collections and patent registries) rather than analytical preconceptions, much in parallel to the debate about spatial delineation (Carlsson et al., 2002). However, this line of thinking seems to have faded, which is likely to be linked to the fact that the TIS framework is predominantly used by transitions scholars interested in the development of specific pre-defined technologies.

While boundaries that define the technology and spatial region in focus can be seen as methodological, in the sense that they correspond to the questions asked in a specific study, a more integral part of the TIS framework concerns how far it stretches within this domain. As discussed in Chapter 3, the interconnected nature of reality implies that everything influences the development, diffusion and use of any technology, at least over sufficiently long time scales. In the foundational literature, Bergek et al. (2008a) suggest that this is an analytical choice, while Markard and Truffer (2008) argue that a TIS should only include structures that actively contribute to the innovation process. The latter position can be contrasted with Edquist's view of innovation systems as including all aspects of the economy that influence the innovation process (Edquist, 2004). It seems, however, as if the proposition that the TIS concept should be reserved for radical innovations has been abandoned by its proponents, since Markard et al. states that "The TIS concept covers both emerging and mature technologies." (2016, p. 332). Although this fundamental issue has not been subject to much debate, most subsequent TIS studies explicitly or implicitly adopt a boundary that confines the system to particularly relevant and important structures. A common rationale for defining this boundary is to include structures that both influence and are influenced by the innovation process, and consider structures that exert a unidirectional influence as contextual. However, the fact that boundaries that specify technologies and spatial regions are generally not set by reference to real-world interactions, implies that some degree of interdependence between a TIS and its context is unavoidable. This has been noted by Bergek et al. (2015) who conceptualize this interdependence as due to a structural couplings, while unidirectional influences are mediated by external links.

4.5.5 Attention to the multidimensionality of technological innovation

As mentioned in Section 4.2.2, one of the strengths of the TIS literature is that it acknowledges that a multiplicity of factors with different origins influence the innovation process. Although the multidimensionality of the results of the innovation process has received far less attention, a number of publications make contributions that focus on the technological and spatial characteristics of sociotechnical change.

With regards to the former, Markard et al. (2009), describe a methodology for prospective analysis of TISs. This involves what they refer to as variance analysis, which aims to identify future development trajectories for the focal technology. However, trajectories are simplistically conceptualized as combinations of technological designs and actor configurations, and thus disregard institutional configurations. Also, the focus is to develop a methodology for identifying trajectories, rather than shaping innovation in desirable directions. An additional example is an exploration of the market dimension by Dewald and Truffer (2011), which highlights the existence of different segments. But their analytical focus is to understand how these segments have supported the overarching innovation process, and they do not discuss how it can be shaped to favor different configurations. Other relevant publications that discuss variety in the structural dimension include, but are certainly not limited to, Hillman and Sandén (2008), Suurs and Hekkert (2009) and Hojcková et al. (2018).

The spatial dimension has been raised in a number of publications, often with links to the broader debate about the geography of TISs (Coenen, 2015; Hansen and Coenen, 2015). These publications tend to focus on describing and analyzing why the emergence of new industries occur in different places, and also offer extensions of the TIS framework. For example, Quitzow (2015) links the formation of spatial trajectories to the performance and cross-country dynamics of 'functions', while Binz et al. (2015) rather refer to the alignment and anchoring of key resources. In addition, Dewald and Fromhold-Eisebith (2015) highlight dynamics across multiple spatial scales (i.e. local, regional, national and international).

While these contributions engage with the different dimensions in which new technologies emerge, they generally fail to move beyond analytical frameworks focused on processes that describe growth. Instead, attention to the direction of change is incorporated by means of analyzing multiple systems at the same time. A different approach is suggested in a recent publication by Yap and Truffer (2018), who propose an analytical framework that focuses on the direction of change within a specific TIS. This directionality is seen as the result of dynamics across different 'functions', but at the same time 'guidance of the search' is pointed out as a key process. Although the authors make an important contribution by trying to create an explicit link between 'functions' and the direction of change, their framework does not conceptualize potential development trajectories beyond referring to alternative technical systems as different products. Moreover, the strong analytical emphasis on guidance of the search contradicts the basic understanding of the direction of change as an emergent property that depends on all 'functions'.

It is accordingly clear that conceptual advancements since the foundational TIS literature have not fully incorporated attention to the direction of change. Relevant contributions have focused either on spatial or technological aspects, while failing to grasp the full multidimensionality of sociotechnical change. Conceptual suggestions have not led to any widely diffused modification of the basic TIS framework, which accordingly remains focused on stimulating rather than shaping technological innovation. In addition, theoretical advancements with respect to the direction of change are arguably hindered by the fundamental ambiguities and contradictions described in previous sections.[34]

[34] These arguments are supported by Yap and Truffer (2018) who argue that existing TIS publications mainly focus on quantitative diffusion of homogenous technologies.

4.6 The conceptual research problem addressed in this thesis

The literature review and arguments presented in the previous sections suggest that there is a need for conceptual development within sustainability transitions research on technological innovation. This line of inquiry is dominated by studies that advance and apply the TIS framework, which is not geared towards investigating the multidimensional characteristics and dynamics of sociotechnical structures associated with new technologies. As a result, it has limitations as a tool for informing efforts to shape technological innovation towards outcomes that are in line with common social and environmental objectives.

Although TIS scholars have taken steps to account for the multidimensionality of technological innovation, these advancements are hampered by ambiguities and contradictions in how core concepts are understood. The system in focus is seen as both social and sociotechnical, with some leading researchers switching back and forth in different publications. While it seems plausible that many scholars today think about TISs as systems that include both innovation and production-consumption activities, the system purpose remains ambiguous throughout most of the literature. Partly as a consequence, the typology of 'functions' used to analyze change is ill-defined; it is not clear where the effects of 'functions' appear, they are conceptually difficult to distinguish from system structure, and most typologies used in the literature exhibit considerable overlaps and fail to show that categories are exhaustive. In addition, most studies fail to clearly define the technology in focus, which has implied that the possibility of different development trajectories in spatial and technological dimensions is rarely made explicit.

Quite surprisingly, these fundamental issues have been subject to little debate in the sustainability transitions community. There has been some discussion at scientific conferences, but few scholars have tried to increase the conceptual rigor 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 making any reference to ambiguities and contradictions regarding the structural and functional boundaries of the system in focus.[35]

[35] Related issues have received more attention by leading scholars in the (non-technological) innovation systems community. Edquist (2004) has noted that the innovation systems concept has come to be used in a loose manner to capture factors that influence innovation processes and calls for more formal theorizing, while Lundvall et al. (2002) see conceptual ambiguity as a strength since it brings flexibility and facilitates practical (policy) application.

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 thesis.

I do, however, believe that there is a need to strengthen conceptual clarity and rigor. 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 transitions scholars. I also know from my own experience that it makes it hard for junior scholars to enter the field. Another reason is that the lack of clarity and rigor hinders cumulative knowledge development. On the one hand, this concerns extensions and refinements of the TIS framework, since persistent ambiguities and contradictions permeate these contributions. It is, for example, difficult to motivate the inclusion of a new 'function' when the basic 'functions' concept is ambiguous, while a clear understanding of system context is beyond reach if the function fulfilled by the focal system is not clearly defined. On the other hand, a more consistent analytical approach would benefit the transferability, comparability and generalizability of findings from empirical case studies. In addition, recent efforts to model transition processes may benefit from conceptual frameworks based on well-defined, mutually exclusive and collectively exhaustive categories, linked by clear causal relations.

While the main priority for conceptual development should perhaps be to strengthen conceptual clarity and rigor, it is also possible that some ways of delineating systems are better than others. In particular, the understanding of system purpose has important consequences for further theorizing that attempts to account for the multidimensional characteristics of technological innovation. After all, describing and analyzing a system that *creates* a configuration of sociotechnical structures is different from describing and analyzing a system that *becomes* a configuration of sociotechnical structures.

The research problem addressed in this thesis revolves around these conceptual issues. Building on empirical case studies, the literature review presented in this chapter and deductive reasoning, I will explore new ways to describe and analyze the characteristics and dynamics of sociotechnical structures associated with specific technologies, try to explain the role of policymakers and other actors in shaping the transformation of these structures, and strive to establish links to their social and environmental consequences. In the end, this will hopefully support efforts to shape sociotechnical change towards desirable outcomes.

To summarize this chapter, I first traced the historical roots of sustainability transitions research, described the emergence of two approaches to studying transitions, and identified the technological innovation systems framework as a suitable conceptual starting-point for this thesis. I then presented a detailed review of the literature that engages with this framework and identified two main areas that call for conceptual development. The first is the lack of attention to the multidimensional characteristics of the dynamics and outcomes of technological innovation. The second is what I perceive as ambiguities and contradictions in the use of the systems concept. In the end, I argued that these areas constitute an important knowledge gap that should be addressed by conceptual development and empirical investigation. In the next chapter, my focus turns to how I intend to go about this challenge.

CHAPTER 5 – METHODOLOGY

The previous three chapters presented the metatheoretical foundation of this thesis, elaborated on the systems perspective that guides the research effort, provided a comprehensive review of the literature, and discussed the conceptual research problem in focus. There are, however, many possible ways to proceed from this starting-point. The focus of this chapter is therefore to describe, motivate and reflect upon methodological challenges and choices.

In the following sections, I will first explain and motivate the use of in-depth case studies as a research strategy. Then I discuss how transdisciplinary interaction and normativity characterizes the work presented in this thesis. I proceed to describe how the research was carried-out. In the end, I offer some comments on reflexivity.

5.1 A research strategy based on in-depth case studies

This thesis has been developed through a research strategy based on in-depth case studies. However, case studies can be very different, and I will therefore dwell slightly on my understanding and use of the term. I will also discuss the extent to which case studies may contribute to general theorizing and their role in human learning.

In a seminal contribution, Eisenhardt (1989) defines the case study as “a research strategy which focuses on understanding the dynamics present within single settings” (p. 534). This is a simple and appealing definition, but problems arise when thinking more carefully about its implications; it seems to suggest that all scientific inquiries are case studies, and that there can be no logical distinction between a case study and a non-case study. To elaborate on my thinking, the starting point has to be the notion of theory. In my view, any theory says something more or less valuable about something more or less relevant. Without delving into a very philosophical argumentation, I also believe that what the theory says something about will always be a slice of reality – a system – one that may range from an organic cell, or even its components, to the world as we know it, which I humbly believe to be less than what it really is. I would therefore claim that there is no such thing as a non-case study; all scientific inquiries concern particular instances of reality that may of course be more or less broadly defined. This is in line with Flyvbjerg's (2006) view that "in the study of human affairs, there appears to exist only context-dependent knowledge" (p. 221), although I go one step further when claiming that it is generally impossible to develop context-independent knowledge since we can only perceive a sub-set of reality.

Fortunately, it is possible to find a narrower, and to me more meaningful, definition of the case study, if it is extended to include a set of research methods. For example, Yin (2009) emphasizes the use of multiple sources of data and triangulation to cope with research inquiries that involve many variables and few data points, as well as the use of prior theoretical constructs to guide data collection and analysis. He thus suggests that the case study refers to an investigation that is methodologically pragmatic in its efforts to understand a particular phenomenon and strives to build a holistic understanding of its characteristics. I am sympathetic to this view, and it is also quite descriptive of my research efforts.

Another topic that is subject to much debate is the extent to which a single case study, understood as a relatively narrow investigation into a phenomenon, can be used to build knowledge that is valid beyond the settings it represents and thus be generalized to a broader class of phenomena. The traditional view is arguably that such research designs are mainly suitable for exploratory stages of larger research programs, where the focus is on generating hypotheses, while multiple cases are needed to build strong theories (Eisenhardt, 1989; Yin, 2009). Flyvbjerg (2006) offers an eloquent critique of this view based on misunderstandings about case-study research. He emphasizes that concrete and context-dependent knowledge, generated by rich single case studies, is essential for human learning and plays an important role in the overall process of knowledge accumulation. In addition, he argues that careful and strategic case selection enables the generation of theory that informs a wider class of phenomena.

It seems to me that the discussion to a large extent revolves around different approaches to developing theories that can be assumed to be valid beyond the immediate experiences and observations that have informed them. The positivistic scientific ideal is a search for regularities in observations, often based on statistical methods. When measurability so allows this approach can be applied to broad instances, which enables the generation and confirmation of theories that are often assumed to be universal. However, many interesting aspects of different phenomena cannot be observed and described in a way that allows for statistical methods.[36] This is where the case study comes in as another approach to developing theory. When multiple case studies of similar phenomena are feasible, it is possible to employ a generalization logic based on replications, falsifications and contrasts. But also a carefully chosen single study can be used to develop knowledge valid beyond the particular instance it represents, by combining case observations with logical deductions (Flyvbjerg, 2006). I my view, these different approaches to theoretical development all contribute with important insights. When feasible without compromising the level of detail, it is certainly preferable to study broad or multiple cases, but there are at the same time questions worth asking that only allow for single-case research design. I follow Flyvbjerg (2006) in my belief that these can also contribute to general theorizing – not to speak of their importance for creating Kuhnian exemplars that are essential for human learning and the emergence of new scientific paradigms (Kuhn, 1970).

In this thesis, I adopt a research strategy based on a few in-depth case studies. They are chosen to highlight emerging technologies that are in themselves interesting for empirical and theoretical reasons, in line with a theoretical sampling approach (Eisenhardt, 1989). Another rationale behind the selection of cases is their relevance from a Swedish policy perspective and, admittedly, the interests of the funding agency. The focus of case selection is accordingly not to enable a generalization logic based on replication, falsification and contrast across multiple cases, although this may still be possible to some extent. As a consequence, this research mainly aims to contribute to general theorizing by examining single cases that can highlight new perspectives. In addition, it will add to a growing body of literature that examines sociotechnical change, which enables future theorizing based on a more replication-oriented logic (Eisenhardt and Graebner, 2007).

5.2 Interaction and normativity

Given the elusive character of the notion of a case study, it is not surprising that case study research takes on many forms. Some of the differences are related to the aspects discussed above, while others can be derived from different ways of collecting and analyzing data. Another important dimension in which research differs has to do with the relationship between researcher and research object. Positivistic approaches emphasize that the researcher should be distanced from the object of study and strive to observe without interfering. When examining the social world, however, this is often difficult to achieve. Empirical methods, such as interviews

[36] As argued by Weaver (1948), statistical methods are geared towards analyzing disorganized complexity, while there is a need for other methods when investigating organized complexity.

and direct observation, will not only produce data, but also impact the phenomenon under investigation. Moreover, researchers have the capacity to respond to research findings by changing their behavior in one way or the other, which paves the way for self-fulfilling and self-defeating prophecies. In systems terms, we may thus note that agents are often, if not always, a part of the systems they observe (Foerster, 1960). This reflexivity implies that even though one subscribes to a realist ontology, it is practically impossible to develop purely objective knowledge.[37]

One approach to this issue is to stay with the positivist ideal, but still acknowledge that any research effort will produce some kind of change in the world. Consequently, the ambition is to use different strategies that minimize the interference of empirical methods, for example 'fly on the wall' approaches to participant observation and interview guides that refrain from the use of leading questions. In addition, reflexivity is brought into the analytical process as a problem that may affect the reliability of findings and often discussed as a weakness.

A contrasting approach is to leave the traditional ideal behind and instead embrace the opportunities that reflexivity gives rise to by engaging in participative research. Rather than observing from a distance, the researcher enters a partnership with the object of study, in which knowledge is co-created through a participative process (Shani et al., 2004). This is often coupled with an ambition to develop knowledge that is relevant not only to the scientific community, but also to the involved individuals, organizations or communities. More action-oriented approaches are also strongly normative in their efforts to produce social or environmental change, and less interested in building general theories (Bradbury, 2015).

In the end, it seems to me that there is a continuous scale between purely quantitative measurements made from a distance, to action-oriented interventions that are sometimes difficult to distinguish from (traditionally) non-academic process management and coaching. And one is not better than the other, just more or less suitable given the intended outcomes.[38]

To position this thesis in relation to this discussion, a starting-point is to clarify that I engage in a type of science that is fundamentally normative in its efforts to promote sustainable

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[37] It should be noted that this argument in principle holds for the physical world as well.

[38] An additional reflection is that somewhere along this continuum, the activities we refer stop being research and rather turn into something else, perhaps a consulting project or an activist intervention. The question is where to draw the line, because I do think it matters, not in terms of how we value the different activities, but in terms of having a common understanding of what we do and how it fits into the broader advancement of human society.

development. However, the research presented in this thesis has not had the ambition to produce immediate change through participative and action-oriented research. Throughout the research journey, my focus has rather been to develop knowledge that finds its main relevance within the scientific community as well as to build personal competence that enables me to drive change by engaging in the public discourse, teaching and future research. But that said, I do believe that the questions addressed in this thesis call for a close interaction with many agents. An ideal understanding of sociotechnical change is clearly based on a close examination of the motivations and capabilities of agents that influence this process. However, my research inquiry also aims to build a holistic understanding, which leaves this ideal far beyond reach. Time and resource constraints do not allow for extensive interaction with the agents involved in the phenomena under investigation, and I therefore have to settle for an approach that is more distanced, building on a quite limited number of interviews with key informants as well as secondary sources. Still, I am fundamentally a part of the sociotechnical change processes I investigate, and I do believe that my research efforts at least to some extent have an impact on how they unfold. This clearly has to be taken into account in the analytical process and when discussing the merits of my findings.

5.3 Carrying-out the research

Conducting the type of research presented in this thesis involves a number of different activities. These are often illustrated and described as a process with a number of steps; beginning with the formulation of research questions and selection of cases, proceeds with the collection of data from multiple sources, and ends with an analytical procedure in which new theory is generated and compared with existing literature (Eisenhardt, 1989; Flick, 2014). This suggests a linear progression where focus and scope are quite static throughout the process. Moreover, the approach is based on ideas from grounded theory (Glaser and Strauss, 1967), where the literature is brought in at a late stage in order to ensure that the resulting theory is grounded in the data and not merely a reflection of pre-existing theories and preconceptions. These features are questioned by other scholars such as Dubois and Gadde (2002) that argue for a more dynamic process where the focus and scope of an inquiry is allowed to co-evolve depending on the findings, and suggest a continuous and systematic matching between existing literature and case characteristics throughout the research endeavor. In the following, I will elaborate on these topics in relation to my research and also reflect upon more concrete issues that emerge from my choice of research methods.

5.3.1 Developing research questions and delineating the object of study

I believe that a necessary first step in any research inquiry is to outline the focus and scope of the investigation; we cannot study everything in the world at the same time, which is why some sense of direction is inevitable. However, I do not view the development of research questions and the delineation of research object as a distinct step in a linear research process, in the way suggested by Eisenhardt (1989), but rather as a process that permeates the research process, which is similar to the approach outlined by Dubois and Gadde (2002). As a result of observations and learning in different stages, the focus and scope of the inquiry are refined and sharpened to pave the way for interesting, relevant and robust findings.

In my research, a key component of this process is to delineate the object of study by defining the system in focus. An important choice made in this process is that between depth and breadth of analysis; a narrow system boundary may allow for a more detailed study, while a wider one constitutes a broader instance from which to learn and may also be more relevant for non-academic stakeholders such as policymakers. One way to reconcile the two is to work with multiple levels of analysis, where one or several more detailed investigations are embedded in a larger case study (Yin, 2009).

5.3.2 Collecting and evaluating data

My empirical approach is pragmatic in the sense that I strive to include all available data that can inform my inquiry. But since the ambition is to build a holistic understanding of a diverse set of sociotechnical change processes, there are important time and resource constraints. These imply that the investigation to large extent revolves around interviews with key informants as well as reviews of secondary sources such as technical literature, reports and documents from public agencies and industry organizations, as well as websites and newspaper articles. The use of interviews and documents as data sources is, however, laden with pitfalls that deserve some elaboration.

One important issue when building on data obtained during interviews is the extent to which we can use statements and impressions to make inferences to phenomena that go beyond the actual interview situation. After all, an answer to a question is in essence nothing more than an exchange of words in a particular situation, and it is therefore not trivial to use statements from such a situation to say something about a broader research case. This can be referred to as internal generalization, as opposed to the external generalization that occurs when a case is used to build theory as discussed above (Maxwell, 2012; Yin, 2009). Here, I think it is important to keep in mind that interviews differ in the questions we ask and the data we want to obtain. In my work, for example, a common theme is the interaction between organizations. During an interview, an interviewee may state that "their organization works together with another organization in a certain project". I would treat this type of statement as a likely reflection of what actually goes on (i.e. what would be revealed if a more extensive study, including other sources such as measurements or multiple interviews), since it is a somewhat objective and uncontroversial view that has been revealed. But if an interviewee instead states that "their organization works together with another organization because they want to access knowledge", I would be cautious. This statement has a more subjective character and it is possible, if not likely, that a more extensive study would find that there are other perspectives on the objectives of the stated cooperation. I believe that this relates very much to the extent to which the data we look for, or that is for some reason revealed in the interview and considered relevant and interesting, has to do with the objective, subjective or intersubjective domains of reality. When we attempt to look into the latter two, which are derived from minds rather than things, we have to remember that there are not only different ways of perceiving the world, but also different subjective viewpoints that may be equally valid, and continuously evaluate the extent to which broader inferences are possible to make.[39]

The problems outlined above are difficult to resolve completely. But by keeping them in mind when designing, performing, interpreting and analyzing interviews, the distortions they give rise to can be reduced to an acceptable level. An important part of this is to contextualize the interview situation and the obtained data as well as to be critical and reflective – what other perspectives and viewpoints can be held, what agenda is the interviewee pursuing, can obtained data be supported by other independent sources, and is communication effective?

Using documents bring similar challenges when it comes to the extent to which text can be used to make inferences that go beyond the actual document. Here, I think it is key to remember that any document is, and should be treated as, a historical record. Learning from historical methods means emphasizing the context in which a document was produced, and I find the essential questions – why, what, where, who, when and how – highlighted by Jordanova (2016) to be a helpful guiding framework when adopting a critical and reflective perspective.

5.3.3 Analyzing and writing

When it comes to analyzing interviews and documents, a key issue concerns the extent to which one should let frameworks of concepts, often in the form of categories or typologies derived from previous research or one's own deductive thinking, guide the analysis. On the one hand,

[39] An additional assumption we have to make to build on statements and impressions from interviews is that the interviewee is, or at least trying, to tell the truth and that they are able to communicate the meaning they wish to convey in an effective way.

bringing this type of preconception into the analytical procedure may lead the analyst to impose expected patterns on the data, and thereby reproduce knowledge embedded in existing frameworks and concepts. This may conceal potentially interesting patterns that are not in line with the guiding preconception; a line of argumentation that is inherent in the grounded theory approach (Glaser and Strauss, 1967) and also emphasized by Eisenhardt (1989). However, I would argue that preexisting theory is not only constraining in an analytical endeavor, but that it may also be enabling. Qualitative data, especially when it is large in volume and concerns complex phenomena, can be overwhelming, and it is easy, if not inevitable, to get lost in one way or the other. And there is more to getting lost than finding things that are not there; one may also fail to see things that are there. It is in this respect that preconceptions may serve as lenses through which the analyst can gain a more comprehensive understanding.

Another issue concerns requirements on transparency and rigor in the analytical procedure that translates qualitative data to a narrative that can be presented in a scientific publication. Here, one can contrast a loose and creative approach where writing is seen as a somewhat mystical process (see for example Sennet (n.d.)), with a more structured view that emphasizes formalization. An example of the latter is the Gioia methodology (Gioia et al., 2012), in which a clear distinction is made between informant-centric terms, research-centric concepts and aggregated dimensions that may constitute or inform broader theorizing. In this type of analysis, the ambition is to maintain a clear link between data and narrative, by clearly describing the reductions made throughout the analytical process. This may also be supported by software that facilitates formal coding procedures.

I personally believe that when engaging in qualitative research, the link between data and narrative will always have the character of a black box that cannot be opened fully. It seems to me that striving for the scientific ideals of formalization, transparency and replicability will always come at the expense of nuance, creativity and storytelling, which are arguably also essential for great research. The challenge is accordingly to strike a good balance that allows for an analytical flexibility that leads to deep, interesting and accessible findings, while maintaining scientific rigor. And it is clearly essential to be transparent about the choice of analytical approach and reflect upon its consequences.

5.4 Reflexivity

As a researcher, I cannot leave my own gender, age, ethnicity, values and beliefs behind, and these characteristics will to different degrees influence all parts of the research process, especially given that a certain amount of subjectivity is difficult to avoid in qualitative analyses (Berger, 2015). Since my research has the ambition to contribute to general theorizing beyond the particular, as opposed to being limited to a more subjective account of particular phenomena, this can be viewed as something that may distort findings. The issue is clearly impossible to resolve completely, but I believe that the bias can be minimized through critical reflection. It is key to understand in what ways subjectivity is introduced, analyze which personal characteristics that are particularly important as potential sources of bias, identify ways to mitigate their influence in the process of collecting and analyzing data, and, finally, to discuss any findings in relation to the subjectivity that will most certainly remain.

For the research presented in this thesis, I think that ethnicity, class and ideology are dimensions that may deserve particular attention. My privileged situation as someone that has grown-up and lives in a rich, peaceful and highly westernized context, my strong values that emphasize human (and non-human) rights, social equality and ecological conservation, and the social democratic ideology that has had a deep influence on the Scandinavia I call home, are all factors that influence the lens through which I look at the world. This is something that constitutes a potential source of bias in my work, and that should be, and also is, met by efforts to limit its influence. But at the same time, it is one of the foundations of my research efforts; my work could not be explicitly normative in its efforts to promote sustainable development if some of my values and beliefs were not brought into the research process.

To summarize this chapter, I first explained and motivated the use of in-depth case studies as a research strategy. Then I discussed how transdisciplinary interaction and normativity characterizes the work presented in this thesis. I proceeded to describe how the research was carried-out. In the end, I offered some comments on reflexivity. In the next chapter, I will elaborate on the more specific research design used in this thesis.

CHAPTER 6 – RESEARCH DESIGN

Whereas the previous chapter provided a general reflection on methodology in relation to the metatheoretical foundation, analytical perspective and focus of this thesis, I will now turn to the more specific research design used to fulfill its purpose.

In the following sections, I will first describe the four main streams of activity that constitute the research process, how they relate to each other, how they have fed into the appended papers, and what contribution they make to the overarching purpose of this thesis. Then I comment on the selection of empirical research cases and describe their general characteristics. In the end, I describe the methods used for empirical investigation and conceptual development.

6.1 Four interlinked streams of activity

As mentioned in the introduction, this thesis has one conceptual and one empirical dimension. In the former I develop new concepts that can be used to describe and analyze technological innovation. This is a stream of activity that has been ongoing throughout the process of developing this thesis. In the empirical dimension, the focus is instead to develop knowledge about the nature of technological innovation and derive policy implications. This has been done through three case studies, which constitute distinct streams of activity.

Figure 6.1 illustrates the links between these four streams of activity and their relation to the appended research papers. To begin with, it should be noted that the three case studies have not been performed in parallel, but rather sequentially. This enabled a continuous learning process where the research designs used in the two later case studies could build on accumulated findings and experience. Furthermore, the case studies and conceptual development have been intertwined from the start. On the one hand, the empirical investigations, in particular the two later case studies, have benefitted from conceptual development by drawing on ideas from this stream of activity. This has opened up new perspectives and enabled the development of new empirical insights. On the other hand, results from the case studies have supported conceptual development by complementing existing research and revealing weaknesses in commonly used analytical frameworks, by enabling testing and illustration of new concepts, and by creating a more personal understanding of the phenomenon of interest. It should also be mentioned that interactions between conceptual development and empirical investigation have not only occurred in between, but also within case studies. This is in line with the abductive approach to case study research suggested by Dubois and Gadde (2002).

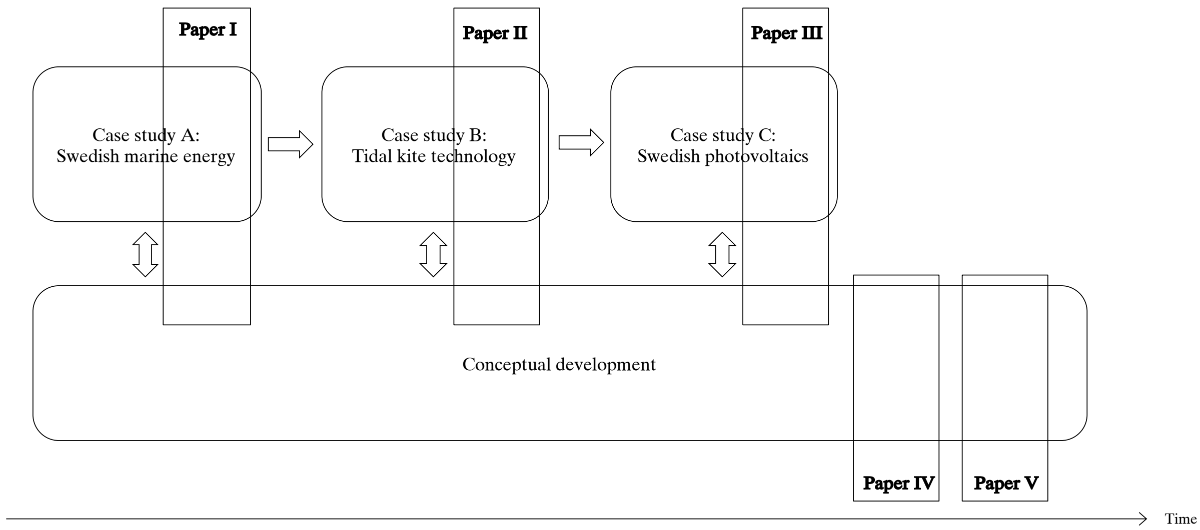

Figure 6.1. Links between streams of research activity and appended papers.

The appended research papers have built on the four streams of activity in different ways, which also reflects their conceptual and empirical orientations. Papers I-III mainly present empirical findings from the three case studies, but also make some contributions based on conceptual development. Paper IV engages exclusively with conceptual development and draws upon a literature review rather than empirical data. And although Paper V provides illustrative empirical cases, it is strongly focused on conceptual development.

6.2 Case selection, characteristics and justification

To explain the selection of empirical case studies, I have to revisit the background to the research project within which this thesis has been developed. In 2013, the Swedish Energy Agency commissioned a study that would examine Swedish innovation activity in six different renewable energy technologies by using the TIS framework. It involved researchers from several Swedish universities and research institutes, including the author of this thesis and the co-authors of the appended research papers (except for Hojcková who has co-authored Paper IV). The aim of the study was to identify ways in which policymakers could accelerate the development of renewable energy technologies as well as to demonstrate the TIS framework for practitioners. Among other interesting findings (see Swedish Energy Agency (2014) for the full report), the analysis highlighted that a small country such as Sweden faces particular challenges when it comes to stimulating domestic industrialization based on new renewable energy technologies, which is one of several objectives that technology policy in this area strives to achieve. This challenge was shown to be particularly important for marine energy technology, since Sweden has a very small domestic natural resource endowment and thus a low market potential. But the study also highlighted that solar energy technologies developed by Swedish actors during the 1980's and 1990's had subsequently been industrialized abroad. These findings inspired a research proposal that was granted funding from the Swedish Energy Agency and enabled the development of this thesis. Already at the outset, this research thus focused on marine and solar energy, and also had a Swedish policy perspective.

Since I had been involved in analyzing Swedish marine energy technology in the preceding study, this became a natural point of departure for the first case study. Case study A thus focuses on Swedish innovation activity with respect to this technology and covers developments until 2014. While building on data that describes historical activities, the analysis has a prospective and prescriptive orientation that aims to recommend policy interventions that may accelerate innovation. It is based on a version of the TIS framework that is largely in line with the approach described by Bergek et al. (2008a).

Inspired by findings from this investigation, Case study B limits the scope of inquiry to one specific marine energy technology concept, namely tidal kite technology, while employing a broader focus in the geographical dimension. One reason for this methodological choice was that it enabled an analysis of the global innovation system for this technology concept, which revealed more detailed transnational dynamics than what was possible in Case study A. The study aims to understand how the resources provided by domestic and foreign regions have influenced developments in the spatial dimension, which implies a more descriptive orientation than Case study A. The analysis was enabled by an adapted version of the TIS framework and covered developments until 2016.

In Case study C, the marine energy domain is left behind, and the focus turns to solar energy, or more specifically, the use of photovoltaics technology to generate electricity. The geographical scope is limited to Sweden and the analysis covers developments until 2018. Since there was more literature to draw upon compared to marine energy, the empirical investigation focused on developments in upstream parts of the value chain, which had received less attention by innovation scholars. Nevertheless, the study had a broad analytical approach that aimed to capture historical activities. In particular, the analysis focused on the dynamics behind different trajectories in spatial and technological dimensions, which also warranted the use of an adapted version of the TIS framework.[40]

Table 6.1 compares the three case studies, highlighting both similarities and differences. Apart from the general focus on technologies that generate electricity from renewable energy sources, it should be noted that all three case studies have a Swedish perspective. In Case study A and Case study C, this geographical focus is reflected in the choice of system boundaries. In contrast, Case study B has a global spatial system boundary, but maintains a Swedish perspective by focusing on a technology concept that is mainly developed by actors in Sweden. Another similarity is that the case studies constitute extreme cases when it comes to the policy challenge of appropriating benefits related to industrialization, albeit for slightly different reasons. Marine energy has a very limited market potential in Sweden, which makes it particularly difficult to stimulate the emergence of a domestic industry. This issue is further emphasized for tidal kite technology, for which there is no Swedish market potential whatsoever. Case study A and Case study B may thus be viewed as nested extreme cases. For photovoltaics, the policy challenge of appropriating benefits related to industrialization had a similar character up until quite recently. However, the situation has changed as the Swedish market has started to reach significant levels, and the current challenge rather stems from the difficulty of finding a competitive advantage in a global value chain dominated by large Asian companies. Case study C can thus be viewed as a different but related extreme case. These characteristics also highlight two key differences between the case studies. Marine energy is a pre-commercial technology field for which the Swedish market potential is very limited, which applies to tidal kite technology as well. In contrast, photovoltaics is characterized by the rapid global emergence of commercial industries and markets, and even though the Swedish market lags behind many other countries, the potential is large. An additional difference is that marine energy revolves around a focal product (i.e. the power plant) that is large, complex and design-intensive, while photovoltaic modules are generally smaller, less complex and manufacturing-intensive. Lastly, although the three case studies all investigate sociotechnical change, they do so in slightly different ways. Case study A has a prospective and prescriptive orientation, and draws upon the traditional TIS framework. This approach is different from Case study B and Case study C, which have a more retrospective and descriptive orientation, and also draw upon adapted versions of the TIS framework.

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[40] Initially, the ambition was to complement the broad analytical approach with a more detailed analysis of a specific technology concept, in line with the nested logic of Case study A and Case study B. This was abandoned within the scope of this thesis in favor of further conceptual development, but may be taken up in future work.

Table 6.1. Comparison of case studies.

	Case study A: Swedish marine energy	**Case study B: Tidal kite technology**	**Case study C: Swedish photovoltaics**
Research ambition	Identify policy interventions that may accelerate innovation	Reveal how resources provided by domestic and foreign regions shape innovation	Explore the dynamics behind geographical and sociotechnical development trajectories
Technological focus	Marine energy technology	Tidal kite technology	Photovoltaics technology
Geographical focus	Sweden	Global	Sweden
Temporal focus[41]	Until 2014	Until 2016	Until 2018
Analytical approach	Prescriptive and prospective TIS framework	Descriptive and retrospective Adapted TIS framework	Descriptive and retrospective Adapted TIS framework
Key characteristics	Pre-commercial technology field Based on a complex and design intensive focal product A number of technology concepts developed by Swedish actors Very limited Swedish market potential	Pre-commercial technology concept Based on a complex and design intensive focal product Single concept mainly developed by Swedish actors but tested and demonstrated abroad No Swedish market potential	Commercial technology field with rapid industrial and market development globally Based on a standardized and manufacturing intensive focal product Several pre-commercial concepts developed by Swedish actors Rapidly growing Swedish market based on imported products

The characteristics of the case studies imply that they can be justified as appropriate for the purpose of this thesis on several grounds. First, they are empirically interesting from a Swedish policy perspective. Case-specific knowledge may thus contribute to the development and implementation of policies that aim to stimulate and shape innovation in these areas. Second, their extreme characteristics make it possible to make some generalizations to broader instances

[41] Notably, the temporal system boundary had an inductively derived beginning (i.e. when relevant activities could first be identified) and a deductively derived ending (i.e. when the empirical investigation ended).

of technological innovation. In particular, the case studies bring insights into the challenge of shaping sociotechnical change, which in turn have implications for both policymaking and theoretical frameworks. Finally, their scope is sufficiently broad to capture interesting innovation dynamics, while at the same time limited enough to enable a mixed-methods analytical approach within the time and resource constraints of the underlying research project. Through investigations that reveal weaknesses in existing theories, enable testing and illustration of new concepts, and create an understanding of the phenomena of interest, this has paved the way for the conceptual contribution of this thesis.

6.3 Methods for data collection and analysis

As noted in previous chapters, this research engages with a complex phenomenon that cannot be neatly measured or assessed through a single quantitative or qualitative method. Nevertheless, by collecting different types of data and using multiple analytical methods, it is possible to create plausible narratives about what was going on in the particular instance under investigation and how things may play out in the future under certain assumptions. This is what warrants the mixed-methods approach employed in this thesis.

The narratives developed as a part of this research are mainly based on secondary data that has been obtained through extensive desktop research, but also draws upon primary data in the form of interviews with key informants.[42] The desktop research covered science collections, news archives and patent registries, public databases with details about research, development and demonstration projects, as well as reports, documents press, releases and websites published by government agencies, firms and other organizations. It thus involved both qualitative and quantitative data, obtained from sources that represent different perspectives. The interviews were conducted with entrepreneurs, representatives from large and small firms, researchers, interest groups, civil servants representing different policy actors, and other key informants. All interviews followed an open-ended interview guide that allowed for follow-up questions and reflections. They were recorded and partially transcribed to enable structured analysis. Most interviews were also conducted on the condition of anonymity and therefore no interviewee identities are disclosed in the appended research papers. Interviewees are, however, placed in broad categories and in some cases their more specific role and affiliation is revealed. In total,

[42] In Case study A, the interviews were complemented with personal communications and direct observations during multi-stakeholder workshops organized as a part of a Swedish policy initiative.

this thesis draws on 66 interviews. Additional interview details per case study are presented in Table 6.2.

Table 6.2. Interview details per case study.

	Case study A: Swedish marine energy	Case study B: Tidal kite technology	Case study C: Swedish photovoltaics
Total interviews	25	12	29
Out of which			
performed by thesis author	5	11	29
performed by thesis author and co-author(s)	6	1	0
performed by co-author(s)	14	0	0
Out of which			
conducted face-to-face	20	6	17
conducted via telephone	5	6	12

To ensure a sufficiently strong empirical foundation for the analysis, data sources were identified through an explorative snow-balling process, in which collected data gradually approached saturation in relation to the ambition of each case study. Put differently, the scope of desktop research and interviews was expanded until the added value of further investigation did not motivate additional efforts. Moreover, data was critically evaluated with respect to the perspective represented by its source, and efforts were made to triangulate whenever possible.

In all three case studies, the first analytical step was to use the collected data to develop a high-level understanding of the historical and concurrent characteristics of the system. Here, the focus was not to analyze observed patterns, but rather to place events along a timeline and describe what had happened and who was involved. It may thus be described as an event history approach (Hekkert et al., 2007; Poole et al., 2000), although the procedure was neither formalized nor quantified. To a large extent, this first analytical step was also carried-out iteratively with the data collection process, which allowed continuous adaptations based on preliminary findings.

The subsequent analytical steps were more tailored to the ambition of each case study. Case study A, which had a prospective and prescriptive focus, largely followed the analytical approach suggested by Bergek et al. (2008a). The collected data was accordingly used to map the current structure of the system as well as to identify its strengths and weaknesses, which in turn enabled the development of policy recommendations. In contrast, Case study B and Case study C, which both had a retrospective and descriptive focus, employed adapted analytical approaches informed by conceptual development. Following these approaches, the collected data was used to construct narratives of structural change in the focal system as well as to identify its underlying drivers.

Nevertheless, the analytical methods were quite similar in the three case studies. The obtained data from desktop research and interviews was analyzed through a coding procedure based on categories from analytical frameworks, which in the end formed the basis of a narrative that corresponded to the research objective. This work was to some extent supported by qualitative data analysis software, but fundamentally relied on more pragmatic and creative ways to organize data (i.e. presentation software and old fashioned post-it notes). In addition, the case studies, in particular Case study C, involved the creation of databases with information about publicly funded RD&D projects, policy instruments and other key features. This allowed quantitative analyses that complemented qualitative data.

To summarize this chapter, I first described the research process which has resulted in this thesis. Then I commented on the selection of empirical research cases and described their general characteristics. In the end, I described the methods used for empirical investigation and conceptual development. In the next chapter, my focus turns towards the results of this research endeavor.

CHAPTER 7 – EMPIRICAL FINDINGS

The previous five chapters presented the metatheoretical foundation of this thesis, elaborated on the systems perspective that guides the research effort, provided a comprehensive review of the literature, discussed the conceptual research problem in focus, reflected upon methodology, and described the employed research design. Against this background, the focus now turns to the results of this research endeavor, starting with empirical findings from the three case studies.

In the following sections, I will first review each case study individually. Then I summarize general findings. In the end, I discuss implications for policymaking and conceptual development. The chapter is based on Paper I, Paper II and Paper III, which is also where full lists of references can be found.

7.1 Case study A – Swedish marine energy

Case study A focuses on marine energy in Sweden. As a technology field, marine energy encompasses a number of technology concepts that are intended to produce electricity from ocean waves and tides, with the latter including both tidal streams and ocean currents.[43] The physical resource potential is estimated at about 90 000 TWh per year, but only a minor part can be exploited due to technical, economic, social, and ecological constraints (Sandén et al., 2014). The realistically expected level of deployment is highly uncertain (IPCC, 2012) and has been estimated at a few hundred (Sandén et al., 2014) or thousand (The Carbon Trust, 2012) TWh per year. While the global potential is not very impressive compared to solar and wind energy,

[43] There is no commonly agreed-upon definition of marine energy. Notably, some choose to let the field encompass other technologies associated with the marine environment, such as offshore wind power, tidal barrage technology, ocean thermal energy conversion, salt gradient energy conversion and current power from inland rivers.

it is quite substantial in some coastal regions. For example, marine energy is estimated to be able to meet 20% of the current UK electricity demand (Carbon Trust, 2011).

Worldwide, hundreds of marine energy technology concepts are being developed and technological diversity is high. Most technology concepts undergo conceptual development and small-scale sea trials, and only a handful have been tested and demonstrated at full scale. There are accordingly very few power-producing installations; the total installed capacity only amounted to about 13 MW in 2014 (OES, 2014), which is less than 1% of that for offshore wind the same year (IEA, 2016). Despite the early development stage, many national governments promote the sector by setting national deployment targets, making detailed resource assessments, providing market incentives such as feed-in tariffs, establishing open test centers, and supporting research, development and demonstration. However, the support offered to marine energy constitutes a very small fraction of the resources dedicated to other renewables (Frankfurt School-UNEP Centre/BNEF, 2016).

In Sweden, the resource endowment for marine energy is very small compared to other regions in Europe and beyond. Nonetheless, a number of promising technology concepts are developed by Swedish actors, there are world-class research activities, domestic industries offer relevant capabilities and competences, and policymakers offer quite substantial innovation support. The strong national position as a technology developer and very small market potential highlights policy challenges related to the issue of benefits appropriation, which makes Swedish marine energy an interesting research case in the light of the purpose of this thesis.

Covering developments until 2014, the case study aims to identify factors that block the development and diffusion marine energy technologies in Sweden as well as to discuss related policy issues. The analytical approach largely follows the conventional TIS approach, as described by Bergek et al. (2008a).

The analysis reveals that the Swedish marine energy innovation system, as well as its global context, were at the time characterized by immature and expensive technologies. Although the Swedish market potential is limited, several promising device developers had emerged together with world-class research activities, but established industrial actors and private investors remained passive. Public funding to the technology field had been quite substantial, but its allocation was questionable, since it strongly favored research, development and demonstration focused on a specific, rather than a collection of, technology concepts. The coordination among policy actors was also poor, and no visions, strategies, or roadmaps were in place. Furthermore, social networks were strong among certain actor groups, with highly concentrated knowledge development, while there was a general lack of knowledge diffusion, collaboration and trust in the innovation system as a whole. In addition, market incentives were insufficient to stimulate testing and demonstration.

These characteristics highlight a number of weaknesses in key innovation processes, which can be explained by seven blocking factors: limited test and demonstration activities; lack of knowledge and coordination among public actors; lack of collaboration among actors; passivity of established actors; small and uncertain domestic markets potential; lack of political direction; and insufficient markets incentives. Analyzing interdependencies in these blocking factors shows that the small and uncertain domestic market potential hindered the development of political direction, particularly around the crucial issue of whether policy interventions should aim to deploy marine energy technologies in Sweden or create an industry that can supply the global market. At the same time, the absence of political direction likely added to uncertainty regarding domestic market potential since policy had not played an active role in shaping expectations. The uncertainties created by these interrelated blocking factors had a number of dynamic impacts that hindered the development and diffusion of marine energy technology in Sweden.

The analysis thus indicates that if policymakers wished to promote marine energy in Sweden in 2014, they primarily needed to address the lack of political direction and reduce uncertainties regarding domestic market potential. If these central blocking factors had been addressed, it is likely that the performance of innovation processes would have been enhanced through increased collaboration and strengthened engagement of established actors, which in turn could have mobilized resources, stimulated research, development and demonstration activities, and led to technological advancement.

7.2 Case study B – Tidal kite technology

Case study B focuses on tidal kite technology. This is a specific marine energy technology concept that is developed by the Swedish industry spin-out Minesto. The technology concept is based on an innovative approach to producing electricity from tidal streams and ocean currents. In particular, it may expand the economically viable global marine energy resource by making it possible to harness low velocity tides and currents. What makes the technology concept particularly interesting for the purposes of this thesis is that Sweden completely lacks a suitable resource endowment. This rules out not only a domestic market, but also ocean testing and demonstration activities. As a research case, tidal kite technology thus makes policy challenges related to the issue of benefits appropriation even more salient. In particular, it raises questions about how the spatial distribution of key resources influences the development and diffusion of a new technology.

Covering developments until 2016, the case study aims to analyze the development and diffusion of tidal kite technology from a Swedish policy perspective. It employs a variation of the TIS framework, which introduces an explicit regional policy perspective by dividing the global innovation system into a domestic and a foreign sub-system. In addition, the investigation adopts a resource perspective by interpreting 'functions' as resource mobilization processes (Binz et al., 2015). The analytical focus is accordingly to analyze how resources mobilized from domestic and foreign regions influence the emergence of system structures in these domains.

The investigation shows that the tidal kite innovation system started its development in Sweden, where early conceptual development activities was carried-out by Minesto in collaboration with universities, research institutes and industry. The system then gradually branched out to the UK. Initially through the establishment of an ocean test site in Northern Ireland, but more recently in the form of preparations for a full-scale demonstration project in Wales. Currently, the tidal kite innovation system also shows signs of spreading to regions beyond Europe through Minesto's market development activities. Although this has implied that a number of international and UK actors have entered the system, including both research organizations and industry, Sweden had in 2016 remained the main location of Minesto's growing research, development and management activities.

The analysis suggests that the spatial development trajectory of the tidal kite innovation system corresponds to the regions from which it has mobilized key resources; Sweden has played a major role, and this is also where the system currently has its center of gravity. However, when examining the observed dynamics more closely, it is clear that the mobilization of resources from one region does not necessarily mean that the technology will be developed, diffused and used in the same place. In fact, it appears as if something has made developments gravitate towards Sweden, even though foreign regions have provided certain key resources. This suggests that knowledge and competence, which have to a large extent been mobilized domestically, are particularly decisive for the spatial development trajectory of an emerging technology. An additional explanation is that early developments in Sweden, such as the basic invention and early support by a university business incubator, shaped the trajectory by creating networks that provided access to crucial knowledge and competence. This seems to have created a path dependency that hindered developments abroad. It should be noted, however, that there is a time lag between the mobilization of resources and structural change in the system. The full results of the influence of foreign regions are therefore obscured within the time frame of the study.

Furthermore, the analysis indicates that other factors will play an increasingly important role as the technology advances further. First, some sociotechnical structures around value chain activities such as installation, operation, maintenance and power transmission are by nature bound to the locations of suitable ocean sites for further demonstration, up-scaling and commercialization. Second, as the focus of innovation activity shifts from concept development to more incremental improvements in components and sub-systems, spatial proximity between different parts of the value chain may become more important and thus create additional incentives for development close to deployment sites. And third, it is likely that different regions will to some extent compete for parts of the value chain that are less bound to deployment sites, for example research and development, production of sub-systems and components, and system integration. Although refraining from arguing for a specific policy strategy, the analysis thus highlights the importance of taking this type of spatial innovation dynamics into account when designing and implementing policies for promoting new technologies.

7.3 Case study C –Swedish photovoltaics

Case study C focuses on photovoltaics in Sweden. Photovoltaics is one of few renewable energy technologies that can meet projected global energy demand without carbon emissions. The physical resource potential has been estimated at 730 000 000 TWh per year, and even though technical, social and economic constraints may reduce the available resource to roughly 1 000 000 TWh per year, it widely exceeds current and projected energy demand (Sandén et al., 2014). A photovoltaic system is based on a module that encapsulates cells of a material that converts photons to electricity, but also includes components such as inverters, mounting equipment and, potentially, storage. The technology can be used in off-grid applications to power satellites, cabins, boats or electric devices, or in on-grid applications that include distributed installations, where small systems are attached to roofs, facades and other suitable surfaces, and centralized installations, where large systems are built on dedicated land or floating sea structures. Furthermore, it is common to distinguish between modules based on silicon wafers and modules based on thin films of other, often more complex, materials. Silicon modules dominate major markets with a global share of over 95%, but thin-film modules are used in some applications that favor light weight, transparency, flexibility or particular cost/efficiency characteristics (IEA, 2018). In addition, new thin-film technologies in early development stages may drastically reduce both costs and environmental impacts.

While the first photovoltaics modules were presented in the 1950's, the market for on-grid systems did not take-off until the late 1990's, driven by strong market subsidies. This led to economies of scale, increased supply of raw materials and process improvements in the production of cells and modules as well as to the emergence of a more efficient downstream value chain. As a result, the price of photovoltaic systems fell rapidly. In particular, the price of silicon modules decreased faster and to a lower level than most experts had expected, while thin-film modules struggled to compete. In 2018, photovoltaics was competitive without subsidies on many markets around the world. After a geographical shift from countries such as the US, Japan and Germany, the global industry was dominated by Chinese firms. China also had the largest national market for photovoltaic systems, both in terms of installed capacity and annual growth.

Sweden is one of many small countries that have taken part in the development and diffusion of photovoltaics technology. Since research was initiated in the early 1980's, the country has built a strong academic knowledge base, given rise to a number venture companies, and seen the rise and fall of a quite substantial industry. Market development lagged behind many other European countries, but in recent years installed capacity has grown rapidly, albeit from low initial levels. However, Sweden has struggled to establish and sustain industrial activity beyond research, development and demonstration, even though policymakers have provided substantial support with domestic industrialization as one of the main objectives. As a research case, Swedish photovoltaics thus involves historical failures to appropriate benefits from successful technological innovation. In addition, some of the policy challenges which characterize the historical developments are likely to persist as the technology field continues to expand in Sweden and globally. This makes Swedish photovoltaics an interesting case to investigate for the purposes of this thesis.

Covering developments until 2018, the case study has a broad focus and aims to review and analyze Swedish photovoltaics innovation from a policy perspective. The analysis draws on the TIS framework but employs a tailored approach that highlights the technological and spatial configuration of sociotechnical change. In turn, this enables an analysis of the differentiated dynamics which shape technological innovation.

The investigation identifies three main development trajectories in the Swedish photovoltaics innovation system. The first one concerns research, development and demonstration of thin-film modules, which has been ongoing since the early 1980's. A number of venture companies have tried to establish thin-film module production in Sweden, but failed to attract the investments needed to advance towards commercial scale facilities. Instead, these venture companies have either been acquired by foreign firms, with module production in other countries as a result, shifted their focus to the production of manufacturing equipment, or remained pre-commercial. The second trajectory concerns commercial production of silicon modules, which first begun in the early 1990's. The industry expanded in the mid 2000's and reached an annual production level of roughly 180 MW in 2008 (Lindahl et al., 2019). Since the Swedish market was at this time very small, most of the output was exported. However, the silicon module industry was increasingly challenged by competition from Asian producers. The output plummeted in 2010 and the last remaining factory closed down in 2015. The third and last trajectory concerns the installation of on-grid systems. Although a small and stable market for off-grid systems had been in place since the early 1990's, emerging without subsidies since photovoltaics modules were competitive in some niche applications, market formation for on-grid systems did not start until Swedish policymakers introduced the first investment support in 2005. This marked the start of an exponential growth trajectory in the distributed segment, which has been sustained ever since, while the centralized segment took-off about a decade later. As a result, the cumulative installed capacity increased from 5 MW in 2010 to 425 MW in 2018 (Lindahl et al., 2019). It should be noted, however, that in 2018, the market was still smaller than the output of Swedish silicon module production at its peak in 2008. And as a result of the current lack of domestic photovoltaics industries, the Swedish market is completely dependent on imported silicon modules.

When analyzing the underlying dynamics of these trajectories, it is clear that the innovation system is characterized by mismatches and fragmentation among key processes. Knowledge development has been dominated by thin-film technology, while both commercialization and market formation has favored silicon technology. And although the latter have revolved around the same type of technology, they have essentially been separated in time. These mismatches have resulted in a fragmented innovation system that has failed to enact a full range of innovation processes in virtuous cycles of positive feedback. Instead, research, development and demonstration of thin-film modules, silicon module production and system installation have emerged as separate development trajectories that depend on industries and markets in the international context. This is in turn likely to have hindered the commercialization of Swedish thin-film research, lowered the prospects of continued silicon module production and slowed down market developments.

The analysis also shows that Swedish policymakers have adopted different roles in relation to these trajectories. While the silicon module industry received little policy attention, research, development and demonstration of thin-film modules, and system installation, have been propelled and to some extent initiated by Swedish policymaking. These findings highlight how public research grants can lead to industrial development abroad, while market subsidies may stimulate the deployment of imported products. Although stopping short of suggesting a policy strategy, the case study thus suggest that policymakers should pay close attention to mismatches and fragmentation with respect to technological and spatial development trajectories in emerging TIS.

7.4 Summary of findings

Since the case studies are different in empirical focus and analytical approach, they are not designed to allow for generalization based on a replication logic. However, this does not imply that they fail to offer knowledge beyond case-specific empirical findings. Through their design, the case studies shine light on technological innovation from a perspective that has received limited attention. This in turn reveals mechanisms that have a general character, in the sense that they are inherent features of the innovation process and the role of policy, even though they are certainly actualized in different ways depending on the specific conditions under which a new technology emerges.

To begin with, the case studies highlight that the result of technological innovation is not only a quantitative level of production and consumption of some product, but also a configuration of sociotechnical structures associated with the technology in focus. They also emphasize the somewhat obvious observation that such configurations are important, not least from a policy perspective. In particular, policymaking that aims to influence the development and diffusion of new technologies in the energy domain commonly emphasizes objectives related to the creation of benefits that have a localized character, which means that the extent to which they will be appropriated by actors in different regions depends on the spatial configuration of industries and markets. For example, the support to new renewable energy technologies offered by Swedish policymakers in the three case studies has been partly motivated by the potential to create domestic jobs, which is contingent on where industries emerge. This implies that the ambition of such policymaking should not be to stimulate the growth new technologies, but rather about shaping innovation towards more specific directions of change.

Furthermore, the case studies reveal some of the mechanisms that determine the configuration of industries and markets that emerge as a result of technological innovation. They show how technological and spatial development trajectories are the result of a complex interplay of factors within and beyond the region in focus. In the three case studies, domestic policymaking, foreign industrial development, the availability and distribution of key natural resources, and historical path dependencies receive particular attention, but there are certainly numerous other factors at play.

The observation that development trajectories depend upon a complex interplay of heterogenous factors should not come as a surprise. Indeed, such dynamics are commonly referred to when explaining the development and diffusion of new technologies in the literature on TIS and beyond. What the case studies highlight, however, is that policymaking and other factors may support different development trajectories. For example, research funding can be oriented towards many different variants of a new technology or favor a specific concept. Depending on the characteristics of policy instruments, they may also be more inclined to support the development of domestic industries and markets, as opposed to contributing to global developments. Nevertheless, policy is just one of many factors that determine the specific direction of change. As a result, the capacity of policymakers to shape developments along desirable trajectories is limited, especially when they represent a region that is very small in comparison to the global development context.

In addition, the case studies offer a number of more specific findings about the formation of development trajectories. First, they highlight the role of natural resources, which have received quite limited attention in the sustainability transitions literature. In particular, Case study A demonstrates how a limited domestic resource endowment may constitute a blocking factor in the development and diffusion of a new technology, while Case study B shows how the distribution of natural resources may shape the spatial configuration of an emerging value chain. Second, the case studies highlight that the causes and effects of technological innovation are often spatially separated, but also indicates that some more specific processes have a 'stickier' character. This is apparent in Case study B, which shows how early knowledge development in one region created a path dependency that favored the continued emergence of research and development activities in the same place, even though many key resources had to be mobilized from abroad. Third, and related to the previous observation, the case studies highlight that fragmented innovation dynamics in a region can reduce the stickiness of innovation processes. This is a key finding in Case study C, which shows how missing links between innovation activities related to different parts of the value chain for a new technology make actors dependent on developments in other regions.

Finally, it should be noted that Case study A in fact emphasizes the importance of direction from a slightly different perspective, by identifying the mere lack thereof as a factor that may hinder innovation process. This particular case studies also highlights the interdependence of problems in the development and diffusion of new technologies and the importance of ranking policy interventions, which supports arguments put forward by Kieft et al. (2018, 2016).

7.5 Policy implications

The findings presented in the previous section have several implications for policymaking focused on specific technologies. To begin with, and perhaps most importantly, they emphasize the importance of having a clear overarching objective that specifies the social and environmental benefits an intervention strives to create. From this objective, more detailed aims related to the technology in focus can be derived. Importantly, however, most objectives imply aims that not only relate to the level of production and consumption of some product, but also to the multidimensional characteristics of sociotechnical change.

Furthermore, the findings highlight the challenges which face regional policymakers that aim to shape the development and diffusion of new technologies towards trajectories that result in domestic industries and markets. Policymaking is only one of many factors that determine development trajectories, especially in small regions that have strong links to their global context. This implies that support to technological innovation may result in benefits that are mainly appropriated by foreign actors.

The key question from a regional policy perspective is therefore how interventions can be designed to promote the development and diffusion of new technologies, while creating incentives that result in domestic industries and markets. Or put differently, how policymaking can not only stimulate, but also shape technological innovation. Although the case studies clearly fail to answer this difficult question fully, they offer some valuable insights.

First, there is a need to distinguish between policy interventions that stimulate innovation processes that drive regional as opposed to global development. For example, financial support to small firms that develop new technologies is certainly likely to stimulate innovation, but it is far from certain that the results, and their associated benefits, appear in the same region. In contrast, policy interventions that contribute to the development of certain sticky resources, such as knowledge embedded in regional networks of actors, is more likely to shape developments towards trajectories that result in domestic industries and markets. Regional policymakers should therefore try to identify interventions that may support innovation processes that involve the domestic formation and mobilization of sticky resources.

Of course, this raises an important question from a global perspective: if regional policymakers only focus on promoting the formation and mobilization of sticky resources that can shape developments towards their spatial contexts, who supports the formation of other resources that may be as critical for successful innovation? This highlights the need for international policy coordination that can counteract potential negative effects of regional competition, which has also been discussed in the context of both wind power and photovoltaics (see Binz et al. (2017) and Quitzow (2015)).

Second, there is a need to avoid a situation where innovation processes at the regional level become fragmented and overly dependent on the global context. This implies that policy interventions should not only support research and development, but also actively promote the emergence of interlinked domestic industries and markets. One such approach involves tailoring market support to favor domestic suppliers, rather than imported products. But while this could potentially facilitate the emergence of domestic industries, it may also come at the expense of broader market formation, if imported products have stronger price-performance characteristics. This highlights tensions between objectives related to industrialization and market development, which further underlines the need for a clear and informed policy strategy.

In addition, the case studies suggest that there are reasons to explore policy interventions that retain some of the benefits of successful innovation, even though industries and markets mainly develop abroad. For example, and as suggested by among others Mazzucato (2015), grants to research, development and demonstration could be made subject to a payback mechanism that delivers a return on public investments no matter where the technology is exploited in the end. This may involve offering conditional loans or taking equity in venture companies that receive financial support.

One reason to use such policy instruments is that they interfere less with the dynamics of a global economy that promotes cost-efficient value chains by allowing market forces, rather than policymakers, to determine where new industries and markets emerge. Another reason is that regions that support technological innovation should get a payback on the investments that this entails. This is not only about distributing costs and benefits in a fair way, but also about capturing value that can be used to fund the next round of technological innovation, and avoiding a situation where externalities erode national incentives for technology policy. In fact, this is analogous to private investments in research and development, which are incentivized through the patent system.

In fact, the reasoning above points to an important paradox in the increasingly global and internationalized nature of technological innovation. On the one hand, global value chains and innovation networks tend to increase efficiency by taking advantage of regional differences in resource endowments, capabilities, knowledge and other determinants of innovation performance (OECD, 2013). But on the other hand, this makes it difficult to ensure that the regional appropriation of localized benefits is in line with the risky public investments that made successful innovation possible. The importance of connecting risks and rewards when it comes to technology policy has been eloquently put forward by Mariana Mazzucato and colleagues (Lazonick and Mazzucato, 2013; Mazzucato, 2015), but primarily in an intra-national context. This thesis follows their line of reasoning but broadens the discussion to the international arena by focusing on the distribution of public support and localized benefits between nations, rather than between actors and social groups within them.

Finally, and from a global perspective, it should be emphasized that the development and diffusion of renewable energy technologies will create urgently needed global benefits no matter which region that ends up building new industries. This means that public investments which over time lower the cost of renewable energy can be considered a form of global stewardship. Moreover, since the need for clean and affordable energy is particularly pronounced in developing countries, there are parallels to foreign aid policy. How much these concerns are allowed to guide public policy naturally varies both within and between nations, and any assessment regarding the extent to which a desire to create global benefits actually drives policy intervention is far beyond the scope of this thesis. However, the presented research results clearly highlight that promoting new technologies is a broad policy concern that is relevant for policymakers representing different interests, ranging from purely economic concerns around growth and competitiveness, to energy security, local environmental issues and even foreign aid.

7.6 Implications for conceptual development

While the results of the three case studies have implications for policymakers, their main role in this thesis is to inform conceptual development. To begin with, the case studies together offer an empirical foundation for the weaknesses identified in existing analytical frameworks used to study technological innovation in the sustainability transitions literature, as discussed in Chapter 4. The empirical findings presented in this chapter clearly illustrate that in order to inform policymaking about interventions that aim to promote the development and diffusion of new technologies, it is necessary to account for the multidimensional characteristics of the innovation process. In other words, there is a need for new analytical approaches that link innovation dynamics to the different configurations of sociotechnical structures they may result in.

It is, as a matter of fact, an important weakness of Case study A that innovation dynamics are analyzed in relation to a somewhat vague analytical goal that primarily involves one-dimensional development and diffusion of the technology in focus. Although policy implications are nevertheless discussed with reference to several objectives, it is possible that different dynamics and problems had been identified if the actual analysis was differentiated in a similar manner.

Furthermore, Case study B and C test and illustrate gradual adaptations to the TIS framework to accommodate for the lack of attention to multidimensionality. Case study B explicitly integrates the spatial dimension in the analytical approach and interprets TIS as systems that also include the industries and markets that emerge as a result of technological innovation. This allows for an analysis that links innovation dynamics to the resulting development of sociotechnical structures along the value chain for the technology in focus. Case study C adopts a slightly different approach by adding the process commercialization to a condensed version of the commonly used lists of ‘functions’. This enables an analysis that distinguishes between innovation dynamics related to upstream (commercialization) and downstream (market formation) parts of the value chain for the technology in focus. Notably, when Case study C is used as an empirical example to illustrate technological directionality in Paper V, it also adopts a more explicit value chain perspective that highlights how the technological characteristics of sociotechnical structures have changed over time.

In addition, both Case study A and B show that the availability and distribution of natural resources is an important determinant of innovation dynamics. This calls into question the common approach of only including social structural components in the system in focus, and highlights the need to account for the material aspects of the innovation process.

To summarize this chapter, I first reviewed the three case studies presented in this thesis and summarized their general findings. Then I discussed implications for policymaking and conceptual development. This provides an empirical foundation that inspires, justifies and informs the conceptual contribution presented in the next chapter.

CHAPTER 8 – CONCEPTUAL CONTRIBUTION

Whereas the previous chapter presented and discussed the empirical findings of this thesis, I will now turn to its main contribution. It consists of a conceptual foundation for efforts to analyze and shape technological innovation, which I refer to as the technological systems framework.

In the following sections, I will first establish and motivate the point of departure when developing the technological systems framework. Then I (re)introduce and elaborate on technological systems as an appropriate construct when specifying the object of study in sustainability transitions research on technological innovation. I proceed to discuss how technological systems change over time and establish a conceptual link to the costs and benefits they bring. In the end, I comment on how the technological systems framework can be applied and provide a brief summary of its constituent parts. The chapter is primarily based on Paper IV and Paper V, but also draws on arguments presented in Paper I, Paper II and Paper III.[44]

8.1 Point of departure

The point of departure when developing the technological systems framework is sociotechnical and technology-oriented. In the terminology introduced in Chapter 3, this means that I adopt a particular approach to setting structural and functional boundaries for the system in focus. In addition, the framework is based on certain ideas about how sociotechnical structures can be

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[44] It should be noted that some of the core conceptual ideas presented in this chapter draw on unpublished work by my supervisor Björn Sandén, together with Marko Hekkert and Simona Negro, at the 8th International Sustainability Transitions Conference in Gothenburg, Sweden (Sandén et al., 2017). I am indepted to the foundation they established and sincerely hope that they see my clarifications, elaborations and modifications as a valuable addition to the literature.

described and categorized as well as on a specific way to think about technology as a bundle of value chains. In the following, I will elaborate on this point of departure.

8.1.1 A sociotechnical focus and technology-oriented perspective

As discussed in Chapter 4, sustainability transitions research on technological innovation is dominated by the TIS framework, which is not geared towards investigating the multidimensionality of sociotechnical change and also laden with ambiguities and contradictions in how core concepts are understood. TISs are defined as both social and sociotechnical systems, with some leading scholars switching back and forth in different publications. While it seems plausible that many scholars today think about TISs as constructs that include both innovation and production-consumption activities, the system purpose remains ambiguous throughout most of the literature. Partly as a consequence, 'functions' are ill-defined; it is not clear where the change process they describe occurs, they are conceptually difficult to distinguish from system structure, and most typologies used in the literature exhibit considerable overlaps and fail to show that categories are exhaustive. In addition, system boundaries most often fail to clearly define the technology in focus.

Advancing the analytical approach accordingly involves strengthening clarity and rigor as well as making important choices with regards to system delineation. To begin with, it seems crucial to clarify whether the analysis should adopt a structural boundary that focuses on social or sociotechnical structures. Here, I strongly believe that the latter is preferable. One reason is that physical artifacts are highly involved in interactions that govern both innovation and production-consumption activities. 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 behavior. And even though I acknowledge that some aspects of this interaction can be captured through the immaterial aspects of technology, as suggested by Jacobsson and Bergek (2011), and also inherent in the multi-level perspective (Geels, 2002), I 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.[45] It is also difficult to incorporate a comprehensive conceptualization of the results and consequences of the innovation process

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[45] 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 polished ice.

without adopting a sociotechnical perspective. In particular, the impact of technological innovation on the natural environment is clearly mediated through physical artifacts.[46]

Another important choice is whether to adopt an innovation-oriented perspective, where the system in focus is one that achieves change, or a technology-oriented perspective, where the system in focus is one that is subject to change. This has important consequences for further theorizing that attempts to incorporate a closer attention to the direction of change – after all, it is different to describe and analyze a system that *creates* a configuration of sociotechnical structures, than to do the same for a system that *becomes* configuration of sociotechnical structures.[47] Here, I see strong reasons to adopt a technology-oriented perspective and thus include all structures that can be considered "specific" to the technology of interest. This implies that the functional boundary ought to include production-consumption activities as well as related innovation activities. The benefit of a technology-oriented perspective is that it 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 sociotechnical change towards specific outcomes. In this respect, a technology-oriented perspective makes the multidimensional configurations that result from technological innovation a property of the system in focus, rather than a feature of its outcome. This in turn enables a closer link to the equally multidimensional objectives that policymakers and other actors aim to achieve. In addition, focusing on the created rather than the creating is 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.

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[46] 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, I maintain that it is less problematic to exclude ecological structures than it is to adopt a purely social perspective. This is because ecological structures can, to a large extent, be conceptually transformed into physical artifacts as they are brought into sociotechnical interactions.

[47] A useful analogy is to think about technological innovation as a car. Whereas innovation-oriented approaches focus on investigating the engine and suggesting ways to increase its power, technology-oriented approaches rather focus on investigating the entire vehicle and suggesting ways to steer it in a specific direction.

8.1.2 Unravelling the sociotechnical

A structural boundary that includes sociotechnical structures implies the system in focus includes social and technical components. The question is how these high-level concepts can be unpacked in a way that both clarifies their meaning and provides a more fine-grained set of sub-categories that can support description and analysis. I will here propose that sociotechnical structure consists of three fundamental components – *artifacts, actors and agreeings* – and also suggest a way to further decompose these into sub-components and sub-sub-components. On the one hand, the reasoning behind this categorization of structural components is based on the ontological foundation of this thesis, as presented in Section 2.3, which is based on the idea that the world we inhabit in constituted by objective, intersubjective and subjective structures. This is a deductively derived set of mutually exclusive and collectively exhaustive ontological categories, and as such they may be used to clarify what social and technical structures actually refer to. On the other hand, the reasoning draws on various strands of the sustainability transitions literature (Bergek et al., 2008b; Geels, 2004; Hughes, 1987; Rip and Kemp, 1998; Sandén and Hillman, 2011; Wieczorek and Hekkert, 2012). Although scholars use slightly different categories to explain and conceptually organize sociotechnical structure, they seem to agree on a limited number of distinguishable components. These are covered by the categorization presented in this section, but labelled and organized somewhat differently.

To begin with, I view technical structure as a sub-set to objective structure. What makes it a sub-set is the delimitation to physical entities that are at least partly produced by human beings,[48] which I refer to as *artifacts*. All artifacts are combinations of less complicated artifacts (all the way down to the molecular level) 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.* Goods include components, sub-systems and physical products that flow through production-consumption processes. In contrast, infrastructures include tools and equipment that support such processes as well as facilities for research, test and demonstration that play a more indirect role. Notably, a given artifact can accordingly 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

[48] As noted in Section 2.3, distinguishing between the technical and ecological is certainly not as straight-forward as this suggests. But in the interest of space, I leave a longer discussion on difference between culture and nature for another publication.

technology focused on the road as such. In addition, it is possible to distinguish between compound artifacts and networks of artifacts. Both categories consist of lower-level artifacts, but the characteristics of their linkages differ; artifacts are made up of hard-linked components (i.e. lower-level artifacts), while networks of artifacts are linked through flexible interfaces such as fueling stations and cars, roads and tires, electric appliances and grid sockets, and so forth.

Furthermore, social structure is mainly derived from intersubjective and subjective structure, but often also has an objective representation. It includes human beings, either as individuals or organized in larger collectives such as organizations or firms. I refer to these as *actors,* to highlight that they are the only source of agency in sociotechnical systems.[49] 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 are mainly defined by their agency, which stems from subjective structure, but also have an objective representation (i.e. human bodies). They may 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, and civil society organizations. Notably, this implies that individual human beings only appear as parts of organizations.

Apart from human beings, social structure includes agreements and shared meanings, which I will for simplicity shorten to *agreeings.* This is a formational category 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 intersubjective structure, they can be embedded in the minds of actors, materialized 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 behavior. 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

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[49] In a dynamically stable technological system that fulfills its purpose, the difference between human agency and the causal powers of some artifacts is not always apparent for an observer – compare, for example, a taxi driver and an autonomous vehicle. However, the difference becomes more apparent, and perhaps more important, when considering how the system emerges and changes over time, since the development and diffusion of novelty most often includes a larger element of creativity and uncertainty.

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.[50] 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).[51] It may be further decomposed into payments, which are made as goods flow through production-consumption processes, and accumulated financial capital.

Figure 8.1 summarizes this way of decomposing sociotechnical structure into fundamental components, sub-components and sub-sub-components. It should be emphasized, however, that other categorizations are certainly possible. It may even be appropriate to adapt the resolution and focus of categories to the analytical task at hand. This means that this section by no means attempts to argue for an optimal way to decompose sociotechnical structure. Instead, the reasoning should be seen as an attempt to create categories that are mutually exclusive and collectively exhaustive, while relying on a clear ontological foundation.

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[50] For example, while knowledge about offshore wind power describes how social and technical components can be organized to produce electricity by harnessing flows of air, cognitive institutions related to the technology rather determine what meaning an actor associates with basic terms such as offshore, wind and power.

[51] Notably, the financial dimension has been largely absent from theoretical accounts in the TIS literature.

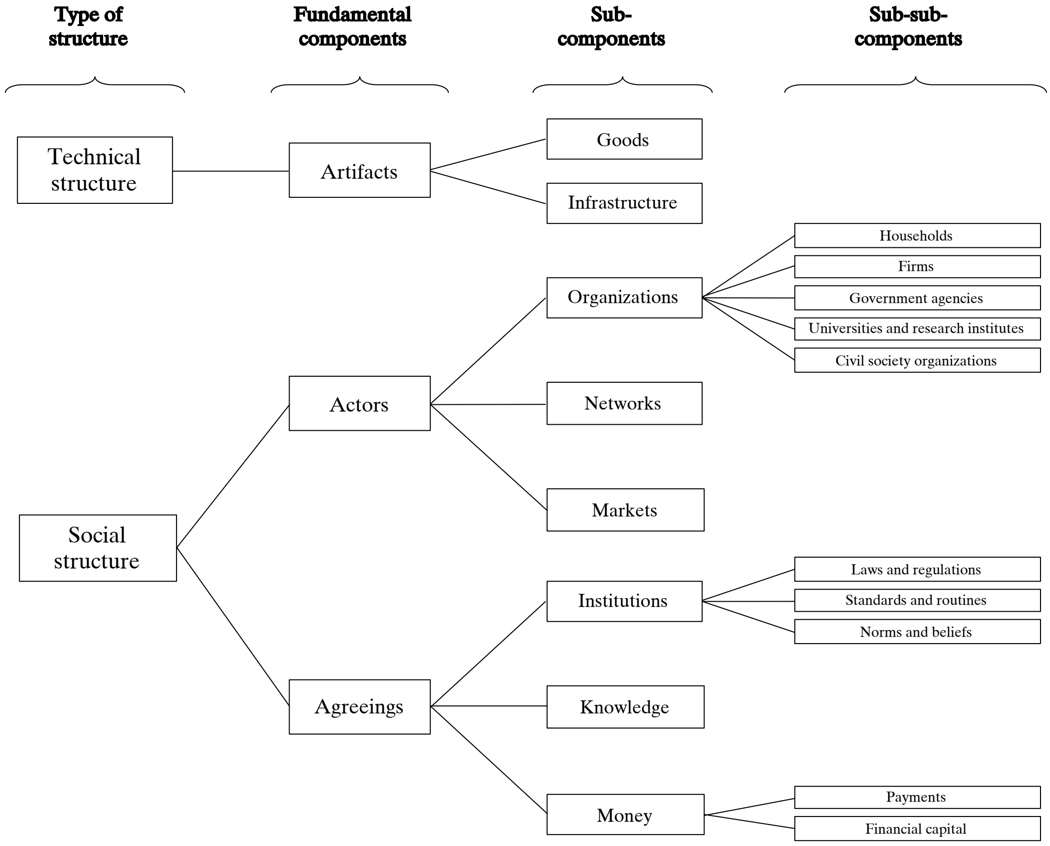

Figure 8.1. A possible sub-division of social and technical structure into its constituent components.

Finally, it may be noted that the terms artifacts, actors and agreeings, which describe the fundamental components of sociotechnical structure, 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.

8.1.3 Technology as a bundle of value chains

A technology-oriented perspective on technological innovation calls for a conceptual framework based on a detailed understanding of technology. This was touched upon in Chapter 3, where I argued that technology is fundamentally an idea about how to convert means to an end. This idea serves as a malleable force of transformation that propels structural change and simultaneously changes its own characteristics. However, to pave the way for the conceptual suggestions made in this chapter, some of the characteristics of technology have to be further elaborated.

Defining technology as a means to an end implies that everything that serves a human purpose can be thought of as a technology. Nevertheless, the term is rarely used to refer to phenomena such as words, language, organizations or economic sectors, at least not in the sustainability transitions community. Instead, the focus tends to be on technologies associated with more or less specifically defined goods and services, such as offshore windmills and wastewater treatment. To capture both goods and services, I will use the term product.

Creating a product involves a number of different processes. For a good, such as a solar module, these may involve the extraction of raw materials, production of components, final assembly and various instances of transportation. More generally, creating a product requires a process that combines many sub-products, which in turn depends on sub-processes that combine sub-sub-products, and so forth (Clark, 1985; Murmann and Frenken, 2006; Simon, 1962). Some sub-products are goods that become a physical part of a product, some are services and consumables that cease to exist after the production of a product, and others are infrastructures that enable the production of many products (before they cease to exist or are used for other purposes). In the end, this implies that a product comes into being as a result of complementary processes that form a value chain of interlinked production-consumption activities.

Any product is also a part of value chains that result in other products. Solar modules complement mounting equipment and electric components to create solar systems, and these can in turn be used as parts of buildings. While technology fundamentally describes how to convert means to an end, it is accordingly intertwined with processes that use this end as a means in the creation of other ends. Put differently, technology is defined by upstream value chains that combine sub-products to create a product, but also strongly associated with downstream value chains that use this product to form what may be referred to as super-products.

The link between the creation and use of a product is particularly important from an innovation perspective. This is because the diffusion of a technology implies the development of both upstream and downstream value chains. After all, if a product is created it will be used in one way or the other. In the end, I will therefore extend my understanding of technology to encompass processes involved in both the creation and use of a specific product, or in other words, both upstream and downstream value chains.

Furthermore, any product can be created and used in different ways. The solar modules referred to above may, for instance, be based on different materials, and also be used in a wide variety of applications. This means that the processes involved in the creation and use of a product form a complex web of both complementary and alternative value chains.

Since reality is interconnected, in the sense that everything contributes to everything over sufficiently long time scales, the web of value chains expands infinitely, or at least to the beginning of humanity, no matter what product is in focus. When specifying a technology, it is therefore common and appropriate to include some processes and exclude others. In particular, upstream processes that are general, in the sense that they are involved in the creation of many other products apart from the focal product, tend to be excluded. For example, the production of standardized nuts and bolts is rarely associated with wind power technology. Similarly, downstream processes that use many other inputs than the focal product are often excluded. While the use of windmills to produce electricity is strongly associated with wind power technology, how this electricity is used is generally not. This way of excluding processes based on their specificity to the focal product corresponds to choosing which parts of complementary value chains that are included in a given technology. However, and importantly, this delineation of complementary value chains does not necessarily have to be based on specificity, but can also be a result of a particular interest or preference of the analyst.

Specifying a technology may also involve excluding some alternative value chains. Upstream, wind power technology can be delimited to horizontal axis turbines and thus exclude vertical designs, and downstream it may disregard off-grid applications. In fact, the exclusion of alternative value chains is sometimes implicit in how products are defined and named. For example, biodiesel and fossil diesel may have the exact same chemical characteristics, but are nevertheless distinguished based on the processes involved in their creation.

At this point, it is worthwhile to provide some illustrations that may hopefully make it easier to grasp this complexity. To begin with, Figure 8.2 shows a set of complementary value chains and thus disregards the existence of alternative processes. It is based on a focal product, P, which is created in an upstream process that combines three sub-products. These are in turn created in another upstream process that combines three sub-sub-products. Furthermore, P is combined with two other products to create a super-product in a downstream process. This super-product is then combined with an additional super-product to create a super-super-product, in another downstream process. Note also that the products and super-products that are combined with P in downstream processes are created through value chains with a similar structure.

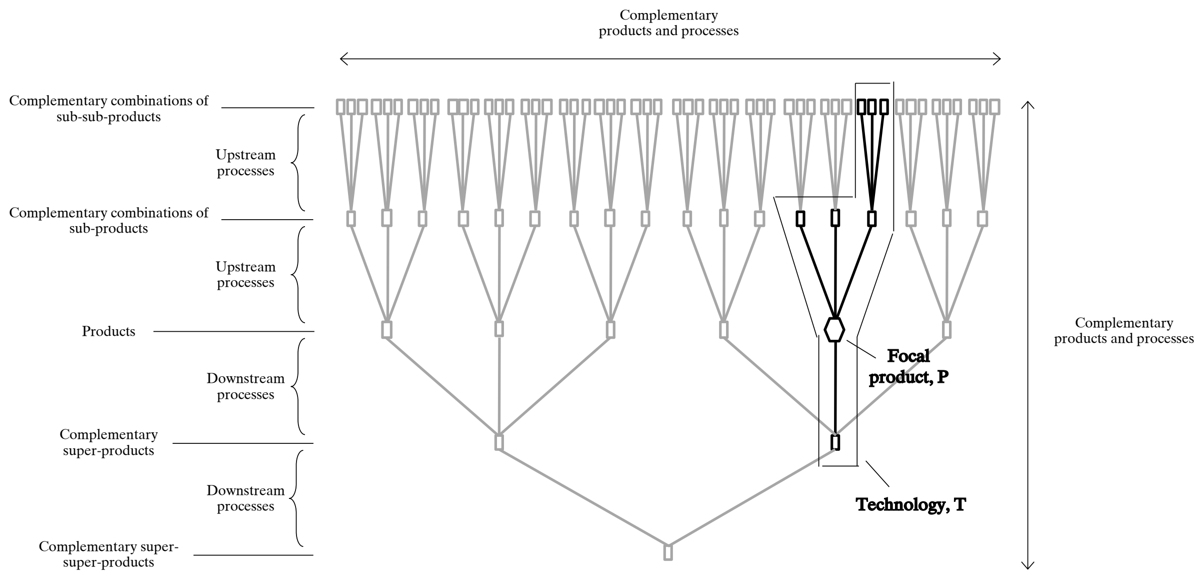

Figure 8.2. Illustration of complementary value chains involved in the creation and use of a focal product, P. Some of the complementary value chains are included in the definition of a technology, T.

Figure 8.2 also defines a technology, T, which includes some of the complementary value chains involved in creation and use of P. Upstream, T includes the creation of sub-products to P, but excludes sub-sub-products to two of the sub-products. Downstream, the use of P to create a super-product is included, but neither its other constituent parts, nor its use in a super-super-product. To concretize the meaning of this technology, we can imagine that P is a solar photovoltaics system, which is created by combining the sub-products electric components, mounting equipment and solar modules. The latter is in turn created by combining the sub-sub-products cells, glass and wiring, which are also included in T. Downstream, the solar photovoltaics system is combined with the products buildings and power lines to produce the super-product electricity. Finally, this electricity is combined with the super-products roads and electric vehicles to produce the super-super-product transportation, but this is not included in T.

A second illustration, presented in Figure 8.3, is based on the same example as Figure 8.2, but only shows the alternative value chains associated with T. These appear since P can be created by any of three alternative combinations of sub-products, which can also be created by any of three alternative combinations of sub-sub-products. In addition, P can be used in three different super-products. In contrast to Figure 8.2, the value chains showed in Figure 8.3 thus include processes that are complementary along the vertical axis, but alternative along the horizontal dimension. As a matter of fact, the vertical axis is the same in both illustrations, which means that they could also be put together in a three dimensional illustration of the web of complementary and alternative value chains that expand from P.

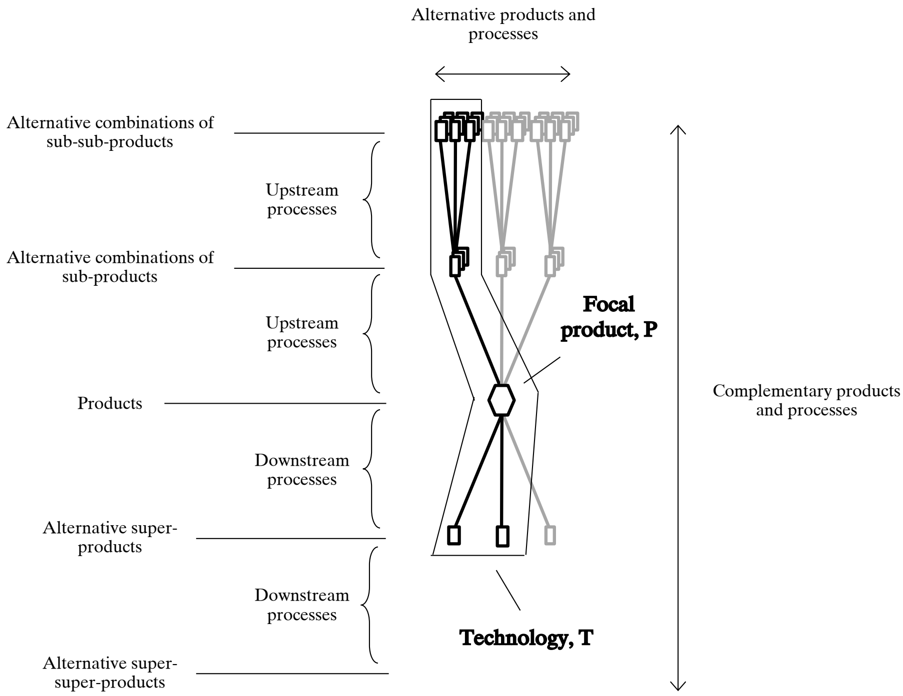

Figure 8.3. Illustration of alternative value chains associated with a focal product, P, and a technology, T. Only some of the alternative value chains are included in T.

Figure 8.3 also specifies T further. Upstream, only one alternative combination of sub-products is included, together with their underlying alternative combinations of sub-sub-products, while the other alternative value chains are excluded. And downstream, only two of the alternative super-products are included. To continue on the concretizing example above, this can be seen as T being delimited to one specific type of solar photovoltaics system, for example one based on silicon modules, which may in turn be based on either amorphous, monocrystalline or polycrystalline cells, as well as to two possible applications, such as building-applied and building-integrated installations.

It is apparent at this point that specifying a technology is a quite complex endeavor that involves specifying a three-dimensional bundle of complementary and alternative value chains that expand from a given product. However, to simplify illustrations and arguments, it is possible to describe such bundles from the perspective of alternative value chains and let their vertical extension indicate the breadth of included complementary value chains as well. The two axes along which complementary value chains are specified in Figure 8.2 are accordingly collapsed into a single dimension, which coincides with the vertical axis in Figure 8.3. This approach allows for a two-dimensional representation of bundles of value chains, and it will be used throughout the remaining parts of this chapter.

Figure 8.4 illustrates the bundle of value chains that define T, using this simplified approach. While the illustration properly highlights P and distinguishes it from other products on the same level, and also shows the included alternative value chains, it only provides an indication of which complementary value chains that are in fact included. What is compromised in this simplified representation is the difference in vertical extension among the complementary value chains, as depicted in Figure 8.2. It should thus be remembered that this type of model is illustrative rather than fully descriptive.

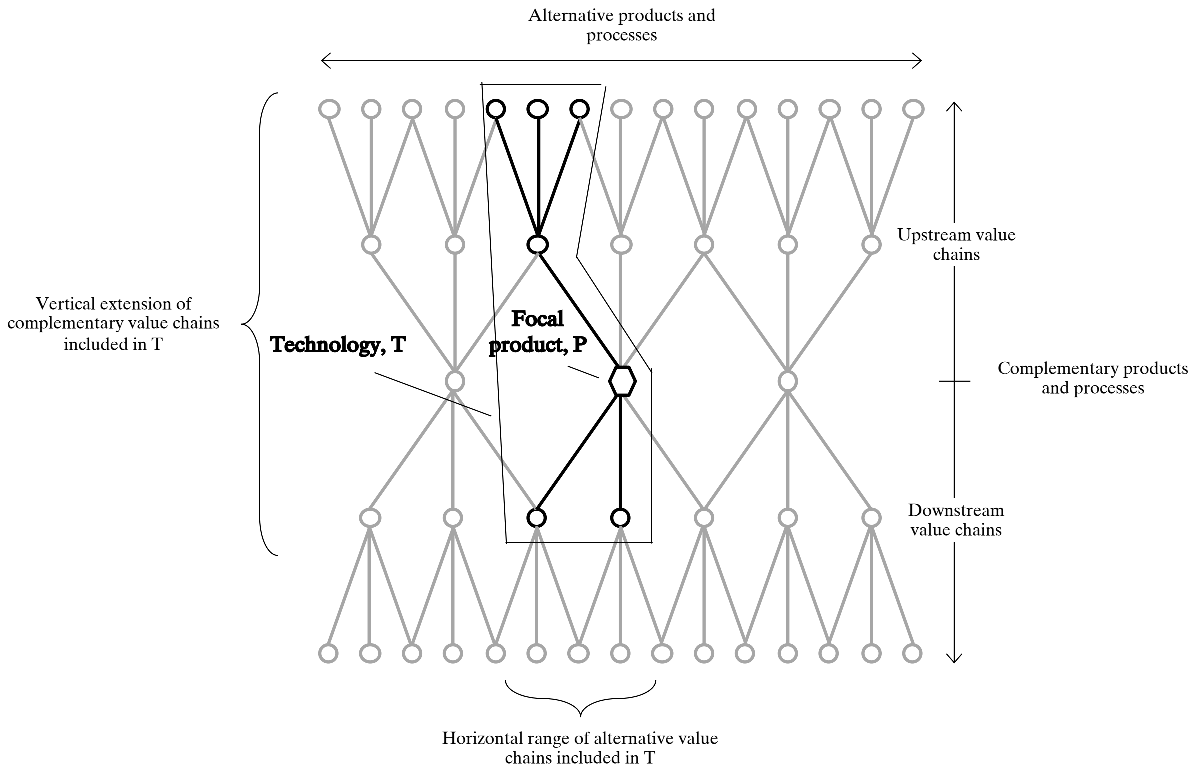

Figure 8.4. A bundle of value chains that define a technology, T, represented in a two-dimensional model.

Finally, two important points deserve to be highlighted. First, the notion of value chains is here employed as an abstract way to organize reality based on how processes and states relate to various purposes. This is different from how the concept of value chains, and related ones such as supply and product chains, are sometimes used in the literature on management and industrial economics. In my understanding, a value chain process involves a wide range of sociotechnical structures, and not just goods, services, firms and individuals. Also, a value chain may not align with concrete flows in the economy; in fact, it may be purely imaginary. Second, conceptualizing technology in terms of a bundle of value chains implies that I adopt a perspective that foregrounds technology as a set of transformation processes rather than a set of structures. While transformation and structure are intertwined and perhaps impossible to distinguish ontologically, as discussed in Section 2.3, I do believe that they represent two different, and inescapable, perspectives of observation and description. And when it comes to technology, it is not only useful, but also necessary to foreground its manifestation as a set of transformation processes rather than a set of structures. After all, a windmill is not a technology because of what it is, but because of what it does.

8.2 (Re)introducing and developing the concept of technological systems

To incorporate a sociotechnical focus and technology-oriented perspective, this thesis proposes *technological systems* as an appropriate construct when specifying the object of study in sustainability transitions research on technological innovation. This means that I reintroduce a notion that was central in the early development of the TIS framework (Carlsson and Stankiewicz, 1991), albeit with a meaning that, as we will see, is more in line with how it is used in the literature on large technological systems (Hughes, 1987) and in some later strands of the TIS literature (Hillman and Sandén, 2008; Sandén and Hillman, 2011).

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, 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 multiple technologies employed by an industry or in an 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 sociotechnical structures, which implies the exclusion of the ecological part of reality, is an analytical choice, rather than a fundamental part of the conceptual reasoning. This also paves the way for an extension of the technological systems construct towards including ecological structures as well. The potential for such advancement will be brought up in the discussion.

In the following, I will elaborate on the key characteristics of the technological systems construct.

8.2.1 Definition and purpose

For the purposes of the framework presented in this thesis, a technological system is defined as follows:

A technological system is as a set of social and technical structures, that both influence and are influenced by the function of a specific technology, and that exist in a given spatial region and time period.

While this definition captures the essence of technological systems, their purpose deserves some elaboration already at the outset. To begin with, it should be stated clearly that the purpose of a technological system is to perform a technological function. As discussed in the Section 8.1.3, this function can be described and demarcated by specifying a bundle of value chains that describe complementary and alternative ways to create and use a specific product.

Furthermore, my understanding of the purpose of technological systems has two elements. On the one hand, it includes performing production-consumption activities in different parts of the bundle of value chains that defines the technology in focus. This implies that system structures include technology-specific parts of what we commonly think of industrial and consumer sectors in the economy. On the other hand, the purpose includes innovation activities that develop and support the performance of production-consumption activities. This autopoietic element implies that system structures also include technology-specific parts of other sectors such as research, education and policy. In fact, this highlights a link to how we tend to perceive organisms. Take a tree as an example – as a system, this organism includes not only cells that directly perform photosynthesis, but also cells that support and develop its ability to perform this process in the future.

When relating back to the discussion about different ways to delineate systems, presented in Section 3.4, it is also clear that technological systems are in fact a combination of a System A and B. As illustrated in Figure 8.5, the construct captures technology-specific structures that influence and are influenced by the technology in focus, while non-specific structures that only influence, or that are passively influenced, are excluded. This highlights an important aspect of technological systems, namely that they link the determinants and outcomes of the innovation process. As I will return to in Section 9.5.4, this makes the construct an appropriate starting-point for efforts to construct formal models of sociotechnical change.

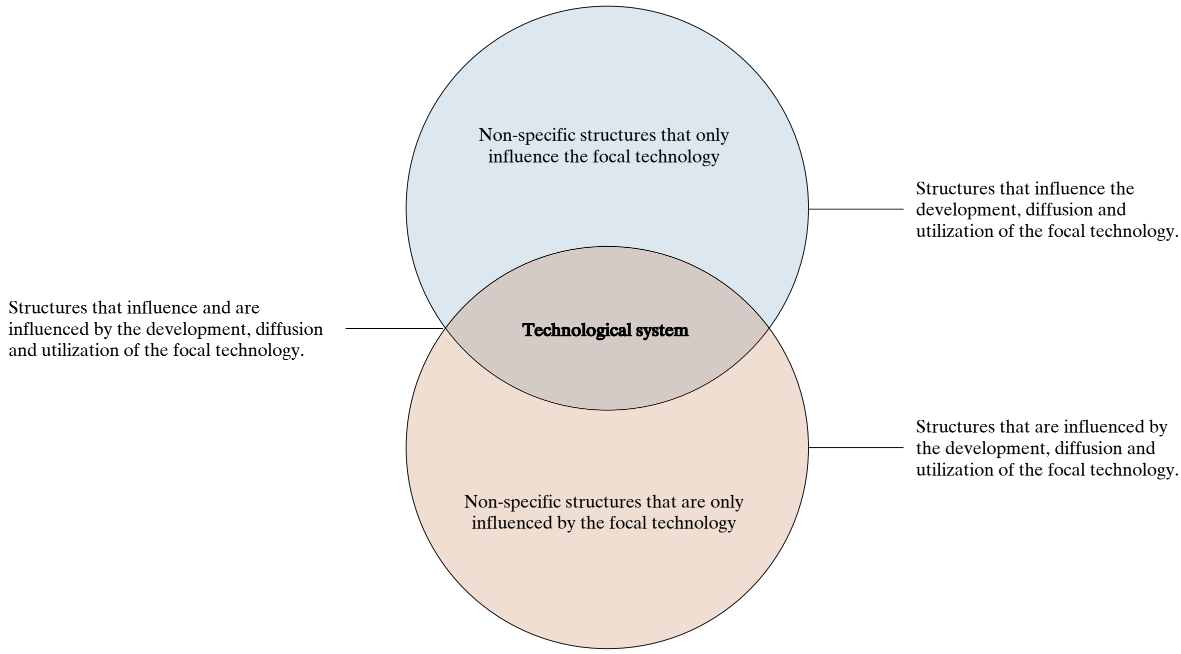

Figure 8.5. Technological systems as constructs that capture structures that both influence and are influenced by a focal technology.

It should be emphasized, however, that the fact that technological systems have a purpose does neither mean that agents 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 function. Nevertheless, what makes the structures in a technological system form a unified whole is that they both influence and are influenced by the function of a technology. In fact, they would not exist, or at least be very different, without it.

Finally, it is worth adding that even though the purpose of a technological system is to perform a technological function, this does 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 technological system should accordingly be understood conceptually; it is used to analytically demarcate a particular slice of reality, not to describe the real characteristics of structural interaction.

8.2.2 Dimensions

The definition of technological systems proposed in the previous section implies that they span technological, structural, spatial and temporal dimensions. These can be seen as distinct perspectives that respectively reveal what system structures do, what they are, where they are and when they are. While the temporal dimension is a fundamental feature of reality, the technological, structural and spatial dimensions are constructs in the sense that they can be further decomposed into sub-dimensions. Within the technological dimension, it is possible to distinguish between the vertical and horizontal expanse of value chains, as discussed in Section 8.1.3. Similarly, following the reasoning in Section 8.1.2, the structural dimension can be decomposed into artifacts, actors and agreeings, or their constituent components. In addition, the spatial dimension is constituted by the three fundamental physical directions of space.

The dimensions of technological systems constitute the key domains for setting system boundaries, observing system configurations and discussing system dynamics. They will therefore reappear in most of the remaining parts of this chapter. To help the reader distinguish the different dimensions, Figure 8.6 summarizes their meaning, essence and possible sub-dimensions.

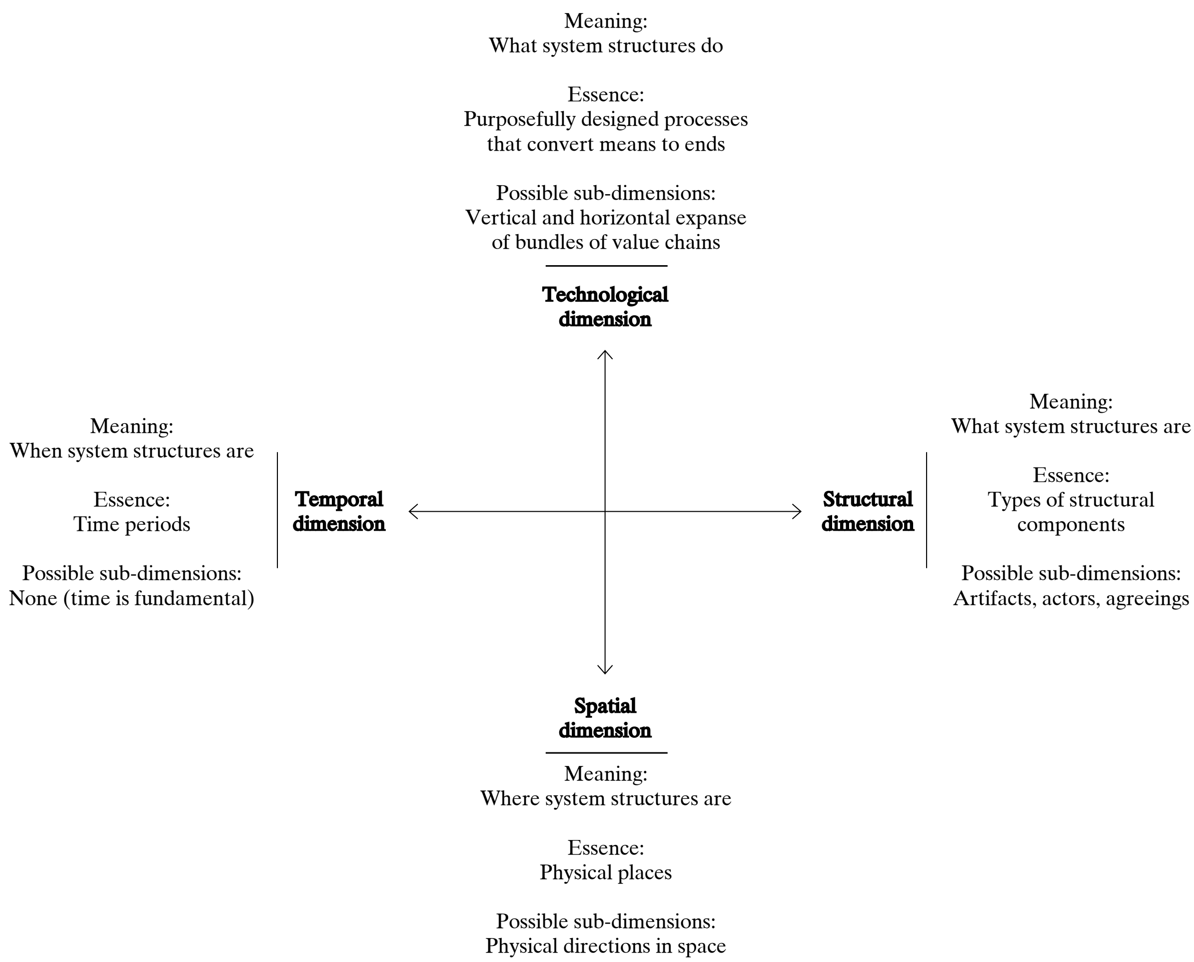

Figure 8.6. The four dimensions of technological systems.

Finally, it should be noted that I here use the notion of a technological dimension, rather than a functional dimension which would have been more in line with the discussion on functional boundary-setting presented in Section 3.4. This is to highlight that the purpose of technological systems is to perform the function of a technology.

8.2.3 Analytical boundaries

So far, technological systems have been defined and discussed in general terms. But to specify a technological system for the purposes of an investigation, there is a need to set analytical boundaries in technological, structural, spatial and temporal dimensions.

First, a technological boundary specifies the technology in focus, and accordingly corresponds to the functional boundary discussed in Section 3.4. As discussed in Section 8.1.3, and illustrated in Figure 8.4, this is done by delineating a bundle of value chains, which involves specifying a focal product as well as a set of complementary and alternative processes that describe its creation and use. 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 windmills. In turn, a technological system focused on the production of renewable electricity using windmills may be limited to highly specific complementary 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. It should be emphasized again, however, that the vertical extension of complementary value chains does not necessarily have to be based on their specificity with respect to the focal product, even though this is common and often appropriate. Instead, the choice to include or exclude a particular process from the definition of the focal technology can be derived from a pure analytical preference.

The technological boundary also specifies criteria for the inclusion of structural components based on the characteristics of their involvement in the included value chain processes. Although the definition of technological systems implies their structures both influence and are influenced by the focal technology, the interconnected nature of reality implies that nothing is neither entirely specific nor completely unrelated. Consequently, the criteria for determining which structures that are sufficiently specific to warrant inclusion have to specified by the analyst on a case by case basis.

In addition, there is an inner technological boundary that specifies the granularity of the bundle of value chains, in other words, how many sub-processes that are observed. For example, distinguishing between alternative downstream value chains that describe how solar modules can be used in centralized, distributed and off-grid applications, implies a narrower inner boundary than merely looking at the use of solar modules as a homogenous phenomenon.

Second, a structural boundary is in fact embedded in the definition of technological systems, which explicitly confines the system to social and technical structures, and thus excludes the ecological parts of reality. This boundary refers to types of structural components, rather than their relation to the technology in focus, as discussed in Section 3.4. Actually, the discussion about whether sustainability transitions research on emerging technologies should have a social or sociotechnical focus, elaborated in Section 8.1.1, thus refers to where this fundamental boundary should be drawn. In the remaining parts of this chapter, I will take the restriction to sociotechnical structures as given. This will, however, be questioned in the discussion, as I point to the possibility of including ecological structures as well.

In addition, an inner structural boundary specifies the resolution at which structural components are observed. The basic distinction between artifacts, actors and agreeings, made in Section 8.1.2, thus corresponds to a wide inner boundary, while sub-categories and sub-sub-categories of structural components are examples of more narrow delineations.

Third, a spatial boundary restricts the system to structures in a 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. In addition, there is an inner spatial boundary that specifies the resolution at which different regions are observed within the system.

Fourth, and lastly, a temporal boundary restricts the system to structures that exist in 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, a topic that I will return to in Section 8.5. 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. In addition, an inner temporal boundary specifies the resolution at which the timing of events is observed within the system.

While a technological system is specified by both outer and inner boundaries, as discussed above, it should be noted that the former tend to be more visible and perhaps relevant for practical purposes. In contrast, inner boundaries often appear implicitly in the choice of analytical detail and manifest as the resolution at which the system is observed. Nevertheless, properly specifying the meaning of inner boundaries is important to strengthen conceptual rigor and may also enable analysts to sharpen their system specifications in a way that facilitates cumulative knowledge development about empirical phenomena.

It is also worth emphasizing that what makes the boundaries discussed in this section analytical is that they are not necessarily aligned with the expanse and characteristics of real system structures, a topic I will return to in Section 8.2.5. 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. 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.

8.2.4 Hierarchies and sub-systems

Just like technology, technological systems are inherently hierarchical in the sense that they can be decomposed into sub-systems defined at a lower level of abstraction. This also means that any technological system can be seen as a sub-system in a higher level system. On the one hand, decomposing technological systems into 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 narrower phenomenon, since these may maintain a wide system specification but focus on a particular sub-system. On the other hand, delineating sub-systems allows an analyst to distinguish different parts of a technological system, which may support comparative analyses.

Specifying sub-systems corresponds to setting multiple analytical boundaries. In the technological dimension, sub-systems can be defined to cover any part of the included bundle of value chains. This part may range from the quite general, such as all upstream value chains or a broad alternative value chain, all the way down to an individual process. Depending on how sub-systems are delineated, they can be distinct or overlapping, and more or less exhaustive. In the structural dimension, sub-systems could be constructed to capture different types of structures, for example by distinguishing between artifacts, actors and agreeings. But since one of the basic ideas of sustainability transitions research on technological innovation is to analyze the systemic interaction of different structures, this kind of distinction seems to lack practical applications. Nevertheless, it remains a conceptual possibility that may be useful for some analytical purposes. In the spatial dimension, sub-systems can be defined to cover any region included by the spatial boundary. This region may be large or small, ranging from a municipality or even neighborhood, to an entire continent. Here as well, sub-systems can be distinct or overlapping, and more or less exhaustive. In the temporal dimension, lastly, sub-systems distinguish between different time periods. But while this is common practice when analyzing technological innovation, it is rarely described in terms of sub-systems.

Although sub-systems require boundaries in all four dimensions of technological systems, it can be useful to foreground some of these domains. For example, sub-systems that have different boundaries in technological and spatial dimension distinguish important system properties (i.e. what system structures do and where they are), which can be highlighted by backgrounding structural and temporal aspects. Figure 8.7 illustrates a stylized technological system that is decomposed into five non-overlapping and exhaustive sub-systems (1-5) in technological and spatial dimensions. It should be noted that from a technological perspective, sub-system 2 and 3 are alternative, while sub-system 2 and 5 are complementary. And if sub-system 2 and 5 were merged, the resulting sub-system would be both complementary and alternative to sub-system 3.

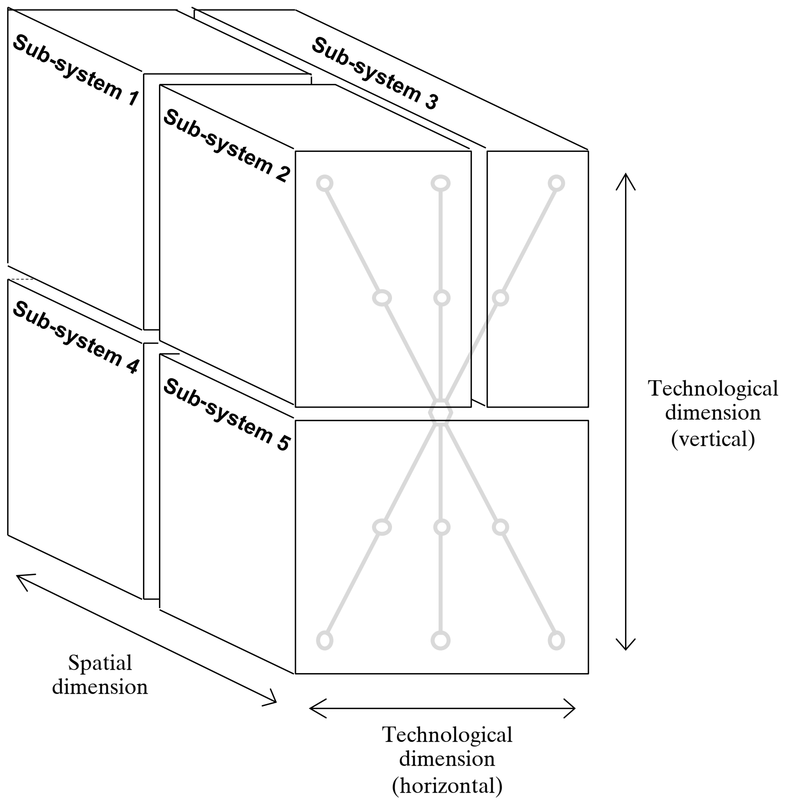

Figure 8.7. Illustration of five non-overlapping and exhaustive sub-systems with different boundaries in technological and spatial dimensions.

8.2.5 Expanse and performance

In the two previous sections, I discussed how a technological system is specified by analytical boundaries in technological, structural, spatial and temporal dimensions, and also commented on how it can be decomposed into sub-systems by employing multiple such boundaries. However, these analytical specifications say little about real system characteristics. In this section, I will shift the focus to the latter and elaborate on system expanse and performance.

To begin with, it is worth repeating that while the analytical specification of a technological system can be more or less based on empirical observations, it does not describe the expanse and characteristics of real system structures. Technological, structural, spatial and temporal boundaries rather define a multidimensional space in which structures may expand and contract. In principle, the analytical domain can in fact be empty, in the sense that the system is devoid of structure. Conversely, it may also be fully saturated, in the sense that the system structure performs all activities, covers all types of structural components, and exists in all spatial regions and time periods included by its analytical specification.

Furthermore, structures in a technological system can have different expanse in technological, structural, spatial and temporal dimensions. In the former, structures may cover a large or small part of many processes within the technological boundary, or be limited to a part of the bundle of value chains. Similarly, structures may in the spatial dimension cover all included regions or be limited to few. Although more difficult to grasp, the same reasoning can be applied to the temporal and structural dimensions. If a technological system covers a time period in the past, structural expanse in the temporal dimension corresponds to the time period during which structures met the analytical requirements, or in other words, the time from when they first appeared to when they potentially disappeared. However, if a technological system covers a time period which includes the future, empirically observable structural expanse is naturally limited to the time up until the present. After all, the future does not yet exist, at least not in my conception of reality. That said, it is certainly possible to discuss expected or desirable structural expanse, a topic which I will return to in Section 8.5. In the structural dimension, structural expanse corresponds to whether a technological system covers all types of structures or whether it is limited to a few. For an immature technology, there may, for instance, not yet be any laws and regulations that sufficiently specific to be influenced by its related processes, which means that the system structure has not yet expanded to cover this type of structural component.

Notably, the fact that the structure in a technological system may not necessarily cover the whole domain specified by its analytical boundaries, implies that there is an additional set of boundaries that are not analytical, but "real" or empirically discovered. These specify system expanse in technological, spatial, temporal and structural dimensions. I will, however, refrain from referring to real boundaries and rather use the notion of expanse, in order to avoid any confusion regarding analytical versus real perspectives on technological systems.

Finally, it is worth highlighting that there is an important link between structural expanse and system performance. As mentioned, when introducing the concept of technological systems above, system performance describes the extent to which it fulfills its purpose, or in other words, performs its function. In turn, this can be quantified in terms of production (or consumption) levels with respect to the focal product, or in early development stages be understood as the technology-readiness level. This implies that system performance is linked to structural expanse; a system that includes many structures is likely to exhibit a high performance. However, this correlation is not always present. For example, a system can certainly increase its performance with a constant number of actors and even individuals. And there are certainly situations where fewer technology-specific laws and regulations may lead to an increased performance. So, while there is a general link between structural expanse and system performance, they are two different properties of technological systems. What we can say with some certainty, though, is that structural expanse enables system performance, since without artifacts, actors and agreeings that influence and are influenced by the processes associated with a technology, these processes would not be carried-out.

8.2.6 Configurations

As discussed in the previous section, any technological system has a specific expanse within its analytical boundaries, which enables the performance of its function. However, a system can also perform its function in many ways, depending on how its structures are configured within and across technological, structural, spatial and temporal dimensions. In the following I will elaborate at some length on the characteristics of such configurations.

First, *technological configurations* describe what the system does in terms of the level of activity across the bundle of value chains included by the technological boundary. Depending on what is valued by an observer, some technological configurations may be preferred over others. For example, a technological system focused on the creation and use of solar modules can be specified to include alternative value chains that use different materials to produce a reasonably similar product. Some of these alternatives are likely to be more environmentally benign than others, and thus preferred by actors such as policymakers or environmentalists. This preference corresponds to a particular upstream configuration in the technological dimension. Moreover, the same technological system can – at least in cases where it has an analytical boundary in the spatial dimension – be restricted to downstream value chains, while being supplied with the focal product from upstream value chains in other regions. This creates a dependence on foreign actors, which may for certain products, such as medical supplies, be perceived as far from ideal. It is also possible that technological systems in early development stages, where the focus is on research and development rather than the creation and use of the focal product, are limited to certain complementary parts of the bundle of value chain, without covering all vertical processes.

Figure 8.8 shows four stylized technological systems (A-D). They all include a bundle of value chains with three upstream alternatives (U1-U3) and three downstream alternatives (D1-D3), but the technological configuration differs. In System A, the focal product is created in U1 and used in D1. In System B, creation is instead distributed among U2 and U3, and use among D1 and D3. System A and B accordingly exemplify different horizontal configurations with respect to alternative processes in the bundle of value chains. In System C, the focal product is created in U1, but used in value chains outside the spatial system boundary. Conversely, in System D, the focal product is created outside the system, but used in D1 and D3. System C and System D thus exemplify different vertical configurations with respect to complementary processes in the bundle of value chains. Lastly, it should be noted that the examples also demonstrate different structural expanse in the technological dimension.

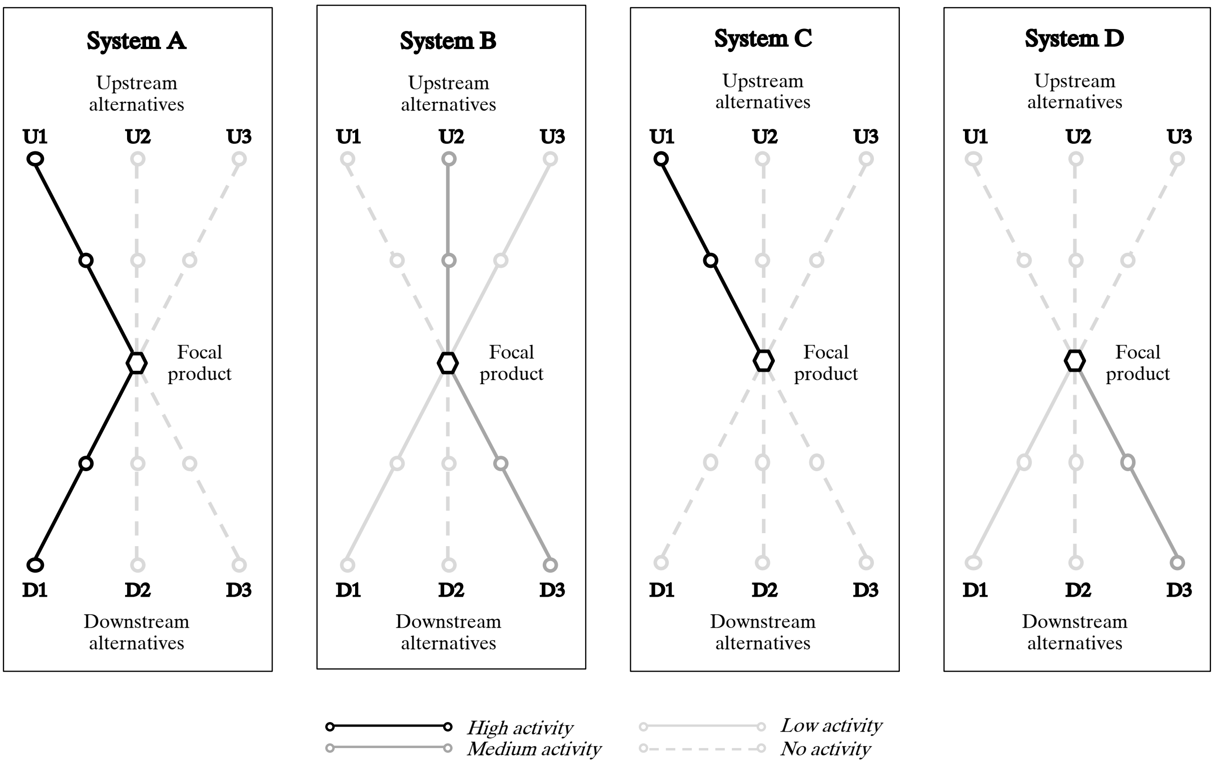

Figure 8.8. Four examples of technological configurations in a stylized technological system.

Furthermore, technological configuration may involve many horizontal alternative processes, or be limited to few (which is in fact illustrated by the difference between System A and B in Figure 8.8). I will refer to this configurational property as the *level of technological standardization* (or conversely the *level of technological diversity*), while noting that some such levels may be more desirable than others. For example, diverse systems may be preferable in early development stages where there is a need to experiment with different solutions, while more standardization is called for in later development phases since it tends to bring lower costs through economies of scale. In fact, increasing standardization is a defining feature of technology lifecycles (Abernathy and Utterback, 1978).

Similarly, a technological configuration may cover many or few vertical complementary processes (which is in fact illustrated by the difference between System C and D in Figure 8.8). I will refer to this configurational property as the *level of technological specialization* (or conversely the *level of technological completion*). It should be noted that specialized systems are complemented by activities in the system context to perform their function. For example, systems focused on upstream value chains, such as System C in Figure 8.8, are commonly complemented by contextual systems in which the focal product is used in downstream value chains.

Technological standardization/diversity and specialization/completion are accordingly configurational properties that together describe system expanse across the included bundle of value chains. This is illustrated in Figure 8.9, which shows nine stylized examples of technological systems. They are based on the same bundle of value chains as in Figure 8.8, and thus include three upstream and downstream alternatives as well as two upstream and downstream complementary processes, but their level of activity differs with respect to alternative and complementary parts of the bundle of value chains. To begin with, the bottom-left corner shows a system that only has activity in a single alternative value chain and complementary process, which implies a high level of standardization and specialization. Along the horizontal and vertical axis, increasingly diverse and complete systems are then found.

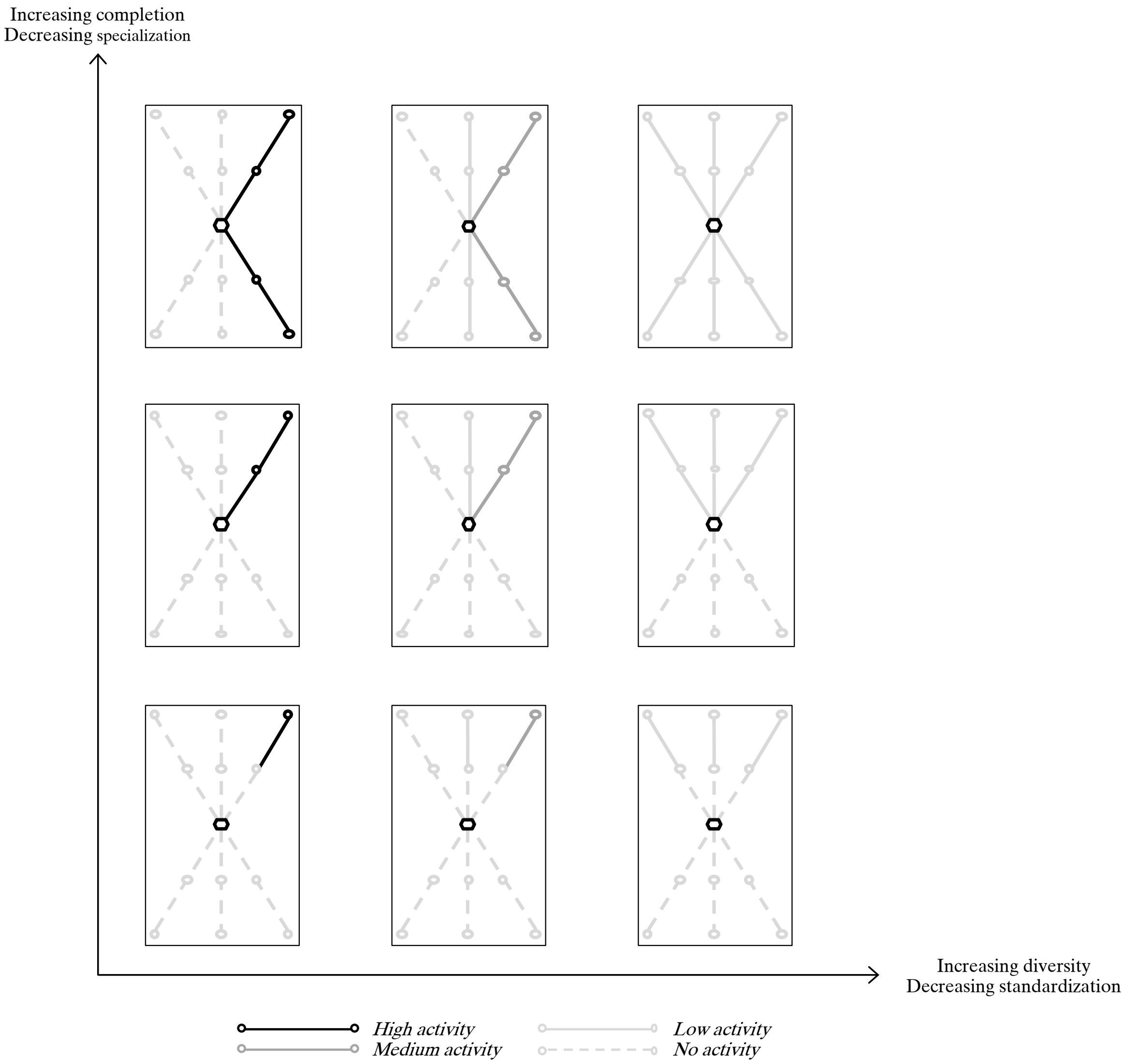

Figure 8.9. Illustration of standardization/diversity and specialization/completion as configurational properties in the technological dimension.

In addition, technological configurations, at least ones that are not fully specialized or standardized, may involve activities that are more or less interlinked, even though they are a part of the same bundle of value chains. For example, a system can have substantial upstream and downstream activities that are disconnected from each other and instead linked to regions outside the spatial system boundary. I will refer to this configurational property as the *level of technological fragmentation* (or conversely the *level of technological cohesion).*

Second, *structural configurations* describe what type of structural components the system consists of. They accordingly capture the different ways in which artifacts, actors and agreeings can be combined and structured to yield a certain system performance. This means a number of important system properties can be derived from the characteristics of its structural configuration. At this point, I will refrain from discussing structural configurations with respect to artifacts and agreeings, and instead focus configurations with respect to actors. This is partly to reduce complexity, but also since actor configurations are key for the realization of many transitions-oriented policy objectives.

Actor configurations describe who is involved in the technological system, or in other words, how human agents are coordinated through different forms of organization. While these are often associated with consumers, firms, universities, government agencies and civil society organizations, they in principle also include networks and markets (Powell, 1990). A given actor configuration can include many or few actors of different kinds. These actors may also have a wide range of more specific characteristics and also adopt different roles in the system. This means that a multitude of different properties can be derived from actor configurations, depending on the perspective from which they are observed. Here, I will highlight three such properties.

To begin with, there is an important difference between a system that is dominated by a few large firms that create and use the focal product, and a system in which many smaller firms collaborate and compete in networks and markets, since this has implications for economies of scale, resilience and competition. I will refer to this configurational property as the *level of operational concentration* (or conversely the *level of operational distribution*).

The second property relates to how firms are owned, which is important since it largely determines their strategic orientation and the distribution of profits (and losses) from various activities. One may distinguish different kinds of ownership, such as public and private or non-profit and for-profit, but also focus on whether there are many or few owners. I will refer to the latter configurational property as the *level of ownership concentration* (or conversely the *level of ownership distribution*). It is also illustrated together with the level of operational concentration/distribution in Figure 8.10.

It should also be noted that operational and ownership concentration/distribution can be further decomposed by relating them to the vertical and horizontal dimensions of the bundle of value chains that defines the focal technology. High vertical operational concentration, for example, corresponds to the vertically integrated firm that has internalized many value chain processes, while high horizontal ownership concentration corresponds systems characterized by monopolistic or monopsonist markets.

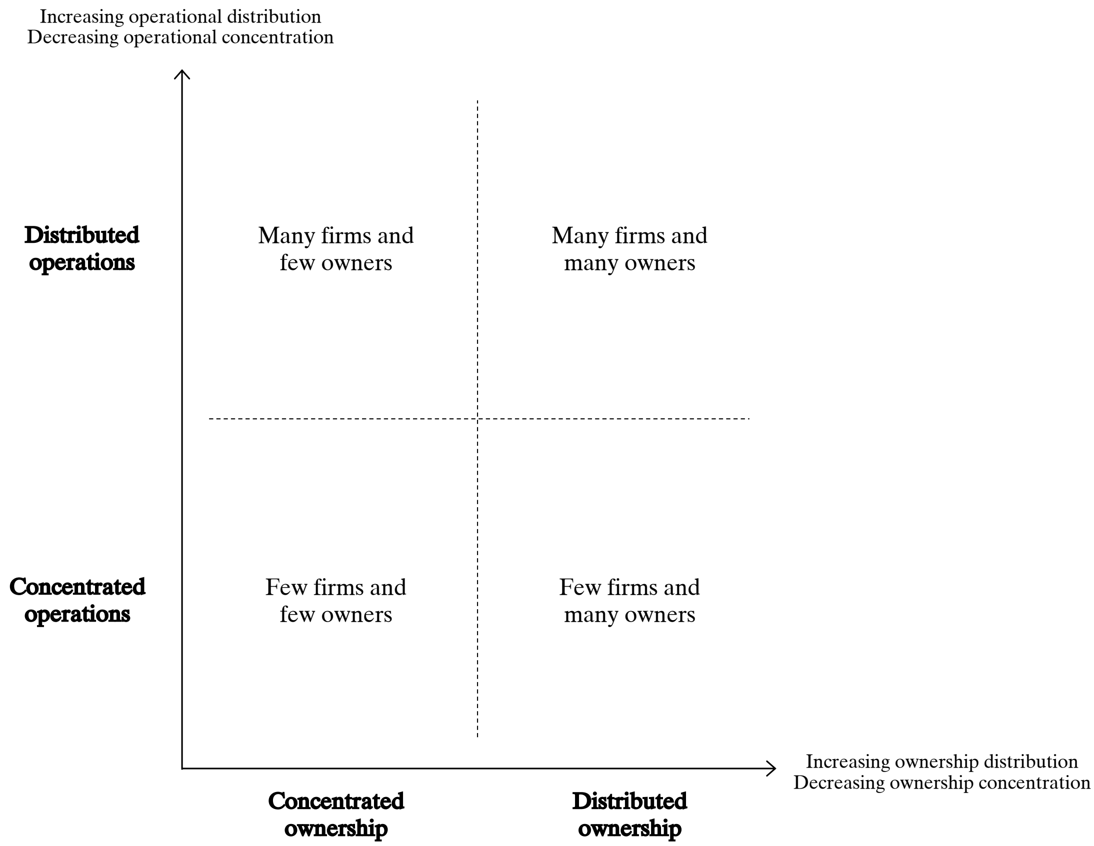

Figure 8.10. Illustration of operational concentration/distribution and owners concentration/distribution as configurational properties with respect to actors in the structural dimension.

In addition, actors may be more or less interlinked, which I will refer to as the *level of actor fragmentation* (or conversely the *level of actor cohesion).* This property is certainly correlated with technological fragmentation/cohesion, since disconnected value chain processes are likely to involve actors that are weakly linked to each other, at least in terms of product flows. Nevertheless, it is possible to imagine a system that has a high level of technological cohesion, but where actors are fragmented in different ways.

It should be added, lastly, that many configurational properties in the structural dimension, both with respect to actors and other structural components, can also be described in terms of alternative value chains. For example, concentrated and distributed ownership of solar modules in some given application can be seen as two different alternative downstream value chains for this product. Whether to capture a given property as a technological or structural configuration is accordingly often an analytical choice.

Third, *spatial configurations* describe where structures in a technological system exist. For example, a global technological system may have a different level of activity in different countries. Depending on the perspective of the observer, some spatial configurations are often more desirable than others. For example, a policymaker that represents a particular country, or the director of a trade union, is likely to prefer that a (desirable) technological system is located domestically, rather than abroad.

A spatial configuration may involve many or few regions, which is a property I will refer to as the *level of spatial concentration* (or conversely the *level of spatial distribution*). While concentration may bring economies of scale or intensified learning through network effects in regional clusters (Marshall, 1890; Porter, 1990; Saxenian, 1996), it can also be argued that distributed systems are more resilient. Notably, this corresponds to system expanse in the spatial dimension.

Figure 8.11 specifically illustrates concentration as a property of spatial configurations. It shows three technological systems (A-C) that each include structures in three different regions (1-3). System A is distributed and has an equal level of activity across the different regions, while System B and C are increasingly concentrated from left to right.

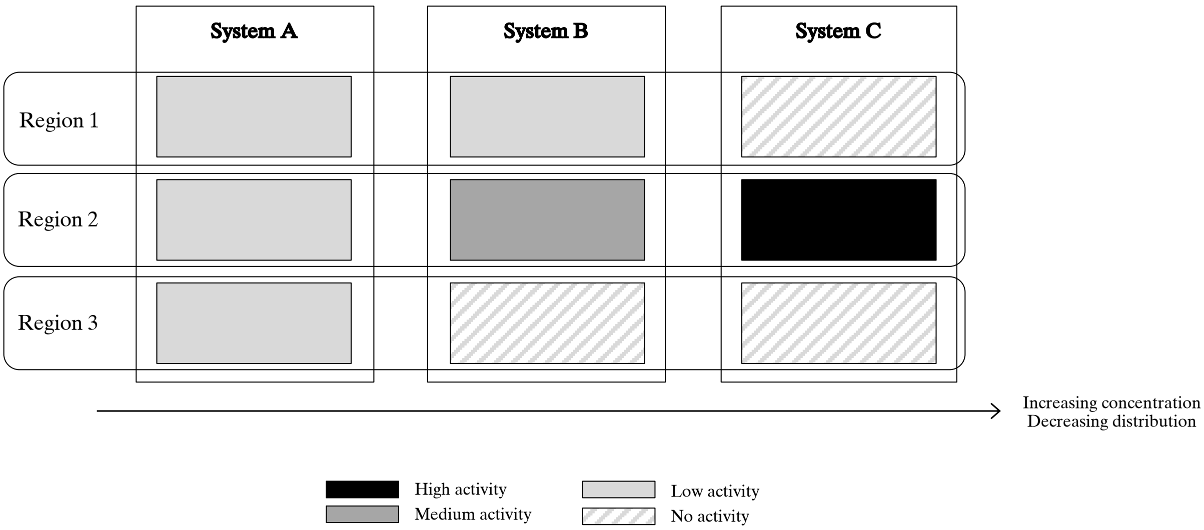

Figure 8.11. Illustration of concentration as a configurational property in the spatial dimension.

In addition, spatial configurations that have some degree of distribution can either refer to a system that exists in many small regions or one that is spread out over a larger region. As in previous sections, I will refer to this configurational property as the *level of spatial fragmentation* (or conversely as the *level of spatial cohesion*).

It should be added, lastly, that the complexity outlined above implies that the same situation can be described as a spatial or a technological configuration, depending how the analytical spatial boundary is drawn. To illustrate this, imagine that there are two regions, I and II, and a single alternative value chain. Upstream industries are located in region I, while downstream industries are located in both region I and II. If the technological system is specified to cover both regions, the lack of upstream industries in region II would be described as a spatial configuration. But if the system only covers region II, it would rather be described as a technological configuration. This highlights the importance of keeping analytical system boundaries in mind when discussing and comparing system configuration.

Fourth, and lastly, *temporal configurations* describe when structures in a technological system exist. This can be understood in terms of how production-consumption activities are allocated within the time period captured by the temporal system boundary. This is clearly crucial, but perhaps easier to discuss in terms of how the system changes dynamically (i.e. over time), rather than as a distribution in the temporal dimension. I will return to this when discussing change in Section 8.3.

Finally, it is worth highlighting that technological systems can have different configurations not only within, but also across technological, structural, spatial and temporal dimensions. This is illustrated in Figure 8.12, which shows two technological systems (A and B) with different expanse of system structures in these dimensions. Here, the temporal dimension is accordingly left out. System A has structures that cover many value chain processes (i.e. has a high level of technological standardization and/or specialization), many types of structural components (e.g. through a high level of operational and/or ownership distribution) and a small region (i.e. has a high level of spatial concentration). In contrast, System B has structures that cover few value chain processes, few types of structural components and a large region.

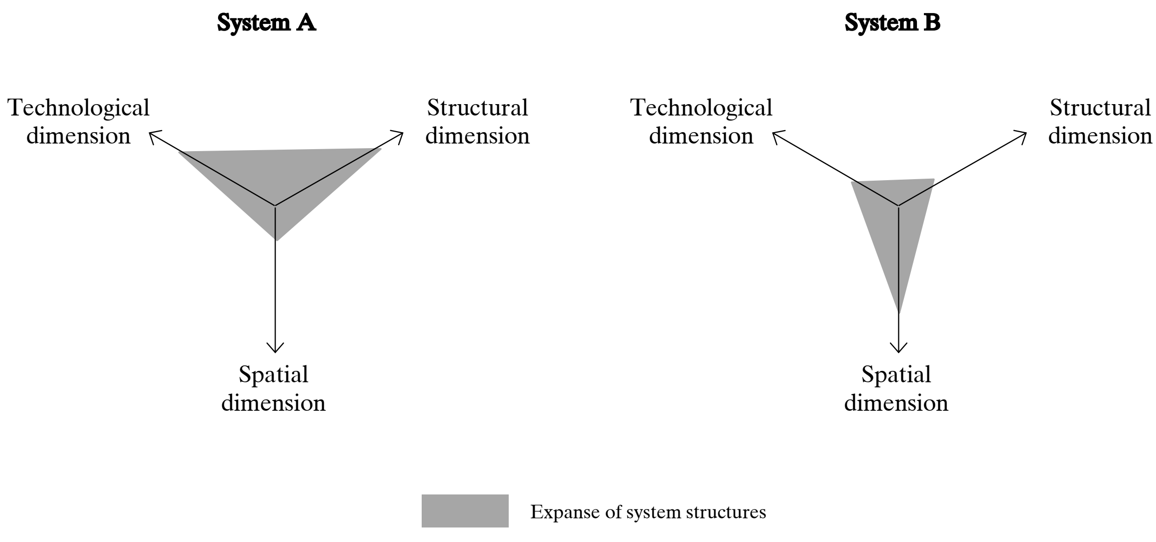

Figure 8.12. Two technological systems with different expanse of system structures in technological, structural and spatial dimensions.

8.2.7 Context

While the previous sections have elaborated on the characteristics of the technological systems construct as such, not much has been said about their context. This is a domain that essentially consists of everything that is not included in their specification. In the technological dimension, there is a plethora of contextual structures that are involved in transformation processes that lie beyond the included bundle of value chains. These may create products that are used by the system in focus, use products that it creates, or lack a sufficiently meaningful link to its function. In the structural dimension, there are contextual structures that are excluded from the system since they are ecological rather than sociotechnical. Ecological contextual structures consist of non-human life forms, such as animals and plants, and various geological entities like rock, soil and water.[52] But although these are not included in technological systems, they are certainly important. In fact, many, if not most, technological processes both depend upon and influence ecological structures, to the extent that one may question this part of structural boundary. As mentioned, I will return to this topic in the discussion. In addition, in the spatial and temporal dimensions, there are contextual structures that are excluded because they are located in spatial regions and time periods that lie outside the system boundaries.

To make the context of technological systems more tangible, a first step is to acknowledge that contextual structures in the technological, spatial and temporal dimensions may be described as a collection of interrelated and overlapping technological systems. In fact, this was suggested in Section 8.2.4, as I highlighted the nested characteristics of technological systems; any technological system can both be decomposed into sub-systems and seen as a sub-system in a higher level system. However, this raises the question of what, if anything, that lies beyond technological systems. Given that technology is here understood as a means to fulfil an end, as perceived by some agent, I would argue that what lies beyond technological systems is ultimately natural phenomena that are purely disconnected from human purposes.

On a high level of abstraction, it is also possible to define contextual systems that describe the overarching sectors which are often discussed in popular language (see Hojcková et al. (2020) for a similar exposition). 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. And 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

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[52] One may add that the natural environment on planet Earth is embedded in a cosmological context.

policy, research, education, finance and media. In addition, we may add an ecological context that captures natural phenomena.[53]

Importantly, technological systems overlap the industrial, consumer and support sectors that exist in their context, since they include technology-specific structures in all these domains (depending on the vertical extension of complementary value chains, 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 in fact restructure large parts of society. However, technological systems do not overlap the ecological context, since their definition does not include ecological structures.

Since technological 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 acknowledge as influential (or influenced) and the rest of the world.

Figure 8.13 shows a technological system that overlaps the industrial, consumer and support sectors that exist in its context. It also 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 influence or because they are influenced by the focal technology.

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[53] If the industrial, consumer and support sectors are defined as socio-techno-ecological systems, in the sense that they may include ecological structures as well, the ecological context can be seen as overlapping these domains.

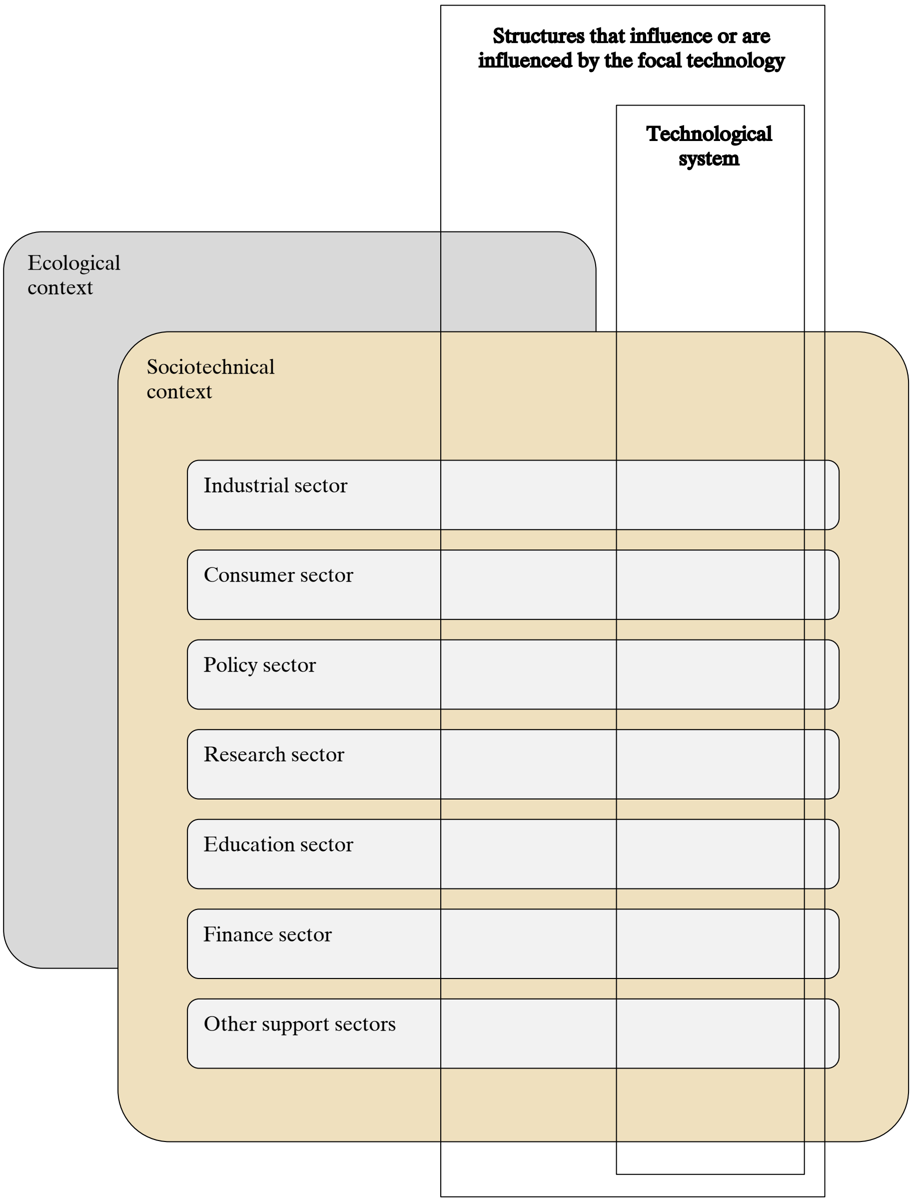

Figure 8.13. A technological system that overlaps industrial, consumer and support sectors in its context, together with a specification of contextual structures that influence or are influenced by the focal technology.

Finally, it should be added that a different type of context exists within the inner system boundaries. This inner context is mainly associated with the structural boundary, which black-boxes the lower-level structures that make-up structural components, such as individual staff in an organization. But as discussed in Section 8.2.3, there are inner contexts associated with technological, spatial and temporal boundaries as well.

8.3 The dynamics of technological systems

Although the concept of technological systems presented in the previous sections is based on the idea of technology as a set of processes involved in the creation and use of a specific product, and in fact developed to support analyses of technological innovation, the discussion has so far painted a quite static picture of system structure. In this section, I will adopt a different perspective and focus on the dynamics of technological systems – that is, on how and why their structures change over time.[54]

To begin with, it is important to distinguish between two types of structural change related to technological systems.[55] The first one is embedded in the system function and may be referred to as its production-consumption dynamics. It describes the structural change that occurs when a technological system performs the technological processes included in its specification. As sub-products are combined to create products and super-products, goods and payments flow through the system while other structures are maintained to continuously support this process. In contrast, the second type of change is related to how the system function changes over time as a technological system increases or decreases its performance, or changes its technological, structural or spatial configuration. Whereas production-consumption dynamics emerge from the utilization of technology, innovation dynamics accordingly correspond to the development and diffusion of technology. In fact, what innovation dynamics essentially describe is a second order change in the characteristics of production-consumption dynamics. This means that a technological system, which exhibits production-consumption dynamics within a given performance and configuration, actually lacks innovation dynamics if its performance and configuration remain unchanged. In addition, it implies that in early development stages, where the focal product is not yet created and used, a technological system may exhibit innovation dynamics but lack production-consumption dynamics.

While production-consumption dynamics are a key feature of technological systems, this thesis mainly engages with innovation dynamics. This is because the latter constitute the process

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[54] 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.

[55] At this point, the reader should be reminded that the conceptual framework adopted and developed in this thesis does not define "structures" as entities that are stable and enduring. The concept is rather used to refer to the constituent components of reality.

through which technological innovation propels sociotechnical change. In the following, I will elaborate on the innovation dynamics of technological systems and sketch the outlines of an approach to analyzing their causes and effects.

8.3.1 *Distinguishing between the pace and directionality of innovation processes*

When conceptually explaining the characteristics of innovation dynamics, an appropriate point of departure is to reiterate that technologies have 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 the entire context in which it was once embedded.[56] This process of technological innovation can be understood in terms of a technological system which creates new structures and gradually mobilizes components that were once a part of its context.[57] In other words, it is analogous to the expansion of structure in a technological system, which in turn largely corresponds to an increased system performance, as discussed in Section 8.2.5. When I henceforth refer to the growth of a technological system, I will take this to mean both structural expansion and increased system performance, even though they are in principle different properties. It should also be noted that structural change related to a particular technology can occur within the boundaries of a technological system, but also stretch beyond the analytical focus these entail. As I will discuss further in Section 8.5, the latter situation may call for a reevaluation of system boundaries.

But as one technology is developed and diffused, others are often abandoned. This is analogous to the contraction of structure in technological systems, which, in line with the reasoning above, largely corresponds to decreased system performance. Here as well, I will take it to mean both structural contraction and decreased system performance, when I refer to the decline of a technological system. However, to simplify the exposition, I will most often use the notion of growth to include potential decline (i.e. negative growth) as well.

Importantly, the growth of technological systems is not a one-dimensional phenomenon, even though conventional s-curves used to illustrate technology lifecycles may suggest so. On the contrary, innovation dynamics can propel technological systems along different trajectories. These not only result in different levels of system performance over time (that is, variation across the temporal dimension), but also give rise to different configurations in technological, structural and spatial dimensions.

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[56] An obvious but useful analogy is the growth of a plant.

[57] It should be noted that creation can be interpreted as the mobilization of structures from the real to the actual domain of reality.

Figure 8.14 illustrates this by showing six potential development trajectories for a technological system. Trajectories A, B and C result in a high level of performance, which is achieved through three different configurations. Similarly, trajectories D, E and F result in different configurations, but a lower level of performance. In contrast, trajectories A and D, B and E, and C and F, have respectively resulted in similar configurations, but different levels of performance.

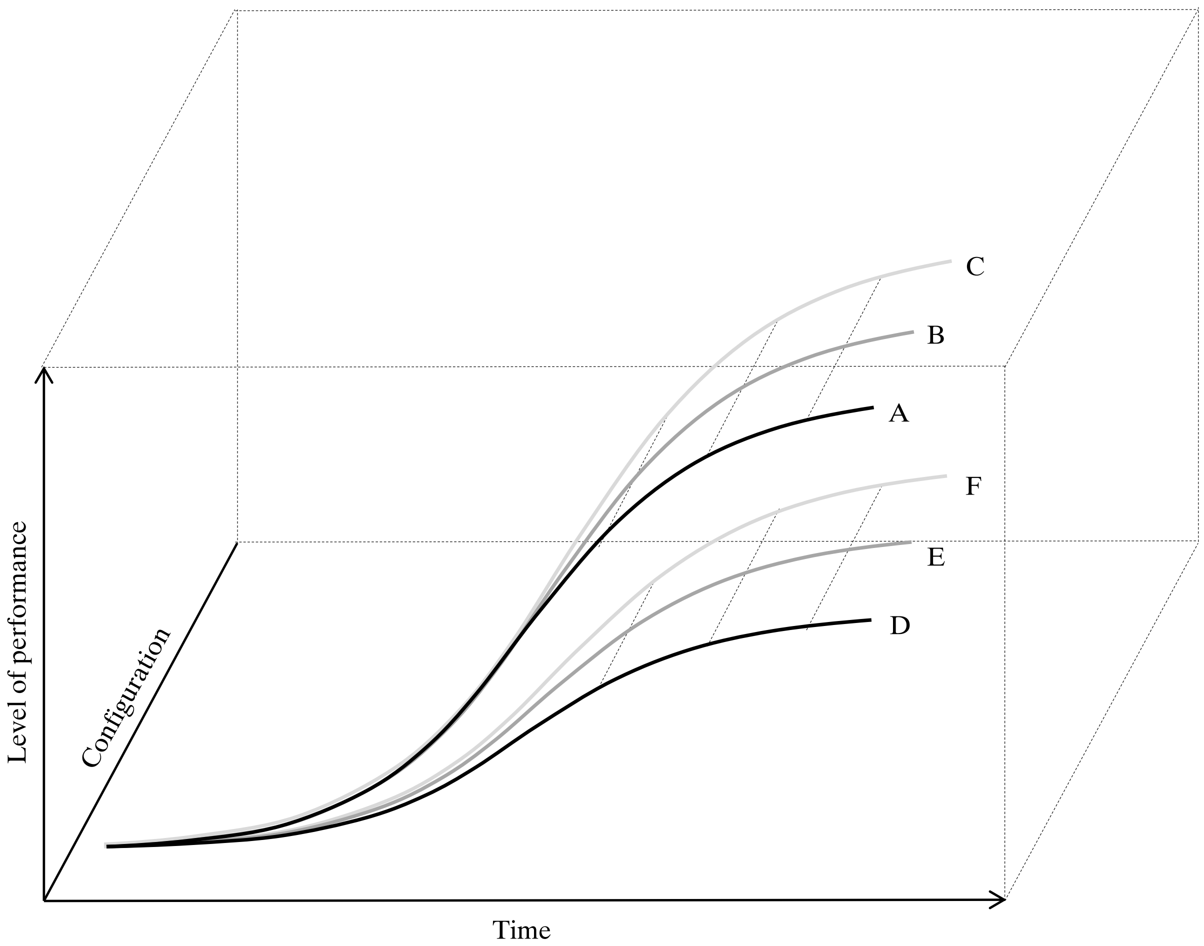

Figure 8.14. Six potential development trajectories (A-F) for a technological system, resulting in different levels of performance and configurations.

Drawing on these ideas, we may now arrive at a key distinction for the purposes of this thesis; the directionality of innovation processes determines the configuration of a technological system, while their pace determines its level of performance. This implies that trajectories A-C, and D-F, in Figure 8.14 are governed by innovation processes that have a similar pace but different directionality. In contrast, trajectories A and D, B and E, and C and F, are governed by innovation processes that have a different pace but similar directionality.

Finally, it should be emphasized that innovation dynamics may in fact not result in growth (or decline), but still lead to changes in technological, structural and spatial configurations. Growth and such reconfiguration are accordingly two distinct, but intertwined aspects of how technological systems develop over time. To capture both, I will use the term transformation.

8.3.2 Analytical perspectives on the transformation of technological systems

A structured approach to analyzing the transformation of technological systems requires an analytical perspective that accounts for both the pace and directionality of innovation processes. In other words, there is a need to differentiate between potential configurations. As suggested by the discussion in Section 8.2.6, such analytical perspectives can focus on different configurational properties within and across technological, structural and spatial dimensions.

Although numerous approaches can be relevant depending on the analytical ambition, a possible starting-point is to foreground technological and spatial configurations. This results in a techno-spatial framework that describes how and where the focal product is created and used, within the technological and spatial boundaries of a given technological system. What makes this perspective particularly relevant in a sustainability transitions context is that it shines light on many important characteristics of benefits that are often sought by policymakers that attempt to shape technological innovation. First, different complementary parts of a bundle of value chains give rise to different benefits. For example, the upstream production of windmills is associated with job creation and potential export revenues, while their downstream use rather has positive effects on the energy system. And depending on where complementary processes occur, localized benefits are distributed in different ways across spatial regions. Similarly, the distribution and scale of negative environmental impact from production and use depends on where different parts of the value chains are localized. Second, some alternative value chains are often more desirable than others. A specific way to produce windmills can, for instance, have a particularly low climate impact. Third, there may be reasons to prefer a specific level of technological standardization and specialization, both generally and in different phases of the technology lifecycle. Fourth, and lastly, some parts of value chains could require a certain level of spatial concentration to enable technological specialization, economies of scale and learning, even though there are certainly arguments in favor of more distributed spatial configurations as well.

While the techno-spatial perspective does not foreground the structural dimension, it still suggests where structural components such as firms and consumers in a technological system are located in space and which value chain processes they are involved in. However, it says little about the more specific configuration of artifacts, actors and agreeings. Since these are clearly important – for example, they determine how localized benefits are distributed among actors within a specific spatial region, and also have consequences for the level of competition and resilience within each value chain process – some studies may choose to integrate the structural dimension more explicitly. This can be done by adopting a techno-structural perspective that downplays spatial configurations, by maintaining a technological-spatial perspective and merely comment on key characteristics of structural configurations, or even by developing a more comprehensive techno-spatio-structural framework.

The analytical perspectives discussed above enables analyzing the transformation of technological systems in different ways. One is to delineate sub-systems along the foregrounded dimensions, as discussed in Section 8.2.4. This allows the directionality of innovation processes to be investigated by comparing their pace within these sub-systems. In a sense, this approach retains a focus on growth, but investigates it at a lower level of abstraction, building on the logic that system transformation is analogous to the combined growth and decline of sub-systems.

However, there are situations where it can be difficult to analyze the transformation of technological systems by delineating formal sub-systems. This could, for example, be the case when technological configurations are highly varied and fluid, which makes it difficult to distinguish between alternative value chains. It may also be challenging if configurations with a high resolution are relevant to explore in multiple dimensions, since this quickly renders a large number of sub-systems. In addition, there are some configurational properties, such as the level of technological and spatial specialization as well as the centralization of ownership in the structural dimension, that are less straight-forward to think about in terms of sub-systems. In these situations, the directionality of innovation processes can be analyzed in a less formal way, by complementing investigations of their general pace with assessments of their more specific technological, structural and spatial characteristics. This also opens up for focusing on configurational properties that are of particular interest. For example, some analyses may focus on directionality with respect to different parts of the bundle of value chains or spatial regions, while others are more interested in whether innovation processes propel increasing or decreasing standardization, completeness and concentration.

8.3.3 Deriving typologies of innovation processes

To describe and analyze the transformation of technological systems, the innovation process must be decomposed into its constituent parts.[58] Preferably, this should be done in a way that

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[58] As highlighted in Chapter 4, 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

results in categories that are non-overlapping (i.e. mutually exclusive), while covering all aspects the innovation process (i.e. collectively exhaustive). One approach to developing such typologies is to identify sub-processes based on their effect on system structure. However, effects on system structure can appear in technological, structural and spatial dimensions, which means ideal typologies are in fact three-dimensional. In the following, I will first elaborate on a typology derived from the structural dimension, before commenting on the potential for deriving similar typologies from the technological and spatial dimensions.

Decomposing innovation processes based on their effect on system structure in the structural dimension is analogous to decomposing structural components into sub-categories, as was done in Section 8.1.2. 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 agreeings, 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 captured by the 'functions' used in the TIS literature. I will return to these similarities in the discussion.

In Table 8.1, I propose a typology of nine innovation processes that describe the transformation of system structure with respect to different types of structural components. It is based on the sub-categories presented in Figure 8.1, except for money which is decomposed into financial capital and payments. The reason is to highlight the difference between money that flows through the system as a part of its production-consumption dynamics, 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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conceptual links to both causes and effects of technological innovation are obscure. The reasoning in this section offers a contrasting and potentially complementary perspective.

Table 8.1. A typology of innovation processes that describe the transformation of system structure with respect to different types of structural components.

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 8.2, I 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. However, to the latter I have to add the financial dimension, which is difficult to associate with a specific category.

Table 8.2. Three ways to categorize the innovation processes described in Table 8.1.

The creation and mobilization of...		
...artifacts • ...goods • ...infrastructure **...actors** • ...organizations • ...networks • ...markets **...agreeings** • ...institutions • ...knowledge • ...financial capital • ...payments	**...actors** • ...organizations • ...networks • ...markets **...resources** • ...goods • ...infrastructure • ...knowledge • ...financial capital • ...payments **...rules** • ...institutions	**...technology** • ...goods • ...infrastructure • ...knowledge **...actors** • ...organizations **...networks** • ...networks • ...markets **...institutions** • ...institutions **(...money)** • ...financial capital • ...payments

Finally, decomposing innovation processes based on their effect on system structure in the technological and spatial dimensions follows a similar procedure. The difference is that the starting-point for categorization is technological processes and spatial regions, rather than different types of structural components. For example, the innovation process could in the technological dimension be decomposed into ‘the transformation of system structures in upstream parts of the value chain’ and ‘the transformation of system structures in downstream parts of the value chain’. Similarly, the innovation process could in the spatial dimension be decomposed into ‘the transformation of system structures in Sweden’ and ‘the transformation of system structures in the rest of the world’.

8.3.4 The causal factors behind innovation processes

While the previous sections have mainly focused on the effects of innovation processes, not much has been said about the factors which determine their pace and directionality. Given the ontological foundation of this thesis, it may already at the outset be established that these factors are found in the causal powers of a wide range of structures. However, since technological innovation is about purposeful design, the agency of actors is particularly important. As often suggested in the literature, actors are the main drivers of change in sociotechnical systems. But it is nevertheless beyond doubt that natural phenomena with no discernible link to agency play important roles as well; for example, innovation in marine energy technology is strongly influenced by the characteristics and distribution of waves, tides and current in the ocean. When discussing from where the factors which explain innovation processes emerge, I will therefore refer to structures, which include actors as a sub-category, rather than to actors alone.

An important initial distinction to make is that the factors which explain innovation processes are either endogenous or exogenous. Endogenous factors not only influence innovation processes but are also influenced by their results. This opens up for self-reinforcing processes of cumulative causation. For example, policy support to research may lead to new knowledge, which leads to cheaper products, which increases the legitimacy of the technology, which leads to even more policy support to research, and so forth. In contrast, exogenous factors influence innovation processes without being influenced by their results. They may initiate processes of cumulative causation but are not a part of their dynamics. For example, increasing global warming may prompt policymakers to support research in new renewable energy technologies, and thus start self-reinforcing developments as described above. But it will (unfortunately) take a long time before these developments influence global warming in return.

This suggests that the distinction between endogenous and exogenous factors in the dynamics of a particular technological system largely coincides with its boundary; endogenous factors emerge from structures within the system while exogenous factors emerge from structures in its context. But although this may often be the case, and even a desirable outcome when setting system boundaries, the link does not hold in general terms. One reason is that technological systems may have analytical boundaries in the spatial dimension. In this case, there may be structures in the system context which both influence and are influenced by the included technological processes. Although these structures are excluded from the system due to their spatial location, they may nevertheless give rise to endogenous factors with respect to its innovation dynamics. Another reason is that there may be ecological structures, which are by definition not included in technological systems, that have similar characteristics.

For analytical efforts that aim to analyze and potentially model innovation dynamics in a way that separates endogenous and exogenous factors by a system boundary, this implies the technological systems construct cannot be used without making modifications. One possible way to adapt the specification and definition of technological systems is to abandon any analytical system delimitation in the spatial dimension as well as the restriction to sociotechnical structures. But while the resulting wider system boundary would separate endogenous and exogenous factors, it may be in conflict with other analytical aims such as limiting the scope of investigation. Another, but related, possible modification is to maintain the original specification and definition of technological systems, but adopt an additional wider system boundary that corresponds to the previously mentioned approach.

In the remaining parts of this chapter, I will stay with the technological systems construct as described in Section 8.2 and thus refrain from making a clear separation of endogenous and exogenous factors in the innovation process. I will, however, return to the possibility of developing a more formal model of the dynamics of technological systems in the discussion.

Besides the distinction between endogenous and exogenous factors, the causal mechanisms that propel innovation process can emerge from structures with different characteristics. And as has been argued throughout this chapter, these characteristics are found in technological, structural and spatial dimensions. This means that the approach to deriving typologies of innovation processes from their effect on system structure, presented in the previous section, can in fact also be used to categorize causal factors. In addition, a distinction can be made between causal factors that emerge from system internal as opposed to contextual structures, which as explained above is related to whether they are endogenous or exogenous.

When analyzing the factors behind innovation processes, it is accordingly possible to distinguish between their technological, structural and spatial characteristics, position them within the system or its context, and identify whether they are endogenous or exogenous. This in turn forms the basis for the construction of analytical perspectives that can be adapted to describing and analyzing the role played by specific actors or the influence of particular phenomena that emerge from other types of structures. A policy-oriented analysis that aims to investigate how a national government has influenced the emergence of a new technology may, for example, choose to highlight this actor as a factor behind innovation processes, and analyze its role in relation to the influence exerted by factors that emerge from other structures.

8.4 The benefits (and costs) created by technological systems

So far, I have presented how technological innovation can be described and analyzed by adopting the technological systems concept. In this section, the focus turns to the reason why technological innovation is relevant, and in fact urgent, to investigate and shape in the first place – namely the benefits and costs it can potentially create for human society and its natural environment.

Already at the outset, it should be emphasized that I do not attempt to contribute to the extensive literature that focuses on the social and environmental consequences of technology. This academic field has for decades developed methodologies that can be used to describe, categorize and analyze both benefits and costs associated with emerging and mature technologies (Van Eijndhoven, 1997). And there are, as a matter of fact, striking parallels between the conceptual ideas presented in this chapter and some assessment-oriented frameworks. In particular, the life-cycle assessment community – which has developed methodologies that can be used to assess social and environmental impacts associated with the life-cycle of functional units (see Finnveden and Moberg (2005), Moni et al. (2020) and Wu et al. (2014) for overviews) – tends to adopt a systems construct that is quite similar to technological systems. I will discuss these similarities further in the discussion.

For the purposes of this section, the ambition is rather to describe an overarching conceptual link between technological systems and their implications for what we consider valuable and desirable. In the following, I will therefore describe the general characteristics of benefits associated with technological systems, propose that benefits can be conceptualized as properties of contextual systems, and elaborate on how technological systems create benefits by influencing these contextual systems. While the focus is on what I refer to as benefits, the reasoning can be applied to costs (i.e. negative benefits) as well.

8.4.1 The general characteristics of benefits related to technological innovation

Before elaborating on the general characteristics of benefits related to technological innovation, it should be acknowledged that this very notion is highly subjective. What is perceived as desirable for one actor may well be undesirable for another. This calls for caution and requires that any discussion on benefits is linked to a clear actor perspective.

Nevertheless, it is evident that the growth of some technological systems may have implications that support various aims which are shared among a larger collective of actors. Consider, for example, a technological system that captures the creation and use of solar modules. As this system grows, from an early development stage where it might be limited to research and development activities, to a mature stage where it involves global industries and markets, it will likely decarbonize the electricity sector and thus contribute to mitigating climate change. In the regions where solar modules are used, the system may reduce local pollution and strengthen energy independence. And as firms and other organization enter the system to support different parts of the bundle of value chains, the regions in which they are active often see new jobs and increased tax revenues.

In other cases, it may be the decline of a technological system that is perceived as desirable. As a matter of fact, the mitigation of climate change and reduction of local pollution in the previous example presumes that the diffusion of solar modules leads to the decline of a technological system for some alternative product with a higher environmental impact.

Importantly, and as pointed out many times throughout this thesis, not only the growth and decline of a technological system, but also changes in its technological, spatial and structural configuration, can be perceived as more or less desirable. This is particularly evident in the spatial dimension, since localization of activities in different parts of the value chain determines the distribution of many benefits. But there are also reasons for actors to prefer certain technological and structural configurations, which may for instance involve more environmentally benign production practices.

The benefits created by technological systems accordingly have characteristics that create a quite significant complexity. To begin with, they can be related to different aims. While a broad distinction can be made between social and environmental benefits, there are many ways to describe and categorize the more specific value they describe within these domains. Second, benefits can be created in and affect different regions. Some benefits, such as mitigation of climate change, are global, in the sense that they are shared widely irrespective of where they are created. Others, such as the creation of new jobs, have a more local character since they are linked to a specific place. Third, benefits can result from activities in different parts of the bundle of value chains captured by a technological system. Fourth, the realization of benefits not only depends on the characteristics of the technological system in focus, but also on changes in other technological systems and contextual sectors. Lastly, benefits can occur immediately or at some point in the future. This latter characteristic is particularly important in contemporary times, since the climate crisis calls for rapid emissions reductions.

8.4.2 Conceptualizing benefits as properties of contextual systems

To create a conceptual link between technological systems and the benefits they create, there is a need to define the two in similar terms. Given that technological systems is a construct based on systems thinking, a first step is to view benefits from this perspective as well. While this can probably be done in various ways, one possibility is to conceptualize benefits as desired properties of systems that describe phenomena in the context of a given technological system. Consequently, the creation of benefits corresponds to transforming contextual systems towards these desired properties. In fact, this is quite intuitive, at least for aims that are commonly associated with technological innovation. For example, mitigating climate change can be defined as a stabilization of the climate system, while the creation of new jobs in a specific country can be seen as a particular transformation of its economic system.

Given this conceptualization of benefits, their characteristics can be described in systems terms. An environmental benefit appears in a contextual system that captures a natural phenomenon of some sort, and that has a structure that consists of ecological components. A social benefit appears in a contextual system that captures a social, or perhaps socioeconomic or sociotechnical, phenomenon, and that consists of social or sociotechnical structures. Benefits with a global reach appear in contextual systems that have global boundaries in the spatial dimension, while local benefits correspond to more narrowly defined such boundaries. And so forth.

We may accordingly distinguish between different benefits based on the characteristics of the contextual systems in which they appear. In particular, it is worthwhile to establish a simple typology that highlights the difference between benefits that have an environmental or societal character, global or local reach, and short- or long-term realization, as illustrated in Figure 8.15. Within these broad domains, particular benefits can then be defined at different levels of detail, in terms of desired properties of specific contextual systems.

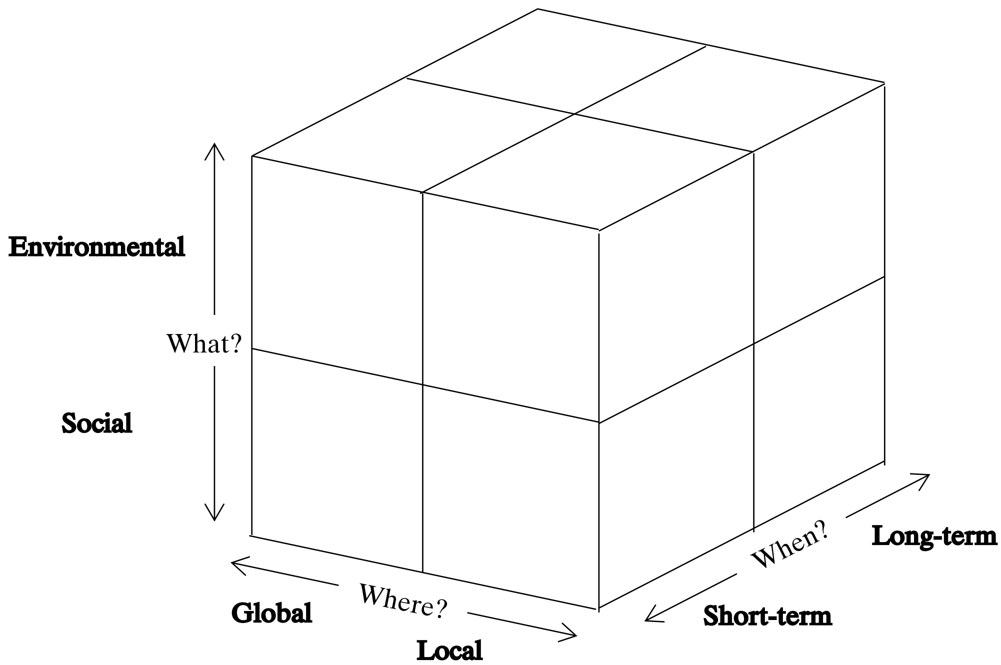

Figure 8.15. A typology of benefits associated with technological innovation.

However, what we tend to think about as benefits from technological innovation are often linked in causal hierarchies. For example, the creation of new jobs is considered to result in increased prosperity, while the decarbonization of the electricity system is thought of as a prerequisite to mitigating climate change. In fact, these chains of causes and effects that link intermediate values extend all the way to the creation of something that is perceived as an ultimate value. Notably, different parts of this hierarchy of values are distinguished by the use of midpoint and endpoint indicators, respectively, in life-cycle assessment methodologies (Bare et al., 2000).

From a systems perspective, the links between different benefits can be conceptualized as structural overlaps and flows between the contextual systems in which they appear. This implies that the transformation of one system (that describes one benefit) may also bring structural change in other systems (that describe other benefits). Coming back to the previous examples, the economic system (in which jobs are created) overlaps a broader social system (that describes prosperity). Similarly, the electricity system (which is decarbonized) influences the climate system (in which change is mitigated) through flows of greenhouse gases.

While it is certainly appropriate, and probably unavoidable, to define and strive for benefits that describe intermediate values, it is important to highlight their links to higher level benefits as far as possible. This is because failing to do so can hide the fact that what is actually desired depends on factors beyond the particular benefit in focus. For example, increased deployment of renewable energy technology has to be coupled with reduced use of fossil alternatives, if the end result is going to be a more stable climate system.

Finally, it should be emphasized that there are certainly more sophisticated approaches to defining and categorizing benefits associated with technological innovation. However, as we will see in the next section, the basic idea of viewing benefits as properties of contextual systems enables the development of conceptual links to technological systems.

8.4.3 The creation of benefits by technological systems

The ideas developed in the previous section implies that technological systems create benefits through their influence on contextual systems.[59] On the one hand, this influence is mediated by structural overlaps. Since technological systems share some of their structure with contextual systems, which is in fact illustrated in Figure 8.5, a transforming technological system will bring structural change in contextual systems as well. Consider, for example, a technological system for solar modules that overlaps a wider electricity system in its context. If the former grows the latter will transform towards exhibiting properties that may be perceived as desirable. On the other hand, the influence is mediated by flows of structures across the system boundary. A technological system for fossil fuels, for example, gives rise to emissions that drive structural change in the climate system. In this case, the decline of the former may, and should, be perceived as desirable, since this implies a reduced harmful flow towards the latter.

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[59] It is possible to imagine benefits that are not related to contextual systems, but rather appear within the technological system. However, this requires that the creation and use of a product, which is the function of a technological system, is perceived as inherently desirable. I would argue that this is a rare normative position and refrain from commenting further on this possibility.

Furthermore, the nature of overlaps and flows imply that a given benefit tends to be linked to a sub-system, rather than to an entire technological system. For example, it is only a spatial sub-system to the global technological system for solar modules which overlaps the Swedish economy, where an actor may perceive the creation of new jobs as desirable. This benefit is thus only realized if the related structural change occurs in this particular sub-system. Similarly, but in the technological dimension, it is mainly the use of solar modules, rather than their creation, which is linked to the reduction of local pollution through changes in local electricity systems. As a result, this benefit is only realized in regions that have activity in downstream parts of the value chain.

This reasoning implies that the creation of benefits depends not only on the performance, but also the configuration of technological systems. It also suggests that it is possible to translate the characteristics of benefits to desirable such configurations. Although presenting a comprehensive procedure for this analytical step if beyond the scope of this thesis, the conceptual ideas presented in this section may constitute a starting-point. In any case, they underline the one of the key themes of this thesis – efforts to analyze and shape technological innovation should be concerned not only with the pace, but also the directionality of innovation processes.

8.5 Applying the technological systems construct

After having elaborated quite extensively on the technological systems construct, its dynamics, and its links to social and environmental benefits, I will in this section discuss how it can be applied by researchers, policymakers and other actors that wish to describe, analyze and shape technological innovation. However, my focus is here on how the framework can be applied to studies and interventions that focus on specific technologies. I will return to how it may benefit explanation and intervention that adopt different points of departure in the discussion.

To begin with, efforts to study technological innovation, and potentially derive intervention strategies, have to clarify the scope of the investigation. Studies focused on specific technologies not only have to describe which these technologies are, but also specify which structures, spatial regions and time periods that are covered. When applying the technological systems framework, clarifying the scope of an investigation corresponds to setting analytical system boundaries in technological, structural, spatial and temporal dimensions. As discussed in Chapter 3, there are two main ways to set system boundaries: an inductive approach based on empirical observations of real structural characteristics and interactions; and a deductive approach based on logical reasoning about what is interesting and possible given the aims and resources of an investigation.

Notably, system boundaries can also be based on a combination of inductive and deductive reasoning.

In addition to setting boundaries that specify the technological system in focus, any study that aims for more than static description has to take parts of the system context into account. This creates a need for another set of boundaries that specify which parts of the system context that is accounted for when describing and analyzing system dynamics. Ideally, these should also be set in technological, structural, spatial and temporal dimensions, since the context of technological systems in fact consists of other technological systems. An important exception is natural phenomena that exist beyond humanly defined purposes and functions, which may have to be specified differently. However, to reduce complexity, the context of a technological system can also be thought of in terms of an industrial sector and a consumer sector, a number of support sectors and the natural environment, as described in Section 8.2.7. This may make it easier to specify which parts of the system context that are brought into an investigation at a reasonable level of detail.

Furthermore, efforts to study technological innovation may have different overarching characteristics. On the one hand, the ambition can be descriptive, in the sense that it does not aim to directly inform any action directed towards a particular direction of change, or normative, and thus aim to inform action towards some objective. On the other hand, the ambition can be retrospective, in the sense that the focus is on what has happened, or perspective, and thus focus on what will or should happen. Depending on these characteristics, a study can aim to provide explanation, prognosis, evaluation or prescription, as illustrated in Figure 8.16. Although there are certainly possible combinations of these different research aims, they may serve as a useful framework when reflecting upon and describing the intention of an empirical analysis. They also call for different analytical procedures when using the technological systems framework.

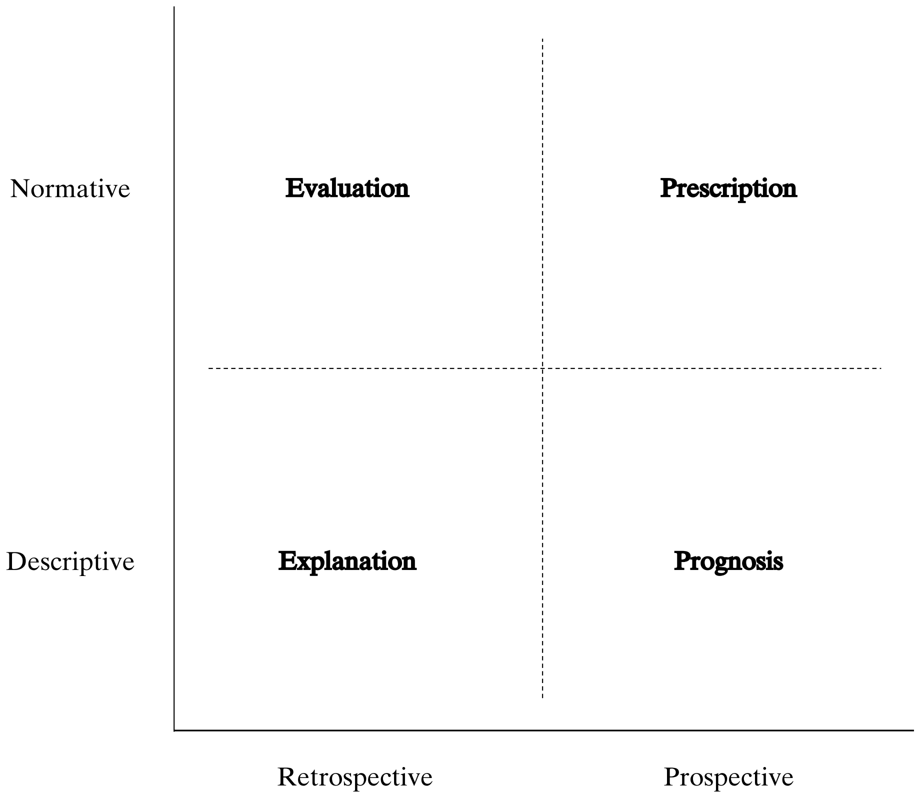

Figure 8.16. Explanation, prognosis, evaluation and prescription as different research aims.

Studies that have an explanatory ambition describe and analyze how the expanse and configuration of the technological system has developed historically, which corresponds to mapping the transformation of structure within the technological, structural, spatial and temporal domain specified by the analytical boundaries. Here, different analytical perspectives can be foregrounded to answer to the more specific questions asked, as described in Section 8.3.2. Some explanatory studies may also aim to analyze why the observed transformation occurred. This involves identifying the causal factors which underlie structural change, which, as described in Section 8.3.4, implies that influential contextual structures have to be taken into account. It should also be emphasized that findings from an investigation that aims to describe and analyze the transformation of structure in a technological system may cause an analyst to reevaluate the analytical boundaries set at the outset of the study. Whether such iteration between deductive and inductive boundary setting is appropriate, and how many iterations that are required to yield a satisfactory focus and scope, depends on the questions asked.

In contrast, prognosticating studies aim to look forward in time and predict how structures in a technological system will transform in the future. However, any prediction about the future has to be based on some idea about historical developments, even though the latter may focus on a short time frame that only captures what we think about as current or ongoing. Prognosticating studies thus involve an explanatory element, or draw upon a purely explanatory study, which gives some insight into how the system has transformed in the past and the underlying causal factors. What enables prognosis is an analytical step that strives to extrapolate this understanding of innovation dynamics to cover a time period in the future. Although challenging, this may at least result in educated guesses about how the expanse and configuration of a technological system will change.

Whereas as both explanatory and prognosticating studies are descriptive, in the sense that they refrain from referring to value statements, studies that aim to evaluate or prescribe add a normative element to the analysis. This element appears since the analytical procedure involves assessing what should have been done or what should be done, and not merely identifying what happened or will happen. Evaluating and prescribing studies accordingly analyze technological innovation in relation to some objective that describes a desired course of development. When applying the technological systems framework, this objective can be conceptualized in terms of desired properties of systems that describe phenomena in the system context, as discussed in Section 8.4. This enables an analyst to identify what configuration the objective corresponds to in the technological system in focus. While this can certainly be done at different levels of detail, and also foreground some perspectives at the expense of other, it is nevertheless a crucial analytical step, since few, if any, objectives correspond to one-dimensional growth of system structure.

Given the desired configuration of the technological system in focus, an evaluating study looks back in time, in order to assess the extent to which this objective was reached and whether the actor in focus made appropriate interventions. The explanatory ambition to describe how the technological system transformed and why, is accordingly complemented with an analytical step that aims to identify the role of a particular actor (i.e. causal factor). This often involves assessing both the influence of actual interventions as well as the extent to which actors could have acted differently and thus potentially altered the course of development. In such investigations, it is important not to view the influence of interventions as unidirectional. On the contrary, an actor not only influences the transformation of system structure but is also influenced in return. This makes it difficult, if not impossible or philosophical, to distinguish an intentional intervention from an action that merely results from system dynamics. In addition, it is certainly challenging to link causes and effects, in particular when adopting a multidimensional view of the innovation process. These and other difficulties call for caution when evaluating the role played by actors in shaping technological innovation.

For a prescribing study, which looks forward in time in order to identify appropriate interventions to reach a given objective, the challenges are similar. But there is also the added difficulty of predicting system transformation based on some idea about its historical development, which is shared with prognosticating studies. It should be emphasized, however, that when the focus is to prescribe rather than evaluate, the actor in focus has the possibility of adjusting their intervention strategy. This suggests that prescribing studies should be performed not as a first step in developing intervention strategies, but as an integrated part of their development and execution. This allows for both updated analyzes based on new empirical observations and potential reevaluation of analytical system boundaries.

Finally, it should be emphasized that even though the technological systems framework is quite comprehensive and complicated, at least in some respects, the core ideas can be applied without necessarily accounting for all details and perspectives discussed in this chapter. It is, however, beyond the scope of this thesis to develop a simplified framework.

8.6 A brief summary

To finally summarize this extensive chapter, it is appropriate to first revisit the motivation for developing the technological systems framework. As argued in Chapter 4, the TIS framework, which is commonly used to study technological innovation in the sustainability transitions community, is laden with ambiguities and contradictions, and also fails to capture the multidimensionality of technological innovation. There is a need to strengthen conceptual clarity and rigor, and also to incorporate a more detailed understanding of the different ways in which new technologies can develop and diffuse in society. When engaging with this challenge, I chose to do adopt a sociotechnical focus and technology-oriented perspective. This means that I have strived to develop a framework based on a systems construct that includes sociotechnical structures, while deriving its purpose from the characteristics of the focal technology. The result is what I refer to as the technological systems framework. Its core part is the technological systems construct, which is defined as "*a set of social and technical structures, that both influence and are influenced by the function of a specific technology, and that exist in a given spatial region and time period*".

In this chapter, I elaborated extensively on the key characteristics of this construct. To begin with, I proposed that technological systems consist of sociotechnical structures, while ecological structures are seen as a part of the system context. I also decomposed sociotechnical structure into three fundamental components – artifacts, actors and agreeings – and suggested a number of sub-categories. Second, I proposed that technological systems perform the function of a specific technology, which can be defined by delineating a bundle of value chains around a focal product. Importantly, my understanding of this technological function has two elements; it not only includes production-consumption activities that occur throughout the bundle of value chains, but also innovation activities that support and develop the ability of the system to perform production-consumption activities. As a matter of fact, this implies that the system captures all structures that are specific, in the sense that they both influence and are influenced by the focal technology. Third, I proposed that technological systems span technological, structural, spatial and temporal dimensions. These are the domains in which a particular system is specified for the purposes of an investigation, and they may also be used to delineate sub-systems. However, the specification of a technological system is not necessarily related to the expanse of real system structures. On the contrary, the latter may cover a small part of the multidimensional space captured by the analytical system boundaries. Fourth, I proposed a sharp distinction between the performance and configuration of technological systems. The performance of a system describes the extent to which the technological function is performed. This property correlates with the expanse of real system structure and can be understood in terms technology-readiness or production levels, depending on the maturity of the focal technology. In contrast, the configuration of a system describes how the technological function is performed. It thus captures the multitude of configurational properties that are possible within and across technological, structural, spatial and temporal dimensions. Lastly, I proposed that the context of technological systems can be seen as an industrial sector, a consumer sector, various support sectors and the natural environment. Notably, a given technological system overlaps not only the industrial sector and consumer sectors, but also the various support sectors.

Based on these basic ideas about the technological systems construct, I proceeded to elaborate on their innovation dynamics. A key distinction I made is that the directionality of innovation processes determines the configuration of a technological system, while their pace determines its level of performance. I also derived a typology of innovation processes that describe the transformation of system structure with respect to its characteristics in the structural dimension, while noting that ideal typologies also account for its characteristics in the technological and spatial dimensions (i.e. they are three-dimensional). In addition, I discussed the causal factors behind innovation processes and emphasized that they are found both in the existing structure of technological systems and in different parts of their context. In fact, the causes of innovation processes have similar characteristics as their effects, and may accordingly be categorized and analyzed in technological, structural and spatial dimensions as well.

To make the framework useful for analysts that have a normative ambition when investigating technological innovation, I also discussed how a conceptual link to the benefits (and costs) of this process can be established. I proposed that a given benefit can be understood as a desired property in a system that describes phenomena in the context of technological systems. Creating this benefit accordingly corresponds to transforming the related contextual system towards the desired property, a process which can be influenced by the transformation of technological systems. Understanding benefits in this way has several implications. First, it creates a rationale for distinguishing between benefits that have social and environmental characteristics, that have a global and local reach, that are realized in the short- and long-term, and that result from activities in different parts of the value chain for a given technology. Second, it highlights that the creation of benefits not only depends on the performance of a technological system, but also on its multidimensional configuration and broader contextual changes. Third, it makes it possible to link the creation of benefits (i.e. policy objectives) to desirable configurations in technological systems.

In the end, I commented on how the technological systems framework can be applied in studies that aim to provide explanation, prognosis, evaluation and prescription with respect to technological innovation. While the need to specify the technological system in focus is common to these different aims, the ways in which the analytical procedure engages with dynamics and benefits differs.

Although I do believe that the ideas presented in this chapter may in the end support efforts to analyze and shape technological innovation, there are certainly a number of issues that deserve to be discussed from a critical perspective; both with respect to the technological systems framework and the research process from which it emerged. This is the focus of the next chapter.

CHAPTER 9 – DISCUSSION

The previous seven chapters established the metatheoretical foundation and analytical perspective of this thesis, positioned the research in relation to existing literature, elaborated on its ambition, described the methodological approach and research design, and presented its results and contributions. The thesis is coming to an end and the time has come to provide a more general and critical discussion about its merits.

In the following sections, I will first adopt a critical perspective and highlight weaknesses in the research process and the main contribution of this thesis. I then discuss how the technological systems framework may benefit the sustainability transitions community and support policy efforts to shape technological innovation. In the end, I adopt a forward looking perspective and suggest future research avenues that may build upon this thesis, or at least consider it a source of inspiration. I also provide a few additional reflections.

9.1 A critical perspective on the research process and its design

Before discussing the contents of this thesis from a critical perspective, it is worth revisiting its purpose, which is to support efforts to shape sociotechnical change towards desirable outcomes. The aim is to develop a conceptual framework, by drawing on three case studies, literature reviews and deductive reasoning. This also implies that empirical findings from the case studies add to the contribution of this research.

When attempting to develop new knowledge about conceptual tools and empirical cases it is rare, if not impossible, to succeed fully, in particular when the research process is a part of an attempt to earn a doctoral degree. This thesis is no exception. The research design, empirical findings and conceptual contribution are all laden with flaws and I will reflect upon some of these in the following paragraphs.

As described in Chapter 6, the research design employed in this thesis aims to treat conceptual development and the three case studies it draws upon as interlinked streams of activity. Empirical findings have continuously fed into the process of developing conceptual tools and frameworks, while the latter have guided subsequent empirical investigations. Combined with a somewhat broad initial purpose, which has offered a large amount of flexibility in the research focus, this has made it possible for me to both identify and develop ideas that may have remained mere notes in a more rigid research setting. I have been able to follow my interest in thinking deeply about conceptual logic and ontological positions quite far, and this thesis is the outcome of that intellectual process. But while the search for conceptual rigor and clarity is what has made my contributions to the literature possible, it has taken much time and effort that could have been spent on other things. As a result, there are a number of important pillars of a complete academic achievement that are simply missing from this thesis.

To begin with, and as the reader is likely to have reflected upon already, this thesis is strongly situated in the small but growing field of sustainability transitions research. This has perhaps been necessary to enable the close scrutiny of the literature and the identification of quite hidden conceptual problems, presented in Chapter 4, and the comprehensive conceptual framework developed in Chapter 8. But at the same time, it has come at the expense of attention to other streams of literature. The thesis draws upon few sources beyond the sustainability transitions literature, with the possible exception of historical work on the core ideas that form the backbone of my conception of technology, innovation and systems. As a result, the conceptual contribution and empirical findings are only weakly linked to broader literature streams that engage with innovation, policymaking and technology assessment. I am the first to acknowledge that this weakens the quality of this thesis and can only wish that I had had the capacity to situate my work in a more comprehensive research context.

Second, the conceptual contribution which lies at the core of this thesis has not been tested and validated in empirical investigations. Although some of the ideas are used to organize and analyze data in Paper II and Paper III, and also briefly illustrated in Paper V, the conceptual framework as a whole has not yet been subject to the challenges brought by empirical application. This unfortunately means that the research presented in this thesis is in a sense incomplete, since the logic which underpins conceptual development based on few case studies involves exposing ideas that have been developed with a major subjective element to empirical investigations. However, refraining from performing this step within the scope of this thesis has been an intentional choice. Together with my supervisors, I chose to prioritize the development of a comprehensive and rigorous conceptual framework, while leaving testing and validation to future research.

Third, the thesis fails to fully explain how both historical and more recent literature has informed and inspired the details of its conceptual contribution. On a scale between full referencing that links every conceptual idea to academic and non-academic sources (which is practically impossible), to a complete lack of referencing (which is not scientifically acceptable), this thesis thus leans further towards the latter end of the spectrum. There are two main reasons behind this situation. On the one hand, the conceptual framework has been developed through an analytical process that has made it difficult to keep track of all sources of information and inspiration. The process has not only endured over more than five years, but also taken different directions with a constantly evolving aim. As a result, lots of literature has been read for slightly different purposes. While many of these publications have certainly made an imprint on my way of conceptually understanding innovation, technology and systems, I have only been able to track some in the process of writing this thesis. In addition, the process has involved many informal discussions with my supervisors and collaborators, which has added to the difficulty of tracking the origins of important ideas. On the other hand, the conceptual framework is in fact based on a substantial degree of deductive reasoning. This part of the analytical process is not based on the existing literature, but rather on ideas derived from the ontological foundation presented in Chapter 2. While writing this thesis, I have strived to make these links as clear as possible.

Fourth, the thesis neither elaborates fully on how the conceptual contribution may benefit policymaking, nor relates its constituent parts to a detailed analysis of strengths and weaknesses in current policy practices. Since the overarching purpose of my research has been to support efforts to shape technological innovation, this is clearly regrettable. At this point, I can only acknowledge that I had the ambition to incorporate empirical investigations focusing on policy practices (rather than the enacted policy instruments which are subject to analysis in the case studies) in the research process. I also wanted to be able to provide a comprehensive account of how my ideas can be applied by policymakers and other actors. But in the end, I failed to reach these objectives.

Fifth, the choice of case studies used to inform the conceptual development process may certainly be questioned. While the empirical findings about marine energy, tidal kite and solar photovoltaics technology have contributed to the conceptual contribution in many respects, as described in Chapter 7, it is possible that a different choice of analytical focus and scope would have been more appropriate. For example, case studies in additional geographical contexts, together with a more comparative analytical ambition, could have shed light on other perspectives on the technological innovation process. Similarly, investigating innovation in other types of technologies may have led to valuable additional insights about the characteristics of sociotechnical change. However, just like technological innovation, the outcome of research projects depends on their history and the path dependencies it gives rise to. This particular research project begun with an empirical focus on new energy technologies in Sweden. And even though the ambition gradually shifted towards more fundamental conceptual development, the initial empirical orientation was difficult to adjust accordingly.

Apart from these overarching weaknesses related to the research design, there are a number of issues related to the more specific methods used to conduct empirical case studies and perform conceptual development. Starting with the former, the quality of empirical findings could certainly have been enhanced through adjustments and improvements in all parts of the research process – from developing specific research questions and collecting and evaluating data, to analyzing and writing. However, most of the obvious ways to strengthen the case studies would arguably have come at the expense of some other part of the research process. Spending more time and effort performing interviews, for example, would have implied less capacity to engage in empirical analysis and conceptual development. In the end, I think the challenge is to find a good balance between all parts of the research process and realize that everything cannot be drawn to the ideals portrayed by textbooks on methodology. I have done my best to navigate this tricky terrain, and given that the core contribution of this thesis is a conceptual contribution rather than empirical findings, I think the methodological rigor of my case studies is at least reasonable.

When it comes to the way conceptual development was performed, most issues relate to the overarching weaknesses discussed above. There are, however, some aspects of the more detailed review of the TIS literature, presented in Chapter 4, that deserve additional attention. For starters, there is clearly a subjective element in the interpretation of the reviewed publications. Although the literature review presented in this thesis have been developed not only by myself, but also by my co-authors in Paper IV, the three of us constitute a small research group. We have engaged in the discussions about the topics raised in this thesis for several years, and although we sometimes think differently, we clearly view reality through similar lenses. The arguments we make are therefore in need of validation by scholars that can bring initiated yet different perspectives to the questions we ask. This is also our intention before attempting to publish the manuscript. Furthermore, and as the literature review concludes, it is difficult to interpret what scholars actually mean when describing their view of the TIS construct. This has forced me and my co-authors to partly "read between the lines", which should be kept in mind by scholars that may want to build on our results. One way to at least partly mitigate this problem would have been to complement the review of publications with a set of interviews where leading scholars were given the opportunity to elaborate on their viewpoints. Unfortunately, this was not possible due to time and resource constraints.

Finally, although these and other weaknesses make this thesis far from perfect, it does present a number of empirical findings and a quite comprehensive conceptual contribution. I do hope that the preceding chapters and appended papers will bring some value to the sustainability transitions community and beyond, and maybe even inspire and support future research.

9.2 A reflection on weaknesses in the technological systems framework

Although the conceptual development process that resulted in the technological systems framework has been guided by an ambition to be comprehensive, while putting a strong emphasis on logical consistency, a number of weaknesses remain. In the following, I will reflect on a number of issues that should ideally have received more attention and potentially call for conceptual reconsiderations.

First, the way I use the term 'structure' may create confusion. Some associate structure with configurations that are stable and enduring, while I rather use the term to refer to the wide range of objective, intersubjective and subjective entities that make up reality. While I hope to have made this clear in my description of the technological systems framework, the possibility for misunderstandings remains a weakness.

Second, and related to the previous point, the term 'structure' is used both to the components in a technological system and its context (i.e. system structures and contextual structures), and to one of the dimensions from which these components can be observed, categorized and analyzed (i.e. structural dimension). This may suggest that system structures only exist in the structural dimension, which is not my intention. On the contrary, system structures neither exist in the structural dimension, nor in the technological, spatial and temporal dimensions. Instead, the dimensions constitute different perspectives that, respectively, describe what system structures do, what they are, where they are, and when they are. Although I have strived for clarity and consistency when defining and using these concepts, I can in hindsight see that other labels could have been more suitable. I have also tried, but failed, to identify alternative terms.

Third, the technological boundary, which constitutes one part of the analytical specification of a particular technological system, has a dual nature. On the one hand, it defines the technological function of the system (i.e. a bundle of value chains) and thus describes what the included system structures do. On the other hand, it defines criteria that determine just how involved different structures have to be in the technological function, to warrant inclusion in the system. These are two different parts of the system specification and I do acknowledge that including both in what

I refer to as the technological boundary implies a risk for confusion. One approach to resolving this could be to add a fifth analytical boundary that specifies the breadth of the system (i.e. the latter part described above). This would, however, add complexity, and in this thesis I chose to prioritize simplicity. It should also be acknowledged that I have not explored how to define criteria for determining which structures that warrant inclusion in the system in much detail. Difficulties may, for example, arise when it comes to structural components that are highly involved in processes that are interlinked with, but still outside, the technological boundary (i.e. competing or complementary technologies).

Fourth, my way to disentangle the different configurations of system structure that can appear within and across technological, structural, spatial and temporal dimensions can certainly be improved. In particular, I only discuss configurations with respect to actors in the structural dimension, even though important system properties arise from how artifacts and agreeing are configured as well. However, elaborating on the latter was beyond the time and resource constraints of this thesis project. It should also be noted that my way to describe configurations could be further grounded in a more comprehensive deductive framework about the different ways in which entities can relate to each other. This would expose the logical similarities of configurational properties within the dimensions of technological system and potentially give rise to new insights.

Fifth, the context of technological systems is only described briefly and fails to discuss its complexities. Although I do believe that it is useful to think about context in terms of an industrial sector, a consumer sector, various support sectors and the natural environment, the characteristics of these domains and their links to technological systems call for more attention (see Hojcková et al. (2020) for one of many promising starting-points).

Sixth, although I broadly define the difference between the production-consumption dynamics and innovation dynamics of technological systems, which is in itself useful, the characteristics of the former are not discussed in detail. While this is beyond the scope of this thesis, it remains a weakness that should be addressed to increase the applicability of the technological systems framework.

Seventh, an important consequence of how I define the technological systems construct – which is arguably shared with most alternative systems constructs used to investigate technological innovation – is that its analytical boundaries do not separate between endogenous and exogenous factors involved in the innovation process. However, I do not discuss the practical implications of this observation at length.

Eighth, many details in the conceptualization of benefits (and costs) created by technological systems remain unexplored. In particular, I do not provide a clear procedure for translating an objective related to technological innovation (i.e. the creation of a benefit) to a desirable configuration in a technological system. But while the part of the technological systems framework which deals with benefits can be perceived as rudimentary, I hope that it conveys a logic that can serve as a bridge towards the extensive literature that engages specifically with technology assessment.

Ninth, I do not elaborate on how analysts can, and should, use empirical observations to learn about the structure and dynamics of technological systems. Although I do not believe that anything in particular prevents the use of mixed methods approaches, common to the ones used in the case studies presented in this thesis, future efforts to apply the technological systems framework to empirical investigations may certainly identify conceptual choices that have to be reconsidered.

Tenth, and lastly, the point of departure when developing the technological systems framework was a focus on sociotechnical structures. As a result, the systems construct does not include ecological structures that make up the natural environment. The structural boundary this implies can certainly be questioned. In hindsight, I can only regret that I did not develop a systems construct that also includes ecological structures, or at least proposed that the structural boundary should be an analytical choice on a case by case basis.

In addition to these issues, which concern the ideas presented in this thesis, there are certainly a number of more overarching ways in which the technological systems framework could be extended and improved. I will return to how this thesis can inspire and inform future research in Section 9.5.

Finally, I certainly acknowledge that an attentive reader has probably identified many other weaknesses that could have been brought up in this section. But I still hope that the merits of the core ideas behind the technological systems framework have come across as useful for efforts to analyze and shape technological innovation. In the next section, I will discuss what the framework actually brings to the sustainability transitions community.

9.3 Conceptual contribution to the sustainability transitions community

Before elaborating on how I believe that the technological systems framework may benefit sustainability transitions research, it is appropriate to offer a more personal comment on the background to this thesis. While many factors have influenced the orientation of my research, it is clear that the conceptual contribution I make has grown out of two observations that I made in the early days of my time as a doctoral student. On the one hand, I sensed that the core concepts that form the backbone of the TIS framework were defined somewhat ambiguously, which allowed for different interpretations. In particular, it seemed to me that some scholars thought about the system in focus as one that solely performs innovation activities, while others included production-consumption activities as well. This in turn made it difficult for me to understand how I was supposed to think about 'functions' – the core concept used to analyze change – in relation to structure within the system and its context. Since my research was initially focused on how technological innovation can be shaped in way that promotes industrialization in specific places, which implies an interest in both the dynamics and consequences of innovation, this conceptual ambiguity was difficult to disregard. On the other hand, and given that I eventually realized that the TIS construct was perhaps not supposed to include production-consumption activities, at least according to some of the scholars behind the foundational papers, I kept finding myself questioning this way of delineating the object of study. It seemed to me that incorporating the outcomes of innovation processes within the system in focus was necessary to pay proper attention to the creation and distribution of various benefits (and costs). And I struggled to find an alternative analytical approach that did just that, while still focusing on a specific technology and maintaining a sophisticated understanding of innovation dynamics.

This background is important because it hints at the two main ways in which the contribution of this thesis may benefit the sustainability transitions community – it outlines a rigorous approach to defining system constructs, and it offers a conceptual framework that accounts for both the dynamics and outcomes of technological innovation.

The first of these contributions is in fact introduced already in Chapter 3, where I discuss technological innovation from a systems perspective and show that systems constructs require boundaries in functional, structural, spatial and temporal dimensions. I also highlight different approaches to setting functional and structural boundaries when investigating technological innovation (see Figure 3.1 and Figure 3.2), which is then used to review the literature in Chapter 4. The four-dimensional perspective on systems is then elaborated as I introduce the technological systems framework in Chapter 8, where adopt the term 'technological', instead of 'functional', when referring to the dimension which captures what function the system performs.

What makes this perspective different from how systems are commonly discussed and defined, by systems thinkers in general and sustainability transitions scholars in particular, is that it highlights how the system purpose or function in fact corresponds to a boundary which includes some processes and excludes others. This boundary is needed to specify most, if not all, systems, since we tend to be interested in a set of structures defined not only by what they are, but also by what they do, where they are and when they exist.

The distinction between technological, structural, spatial and temporal dimensions, as different perspectives from which real-world structures can be observed, evaluated and categorized, is a core part of the technological systems framework. But I do believe that it is in fact a useful way to think about system definitions and specifications, no matter whether one supports the idea of using the technological systems construct when investigating technological innovation. For example, it should be possible to develop systems constructs that highlight other aspects of the technological innovation process, or to clarify how core concepts in existing frameworks should be understood. I will return to this in the next section, where I discuss links between the technological systems framework and other approaches in the sustainability transitions literature.

The second contribution is the ideas, concepts and analytical choices that together constitute what I refer to as the technological systems framework. This line of thinking is introduced and discussed at length in Chapter 8. The core part of the framework is the technological systems construct, which is defined by a specific approach to setting technological (i.e. functional) and structural boundaries. This approach leads to a system that includes sociotechnical structures which are specific to a given technology. Apart from defining the technological systems construct and elaborating on its characteristics, the framework discusses the how it can be used to describe and analyze innovation dynamics. In addition, it establishes a link between common policy objectives and the properties of technological systems.

Although this first version of the technological systems framework fails to address many relevant questions, and also suffers from a number of conceptual weaknesses, it does offer a new conceptual toolbox to sustainability transitions scholars. The most important part of this toolbox is a systems construct that shifts the focus from the creating to the created, in the sense that it is the consequences of technological innovation that form the point of departure when setting system boundaries. In my view, the main benefit of this approach is that it enables analysts to understand the different possible outcomes of technological innovation processes as multidimensional configurations of the system in focus, rather than as properties of some other object, system or domain. This facilitates efforts to describe and analyze the directionality of innovation processes, and enables a conceptual link to their benefits and costs. Both of these aspects may arguably support research that strives to inform policymaking that aims to shape technological innovation towards specific outcomes.

In fact, the technological systems framework can be seen as a first step towards a conceptual bridge between the scientific communities that engage with technological innovation and technological assessment. While these perspectives were historically addressed by interlinked research fields with a common interest in management and governance of technology (Coates, 1972; Porter et al., 1991), they have over the years, with increasing volumes of research, increasingly been treated as separate topics. This can be seen as a part of a broader disintegration, where the dynamics of technological change on the one hand, and its social and environmental consequences on the other, have since the 1970's increasingly been treated as separate topics by specialized researchers and policymakers (Bechmann et al., 2007; Sveiby et al., 2012). And as a result, conceptual frameworks used in the innovation and sustainability transitions community rarely incorporate ideas from, or develop analytical interfaces to, industrial ecology and technology assessment frameworks (Green and Randles, 2006), and vice versa (Sandén and Karlström, 2007). While I do certainly not claim to have developed a rigorous integration of innovation- and assessment-oriented frameworks, I still believe that the technological systems construct is a promising first step.

When relating the conceptual contribution of this thesis to existing approaches to studying technological innovation in the sustainability transitions community, a first observation is that the technological systems construct is likely to be in line with some interpretations of the TIS framework. As I argued in Chapter 4, some publications seem to think about a TIS as a construct that captures not only innovation activities, but also production-consumption activities (see for example Mäkitie et al. (2018) and Stephan et al. (2017)). In other words, a TIS is seen as an emerging industry, rather than as a collection of structures that merely propel the emergence of an industry. What the conceptual contribution of this thesis brings is a rigorously defined and extensively developed framework that captures this view, while clearly distinguishing it from other possible interpretations of the TIS framework.

But the ideas which underlie the technological systems framework can also be used to clarify other interpretations of the TIS framework. If a TIS is seen as a system that only captures structures that influence innovation activities related to a specific technology, it is in fact a system that creates, expands and transforms a related technological system. An implication of this link is that the conceptual contribution of this thesis may support TIS-oriented scholars. To begin with, it could enable more rigorous definitions of the technology (i.e. technological system) in focus. As was highlighted in Chapter 4, the TIS literature rarely moves beyond vague references to some product when specifying the technology in focus, which means that the vertical and horizontal expanse of value chains included in the analysis is not specified. The contribution of this thesis not only identifies this issue, but also discusses a rigorous way to define technological system boundaries. In addition, the technological systems framework could enable more comprehensive specifications of the analytical goal employed in evaluative or prescriptive TIS studies, which can be formulated in terms of a desirable configuration in a technological system.

It should also be highlighted that the conceptual link discussed above is actually suggested by the similarity between the typology of innovation processes derived in Section 8.3.3 and the lists of 'functions' used to analyze innovation dynamics in the TIS literature. If the latter are viewed as a way to decompose the system function into its constituent parts, the similarity should not come as a surprise. After all, if the function of a TIS corresponds to achieving structural change in a technological system, it is possible to view TIS 'functions' and the typology of innovation processes proposed in this thesis as two attempts to decompose the same phenomenon; one based on an inductive approach focused on what has been observed in the literature, and another based on a deductive approach focused on conceptual logic. If this is accepted, there is clearly an important synergy that could be exploited by future research efforts that aim to develop stronger analytical lenses through which to analyze technological innovation.

In addition, it is worth adding that the conceptual contribution of this thesis highlights that the structures which influence innovation activities may not only stimulate the growth of a technological system, but also shape its configuration and even contribute to its decline. In other words, technological change is about transformation, rather than growth. This compels me to suggest the alternative notion of 'technological transformation systems' as constructs that captures innovation activities related to a specific technology.

When it comes to the other main strand of sustainability transitions research, which is dominated by the multi-level perspective, the links to the technological systems framework are less explicit. After all, niches and regimes are not defined in systems terms, even though it is likely that many scholars think about them as interacting sociotechnical systems. However, it is nevertheless difficult to question that both niches and regimes are domains which capture structures that perform what I have referred to as a technological function, albeit one that foregrounds the overarching role played by economic sectors (in the case of regimes) and alternative ways to carry-out this role (in the case of niches). While these are not commonly defined in terms of a focal product and a bundle of value chains, I would argue that is possible to do so in principle. If this is accepted, nothing prevents us to interpret the multi-level perspective as an analytical lens that highlights how mature and entrenched technological systems, defined broadly to cover an economic sector, interact with immature and novel technological systems, defined more narrowly to cover new products and processes. This opens up for potentially important synergies. On the one hand, the technological systems framework may support the multi-level perspective by offering a rigorous approach to defining the boundaries of both regimes and niches as well as a comprehensive understanding of fundamental characteristics of their constituent components and configurations. On the other hand, the multi-level perspective may support scholars interested in developing and applying the technological systems construct, by offering a sophisticated view on the interaction of technological systems defined at different scales of observation. The future will see whether the possible integration of sustainability transitions frameworks that this suggests will prove to be a fruitful line of development.

Another reflection related to the multi-level perspective is that some scholars may view niches and regimes not as systems consisting of interacting sociotechnical structures, but rather as a collection of institutions (Svensson and Nikoleris, 2018). This is in fact suggested by Rip and Kemp, who define technological regimes as “the rule-set or grammar embedded in a complex of engineering practices, production process technologies, product characteristics, skills and procedures, ways of handling relevant artefacts and persons, ways of defining problems; all of them embedded in institutions and infrastructures” (1998, p. 340), and also a possible interpretation of later elaborations presented by Geels (Geels, 2005, 2002). While discussing the appropriate understanding of regimes and niches is beyond the scope of this thesis, its conceptual contribution does in fact reformulate the debate in terms of where the structural boundary should be drawn; do niches and regimes, understood in systems terms, consist merely of agreeings or do they include artifacts and actors as well?

Additional links can be found between the technological systems framework and innovation systems approaches that do not focus on specific technologies (which makes them related to, but not necessarily a part of what I refer to as sustainability transitions research). To begin with, the technological systems construct can be used to reformulate the purpose of national and regional innovation systems. These can be understood as systems that capture structures which influence innovation activities related to a technological system with a very broad technological boundary, (which in fact captures all possible products and value chain processes), but with a spatial boundary that corresponds to a nation or region. Furthermore, and similarly, a sectoral innovation system can be understood as a system that captures structures which influence innovation activities related to a technological system with a technological boundary that coincides with the idea of the sector in focus. This also implies that the technological systems framework may enable more specific definitions of sectors and thus support scholars in the sectoral innovation systems tradition.

Finally, the relationship between technological systems and recent efforts to develop mission-oriented innovation systems (Hekkert et al., 2020) deserve some attention. In contrast to traditional innovation systems approaches, mission-oriented innovation systems depart from a policy ambition, often focused on a social or environmental problem, and identifies relevant structures accordingly. For this type of analysis, the technological systems framework could be a valuable addition, since it can be used to specify the technological change needed to achieve the mission in focus. More specifically, missions can be thought of as the creation of benefits and accordingly be defined in systems terms by following the logic outlined in Section 8.4. In turn, this makes it possible to identify which technological systems that need to change and how. Adopting the mission-oriented innovation systems construct to capture the structures which influence innovation activities related to these technological systems is likely to be a good idea, even though I, as mentioned above, would argue the ‘transformation’ is a more suitable term.

9.4 How the technological systems framework can benefit policymaking

Besides inspiring and supporting academic research that will better align with policy objectives, the conceptual contribution of this thesis has a number of more immediate implications for policymaking related to innovation and sustainability transitions. To begin with, it is possible that the conceptual distinctions offered by the technological system framework can support the discourse about different types of policymaking. The last years have seen the emergence of new concepts, such as mission-oriented and transformative innovation policy (Diercks et al., 2018; Mazzucato, 2018; Robinson and Mazzucato, 2018), which complement the long-standing tension between technology-specific and more general innovation policy (Sandén and Azar, 2005). But it is not always clear what type of policymaking these concepts refer to. Here, the technological systems framework offers one approach to establishing quite clear definitions, or at least suggests one possible interpretation. If we start by distinguishing between growth and transformation as different objectives, and between efforts that focus on a specific technological system as opposed to technological systems in general (i.e. the economy as a whole), it is possible to construct a simple matrix that highlights a possible categorization of innovation-related policymaking. This is illustrated in Figure 9.1, where I also suggest a way to position the existing concepts.

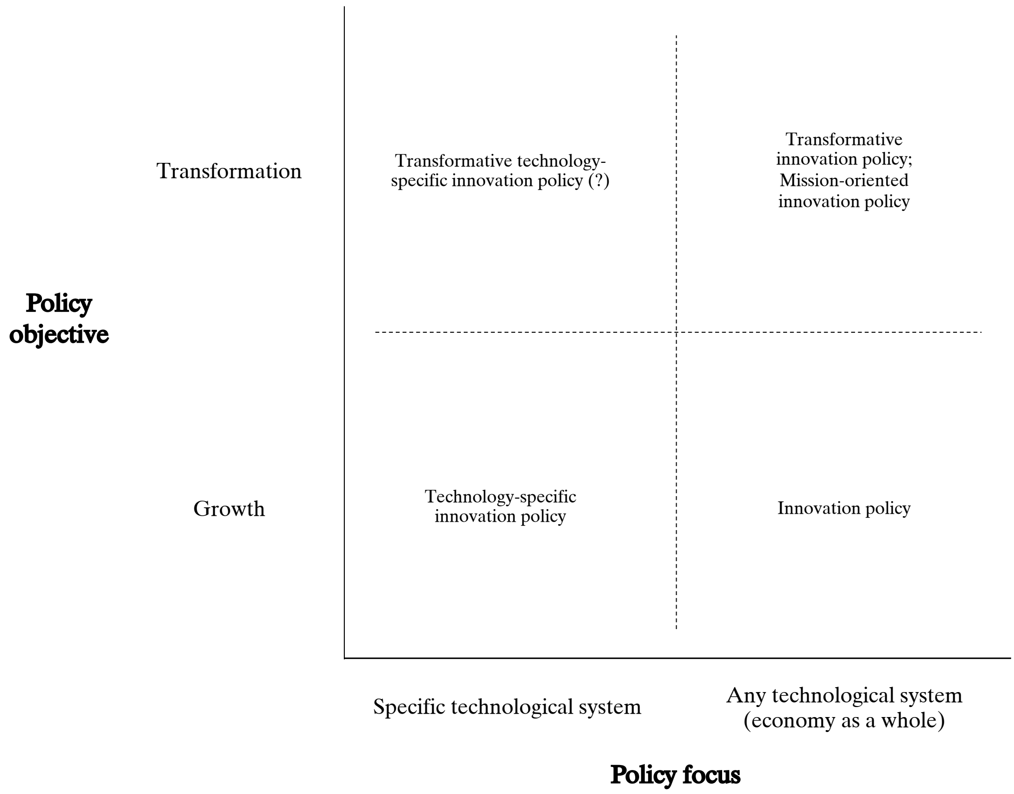

Figure 9.1. A possible categorization of innovation-related policymaking.

Although it is certainly possible to question this interpretation – for example, some would probably argue that technology-specific innovation policy not only strives for growth but also transformation – it suggests that there is a need for an additional concept that describes policymaking that aims to transform a specific technological system. For example, this could be referred to as 'transformative technology-specific innovation policy', as highlighted in Figure 9.1.

Furthermore, the technological systems framework highlights that technology-specific policymaking which has a transformative, rather than growth-oriented, ambition involves promoting more or less specific configurations in the multiple dimensions spanned by technological systems. This perspective can in fact serve as the basis for a new approach to categorizing and discussing the effects of different policy instruments based on their impact in technological, structural and spatial dimensions. Although tentative and in need of further development, I illustrate this idea in Figure 9.2. Notably, the approach can also be complemented with the temporal dimension, to highlight whether policy instruments have their impacts in the short- or long-term.

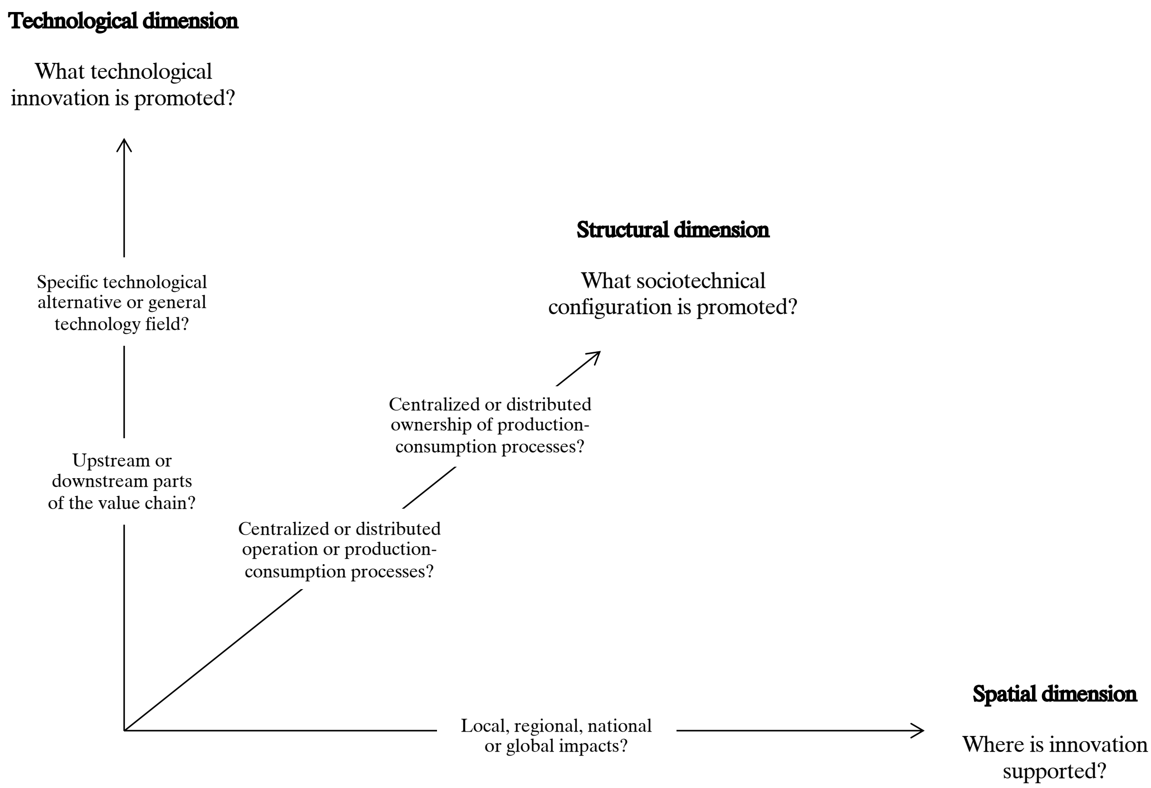

Figure 9.2. A tentative approach to categorizing innovation policy instruments

In addition, the technological systems framework may inform more specific analyses conducted within government agencies that develop and implement policy instruments that aim to shape technological innovation, even though there is certainly a need for further development and simplification to make its core ideas more accessible to practitioners. What the framework could bring is perhaps first and foremost an overarching conceptual logic that establishes links between policy objectives, desired configurations of sociotechnical systems, innovation dynamics and the role of policymakers, as actors that not only influence technological innovation, but are also affected by its outcomes. This logic ought to be useful both when evaluating and learning from past policy interventions, and when designing and implementing strategies going forward. But it is also possible that some of the more fine grained ideas that make up the framework could be valuable, both as a way to clarify the concepts used to carry-out analyses along existing lines of inquiry, and by opening up new perspectives on the different ways in which sociotechnical change unfolds in technological, structural and spatial dimensions.

9.5 Suggestions for future research

Although the previous section highlighted a few ways in which this thesis could benefit policymakers, other non-academic actors and the wider societal discourse around technological innovation, its main contribution is its potential to inspire and inform future research. In this section, I will discuss four overarching lines of research that depart from the empirical findings and conceptual contribution of this thesis.

9.5.1 Exploring the directionality of technological innovation

While this thesis presents a contribution that focuses on presenting a new conceptual framework, it also highlights the need to investigate not only what makes new technologies develop and diffuse, but also the factors which determine the more specific sociotechnical change they bring. In other words, it can be seen as a call for more research that focuses on the directionality of technological innovation and the potential for shaping it towards desirable outcomes.

It should be acknowledged, however, that this is not a novel line of inquiry. But the fact remains that most studies focus on directionality with respect to broadly defined technological alternatives, without distinguishing between the different technological, structural and spatial configurations innovation processes may result in. Since these configurations imply different types and distribution of benefits from successful innovation, an important task for future research is to explore directionality further. For example, what are the characteristics of innovation dynamics which underlie development trajectories that lead to different technological, structural and spatial outcomes? How can policymakers and other actors shape directionality towards different configurations? Are some configurations particularly challenging to promote, while others are more attainable? And why?

I do think that efforts to answering these and other empirical questions could benefit from the conceptual toolbox offered by the technological systems framework. But even though other analytical approaches may prove to be more suitable, I hope that the thesis as a whole will draw more attention to this perspective on technological innovation. After all, shaping, rather than stimulating, the development and diffusion of new technologies is necessary to meet social and environmental challenges. And it may even be an increasingly common objective in a world that is gradually leaving neo-liberal ideologies behind.

9.5.2 Testing and validating the technological systems framework

As mentioned in Section 9.1, one of the main weaknesses of this thesis is that its main contribution, has not been tested and validated in empirical case studies. While some of the core ideas have certainly informed the analytical approaches employed in the three case studies which form the empirical part of this work, and also been illustrated by brief empirical examples in Paper V, the technological systems framework has not served as the starting-point for any analysis of technological innovation. This remains an important task for future research.

The overarching objective of such research should be to test the empirical value of the technological systems framework, validate the definition of key concepts and identify necessary modifications. This would ideally involve applying the framework to a wide range of technologies, in different phases of development and in diverse geographical contexts. There is also potential for exploring whether the framework can be applied to other scales of observation than the ones commonly associated with 'technology', such as innovation in specific firms (i.e. a very narrowly defined technology) or the emergence of new macro-level paradigms (e.g. the industrial revolution).

An important part of test and validation efforts should also be to develop research methods that draw on the framework. On the one hand, this would involve developing procedures for linking empirical data to key concepts. It is possible, and even likely, that this will be challenging, since the framework has been developed through a deductive rather than inductive approach. On the other hand, developing research methods would involve identifying appropriate ways to set system boundaries for individual cases as well as procedures for potentially reconsidering this analytical choice throughout the course of a study.

Finally, it should be pointed out that the comprehensive nature of the framework may imply that empirical testing and validation have to focus on a few concepts and perspective at a time. For example, some studies could use the framework merely as a source of concepts to describe the static characteristics of broadly defined or multiple technological systems, while other studies could adopt more narrow system boundaries that make it possible to perform descriptive and normative analyses of innovation dynamics. It is also possible for testing and validation efforts to focus on some aspects of technological systems at the expense of others. Here, the four key dimensions in which system structures can be observed and evaluated constitute a fruitful starting-points, since they can be used to develop more specific analytical perspectives.

9.5.3 Conceptual extensions and improvements

At this point, it is unlikely to have escaped the reader that the technological systems framework has numerous weaknesses, does not address many relevant questions, and has several parts that are in need of further conceptual development. While this is in some sense regrettable, it can also be seen as an opportunity for future research. Before commenting on the main possibilities to extend and improve the framework, I want to emphasize the importance of drawing more on empirical investigations, along the lines proposed in the previous section, when taking the conceptual development process further. That said, I also think that there is a need for additional deductive thinking to strengthen and maintain the rigor of core concepts. In the end, conceptual development and empirical investigation should be intertwined, even though this thesis may not have achieved this ideal fully.

Future research aimed at extending and improving the technological systems framework can proceed along numerous avenues and tackle a variety of issues. In fact, several of these were highlighted in Section 9.2, where I reflected upon weaknesses in current version of the framework. In the following, I will therefore limit the discussion to three potential lines of development that I think merit further attention.

The first line of development is to incorporate the ecological structures which make up the natural environment into the technological systems construct. In other words, the structural system boundary, which restricts the system structures to social and technical components, should not be embedded in the definition of technological systems, but rather constitute an analytical choice that is made when specifying the system in focus of a given investigation.[60]

There are several reasons to proceed along this line of development. First, it would highlight that ecological structures often appear as endogenous factors in the dynamics of technological systems. For example, the availability and distribution of natural resources may exert a strong influence on the development of technological systems,[61] but also be subject to degradation as a result of production-consumption activities. Second, the inclusion of ecological structures would potentially result in a stronger focus on, and perhaps more elaborate understanding of, the environmental impacts of technological systems. This is due the fact that the systems constructs tend to be used to foreground some parts of reality at the expense of others. When ecological structures are by definition contextual, they are easier to disregard, which may result in ignorance towards the true nature of environmental impacts. I do, for example, believe that it would be easier to communicate and act upon the fact that most technologies that are considered 'clean', 'green' or 'sustainable' actually have a detrimental impact on the natural environment, albeit to a lesser extent than some alternative, if we began investigating innovation from a socio-techno-ecological, rather than sociotechnical perspective. Third, and on more general note, including ecological structures in the technological systems construct would result in a framework that is more grounded in the fundamental nature of technology and reality as a whole; society, technology and nature are intertwined, at least according to my ontological assumptions.

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[60] Notably, Sandén and Jonasson (2005) include what they refer to as 'controlled natural systems' in their conception of sociotechnical systems, which represents a step in this direction.

[61] The exogenous influence exerted by natural resources on the innovation process was illustrated in Paper II, where the spatial distribution of tidal currents was highlighted as an important factor in the formation of the observed development trajectory for tidal kite technology.

While the reasons for including ecological structures are plenty, the conceptual development this requires is likely to be challenging. It would not merely be about reformulating the definition of the technological construct in order to relax the structural delimitation to social and technical components, but also involve developing appropriate concepts to describe the constituent components and sub-components of ecological structure, and the different configurations these may adopt in a technological system. Nevertheless, I think it is a task worth pursuing in future research, preferable in close collaboration with scholars from scientific fields where the natural environment is already the analytical focus.

The second line of development concerns the link between technological systems and their social and environmental impacts. In Section 8.4, I outlined an overarching logic based on three core ideas: the costs and benefits associated with technological systems can be conceptualized in terms of desirable properties of contextual systems; the influence of technological systems on these contextual systems is mediated by structural overlaps and flows; and the desirable properties of contextual systems can be used to derive desirable configurations of technological systems. While I do believe that this logic is promising, it clearly fails to provide a procedure for deriving desirable development trajectories for technological systems from an overarching objective related to benefits and costs. There is accordingly a need for further conceptual development to support normative efforts to analyze and shape technological innovation.

However, there is already an extensive literature on technology assessment, which engages specifically with benefits and costs associated with emerging and mature technologies (Van Eijndhoven, 1997). Strengthening the conceptual link between technological systems and their social and environmental consequences should therefore be seen as the development of an interface to this academic field. In fact, it can be argued that such an interface is partly established already, since there are a number of key similarities between the technological systems framework and the methods used in the life-cycle assessment community. While the terminology differs, both approaches use systems constructs to highlight a set of interlinked processes involved in the creation and use of a product (Baumann and Tillmann, 2004). This suggests that it may be possible to integrate the sophisticated understanding of social and environmental impacts, offered by the life-cycle assessment community, with the multidimensional conceptualization of the innovation processes and its results, provided by the technological systems framework. Developing the interface this calls for is a promising task for future research, which may in the end result in a much needed reintegration of the academic, political and societal discourse on the dynamics and consequences of technological innovation.

The third line of development is to improve how the technological systems framework conceptualizes the role of policymakers in shaping the transformation of technological systems.

Although the general characteristics of innovation dynamics are discussed at some length in Section 8.3, the specific nature of policymaking as a driver of structural transformation certainly call for more attention. There is, for example, a need to link the technological systems framework to concepts used to describe the instruments available to different types policymakers, in order ensure that decisionmakers can relate to, and act upon, empirical findings. When engaging with such conceptual development, it is key to build on the extensive literature that engages specifically with innovation-related policymaking as well as on insights developed by scholars that study TISs (Borras and Edquist, 2013; Kivimaa and Kern, 2016; Kivimaa and Virkamäki, 2014; Reichardt et al., 2016; Rogge and Reichardt, 2016; Wieczorek and Hekkert, 2012). In fact, improving how the technological systems framework conceptualizes the role of policymakers can be seen as the development of an interface towards this body of knowledge. This may not only strengthen the ideas presented in this thesis, but also inspire and inform efforts to enhance the understanding of policymaking that aims to influence the direction of sociotechnical change, as suggested in Section 9.4.

9.5.4 Advancing towards a formal model of sociotechnical change

As has been pointed out several times throughout this thesis, the technological systems framework paves the way for developing a formal model of sociotechnical change. Although fully disentangling the causal factors which determine the dynamics of technological systems, and developing a predictive theory that can be tested against empirical investigations, will probably remain beyond the reach of science, it remains a worthwhile endeavor. One reason is that the mere ambition to create a formal model forces us to sharpen the definitions of, and links between, key concepts. This can lead to more rigorous and useful conceptual frameworks, even though the modelling as such may fail to bring any additional insight into empirical phenomena. Another reason is that a formal model of sociotechnical change could potentially enable simulation exercises. While it will be important not confuse the results of these with predictions of future developments, simulation may be a useful as a pedagogical tool in order to highlight key characteristics of the innovation process (such as path dependency, interdependency and so forth).

In fact, some attention has already been directed towards modelling the dynamics of sustainability transitions (Holtz et al., 2015; Köhler et al., 2019). In particular, Walrave and Raven (2016) have developed an approach to modelling the dynamics of TISs. However, the exercise is based on the list of 'functions' suggested by (Hekkert et al., 2007), which they interpret as emergent system properties that can be used for diagnostic purposes. As a result, the model only accounts for system structures (i.e. the outcomes of the innovation process) at an aggregated level – that is, with respect to their general growth and decline, rather than more specific configurations.

Although the contribution made by Walrave and Raven (2016) is a promising first step towards modelling sociotechnical change in a sustainability transitions context, I would argue that there are reasons to believe that technological systems framework may constitute a more appropriate foundation for future efforts. To begin with, the framework is based on a logic that clearly distinguishes between, and links, the innovation process and its results. Second, it accounts for multidimensionality, which makes it possible to focus on configurations and directionalities, rather than one-dimensional growth and decline. In addition, it offers, or at least strives to offer, a way to decompose system structure into a set of mutually exclusive and collectively exhaustive sub-categories.

It is, however, beyond the scope of this thesis to elaborate fully on how the technological systems framework can be advanced towards a formal model. I will therefore limit myself to a short discussion about what this might entail, drawing partly on ideas developed by Sandén et al. (2017) and Sandén and Hillman (2011).

A first observation is that modelling efforts are likely to require a clear separation of endogenous and exogenous factors in the innovation process. As discussed in Section 8.3.4, the technological systems construct fails to do so due to its structural and spatial boundaries, which may imply that endogenous factors appear in the system context. However, for modelling purposes, we may choose to relax structural and spatial boundaries. Since the technological boundary of technological systems is defined to include structures that both influence and are influenced by the innovation processes, this would in fact result in a systems construct that includes endogenous factors but excludes exogenous factors. From a modelling perspective, we accordingly find dependent variables inside the technological system, while independent variables are a part of its context.

Moreover, there is a need to introduce causality. One way to do so is to adopt an actor-based perspective. This means that we consider actors to be the sole decisionmakers, in the sense that they have the capacity to achieve structural change in the system. Importantly, we also acknowledge that the behavior of actors is not only the result of their free will, but also influenced by existing structures in the system and its context. Given these characteristics, each actor in the system can be represented by a function that relates achieved structural change, at time t_{n+1}, to existing system structure, contextual structure and a random variable representing actor autonomy, at time t_n.[62] To account for the multidimensional nature of technological systems, the functions which represent actors should be seen as three-dimensional vector functions, while the variables that describe system structure and contextual structures are in fact matrixes which capture their characteristics in technological, structural and spatial dimensions.

Although this type of agent-based model is likely to be a fairly accurate description of how actors transform technological systems over time, it is complex and perhaps not very useful for illustrative purposes. It is, however, possible to adopt another perspective by letting functions represent structure rather than individual actors. In fact, this results in a simple formal description of the core dynamics of technological systems. If we let the three-dimensional matrixes T, C and R represent system structure, contextual structure and an element of actor autonomy, respectively, while t indicates a given point in time, it is possible to construct the mathematical expression '$T_{t+1} = f(T_t, C_t, R_t)$'. This can in turn be used to derive the differential equation '$dT/dt = g(TS, CS, R)$', which is a formal way of stating that the dynamics of a technological system depends on its internal structure, contextual structure and some random element brought by the free will of human beings.

An additional point that deserve to be made is that it possible to unpack the matrixes T, C and R along one dimension at a time. If this is done in the structural dimension, the differential equation derived in the previous paragraph can decomposed into a set of similar differential equations, each of which correspond to the transformation of a specific structural component. This suggests that typologies of innovation processes can in mathematical terms be understood as derivatives of functions. In turn, this makes the similarity between the typology of innovation processes derived in Section 8.3.3, and the commonly used lists of 'functions' used in the TIS literature, even more enticing.

Finally, it remains to be seen whether these ideas will prove to be useful in future efforts to model sociotechnical change. But nevertheless, I do think that the mere ambition to think in terms of formal models is valuable for conceptual development. Indeed, this thesis would be very different without it.

[62] Notably, contextual structures beyond the system boundary are represented by an independent variable. In a similar vein, the autonomy of actors can be seen as stemming from beyond the inner system boundary, which explains why this is also represented by an independent variable.

9.6 Additional reflections

Before concluding, I want to add some more general and perhaps personal reflections about the reasoning, arguments and contributions presented in this thesis. This may hopefully address some of the many questions and objections that I am sure the reader has at this point.

To begin with, I make extensive use of the systems concept as a way to describe and demarcate the structures which make up reality. Although this is common practice in my research context, some would probably argue that this thesis adopts the systems concept in an uncritical way, while others may even suggest that it should be avoided altogether. There are certainly many different ways to arrive at such opinions, but I do believe that two lines of reasoning are reoccurring. First, the systems concept can be seen as inherently conserving by creating an analytical path dependency that foregrounds whatever the system in focus captures at the expense of what exists in its context. And I am the first to agree with this observation. However, I would also argue that analytical path dependencies are always there, no matter whether systems thinking is applied or not. What the systems concept does is rather to make these issues explicit and transparent, at least if used properly. It also makes it possible to express problems with analytical path dependencies in terms of an unwillingness to reevaluate system boundaries. Second, the systems concept can be perceived as a mechanistic and deterministic way to frame reality, which downplays the role of human agency and emphasizes the influence of (non-agential) structures. Although this is probably a valid critique against some systems approaches, I would argue that the systems concept as such is compatible with most ontological assumptions. At least if it is seen as a metatheoretical construct that is used to delineate a particular slice of reality, rather than as a label for certain characteristics of structural interaction and change. The extent to which a particular investigation accounts for, and foregrounds, the role of agency, accordingly depends on how the systems concept is used, not on whether it is used.

Furthermore, I position the contribution of this thesis in quite sharp contrast to the TIS literature. Not only do I argue that the TIS framework is laden with ambiguities and contradictions, but I also suggest an alternative approach to describing and analyzing technological innovation. And I realize that this criticism can be perceived as harsh and naïve – something that is difficult to avoid when trying to prove a point, especially as a junior scholar. However, I want to emphasize that I do believe that the TIS approach has very strong merits, which is also demonstrated by the rich literature it has informed and inspired. It provides a sophisticated understanding of innovation dynamics and a practically useful procedure for describing and analyzing their characteristics. And it represents an important step away from the focus on general innovation and economic expansion, which is inherent in many other innovation systems approaches. Indeed, the research presented in this thesis would not have been possible without this foundation. At the same time, I maintain that there is a need to strengthen conceptual clarity and to distinguish between analytical approaches that focus on the creating as opposed to the created. This something that I think will be valuable both for scholars that continue applying and developing the TIS framework and for those that choose to adopt other perspectives. And I do hope that this thesis has made a small contribution in this respect.

In addition, I conceive of technological innovation as a phenomenon that can and should be shaped. This is not only indicated by the title of this thesis, but also something that permeates the reasoning in every single chapter. Of course, this may strike some as an inherently problematic starting-point. On the one hand, it can be questioned if it is even possible for actors to shape technological innovation. It is certainly possible to argue that the direction of sociotechnical change is an emergent phenomenon whose dependence on historical path dependencies and non-agential structures is so strong that actors simply lack the capacity to influence its characteristics. However, I do believe that the literature, including the empirical findings presented in this thesis, shows that both policymakers and other actors not only can, but also do shape technological innovation. That said, the capacity of individual actors is clearly limited, and their actions may often be overshadowed by the influence of occurrences beyond their reach.

On the other hand, and perhaps more importantly, it can be questioned if technological innovation should be shaped at all, and if so, by whom. I do understand that some readers may get the impression that I have a very strong faith in policymaking, and it is easy to see how my writing could be perceived as a call for more government intervention in the economy, not least when it comes to innovation. As a matter of fact, this is to a large extent a correct understanding of this thesis. I do believe that more active, far-reaching and risk-taking policymaking is needed, both to avert the ecological crisis and increase the well-being of human society. We need to embark on grand missions and achieve great things. And while history can assure us that we have what it takes, it also demonstrates the crucial role of a public sector that not only facilitates private enterprise, but also defines bold visions and deploys the tools at its disposal to get there. However, and importantly, the more specific objectives of such missions will always remain contested. The question is who gets to set the direction and decide what sacrifices that can be made along the way. As a firm believer in the principles of democracy, I am painfully aware that totalitarian, plutocratic and oligarchic regimes are gaining ground in many places around the world. And the missions these regimes embark on are problematic, to say the least. This certainly calls for caution when arguing, working and voting for an expanded public sector and more government intervention. But at the same time, I think it is important to realize that the directions which emerge from a 'free market' are problematic as well. In fact, these times of obscene concentration of power and wealth compel me to argue that the outcomes of a plutocratic regime and a 'free market' are not all that different. At the end of the day, I guess the answer is to deploy the full force of a powerful public sector – we simply have to – but at the same time fight as forcefully to restore and uphold the democratic principles upon which it rests.

On a final note, I would like to return to the grand challenges facing humanity and nature. We are living in times of accelerating climate change and mass extinction of species on planet Earth. And we cannot escape these existential threats by blindly expanding, growing and innovating. Nevertheless, that is exactly what we do. It might even be what defines us. I sometimes find myself thinking that the civilization we have built is nothing but a grand and global innovation system that propels growth, expansion and novelty. And I keep wishing that we could be a part of technological system that makes us happy instead. It will certainly not be easy to transform the complex world we live in towards this utopia – but we have no choice but to shape it until we make it...

CHAPTER 10 – CONCLUSIONS

This thesis set out to support efforts to shape sociotechnical change towards desirable outcomes. Situated in the sustainability transitions community, and with the literature on technological innovation systems as a theoretical point of departure, the aim was to develop a conceptual framework that (i) captures the characteristics and dynamics of sociotechnical structures associated with specific technologies, (ii) explains the role of policymakers and other actors in shaping the transformation of these structures, and (iii) establishes links to their social and environmental consequences. The conceptual development effort required to reach this aim has been informed by the existing literature, three empirical case studies and deductive reasoning. In this final chapter, I will summarize the main findings, contributions and conclusions of this research.

A review of the sustainability transitions literature shows that there is a need for conceptual development. Publications focused on sociotechnical change associated with specific technologies mainly advance and apply the technological innovation systems framework. Although this analytical approach is useful when analyzing the processes which govern successful development and diffusion of new technologies, it fails to fully capture the multidimensional characteristics of sociotechnical change. In addition, there is significant ambiguity in the way key concepts are understood. As a result, it has limitations as a tool for informing efforts to shape sociotechnical change.

The empirical case studies provide rich descriptions of the development and diffusion of three renewable energy technologies in a predominantly Swedish context. They highlight the multidimensional characteristics of sociotechnical change and illustrate the complex dynamics which determine development trajectories in technological and spatial dimensions. In addition, they identify some of the more specific factors that determine the direction of change. Apart from informing and inspiring conceptual development, these findings have implications for policymakers that aim to promote the development of domestic industries and markets based on new technologies. First, they highlight the need to distinguish between policy interventions that promote local as opposed to global developments. Second, they suggest that there is a need to avoid a situation where innovation processes at the national level become fragmented and overly dependent on the global context. And third, they indicate that there are reasons to explore policy interventions that retain some of the benefits of successful innovation, even though industries and markets mainly develop abroad. After all, the capacity of policymakers to shape sociotechnical change is limited, especially in small countries that depend on a large global context.

The conceptual contribution is what is referred to as the technological systems framework. Its core part is the idea of technological systems as constructs that capture a wide range of sociotechnical structures involved in innovation, production and consumption associated with a specific technology. By shifting the focus from the creating to the created, while distinguishing between its technological, structural, spatial and temporal characteristics, the framework offers a multidimensional perspective on the dynamics and outcomes of sociotechnical change as well as a conceptual link to the costs and benefits it brings. This is useful, if not necessary, for researchers and policymakers that are interested in a plurality of social and environmental objectives, rather than mere economic growth. Although future research is needed to test, validate and refine the framework, it constitutes a small step towards a comprehensive approach to analyzing the dynamics and consequences of technological innovation. In fact, the generalized definition of technological systems may even hold the promise of a metatheory that could eventually unify different approaches to sustainability transitions and constitute a bridge to the literature on technology assessment.

In the end, the main contribution of this thesis is a conceptual toolbox that may eventually support efforts to shape sociotechnical change in response to the grand challenges which face humanity. It thus continues along the path cleared by scholars that shifted the focus from promoting the growth of general economies to stimulating the diffusion of specific technologies. But at the same time, it looks further by unpacking the multidimensional development trajectories these may follow. While many steps remain to be taken before the last remnants of the old growth paradigm have been left behind – in academia, politics and society as a whole – I sincerely hope that this research has brought us a little closer to a more noble purpose.

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