Scaling up solar photovoltaic use

A system-oriented assessment of experiences gained in deployment

Strupeit, Lars

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DOCTORAL DISSERTATION
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To my parents

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I would like to dedicate this thesis to my parents Marlies and Wilfried.

Lars Strupeit

Lund, September 2017

Abbreviations

BIPV	Building-integrated photovoltaics
BOS	Balance-of-system
DIN	Deutsches Institut für Normung (German Institute for Standardization)
EU	European Union
GW	Gigawatt(s)
IEA	International Energy Agency
ISO	International Organization for Standardization
kW	Kilowatt(s)
kW_p	Kilowatt peak
MW	Megawatt(s)
OECD	Organisation for Economic Co-operation and Development
PPA	Power-purchase agreement
PSS	Product-service-system
PV	Photovoltaic(s)
R&D	Research and development
RE	Renewable energy
RQ	Research question
SIS	Sectoral innovation system
TPO	Third-party ownership
US	United States

Popular science summary

Solar photovoltaics (PV) is a technology for the direct conversion of solar radiation into electricity. The technology has a wide range of applications for the generation of clean, renewable power, ranging from the installation of a few solar panels on residential buildings to large solar farms. Following a rapid growth of the solar industry in recent years, solar PV now (2017) contributes to about 1.8% of global electricity supply. Yet, PV has still considerable technical and economic potential and can become a central building block in a global transition towards low-carbon energy systems. PV can thereby contribute critically to the global efforts in mitigating climate change. In fact, researchers have sketched future scenarios in which PV could meet 30% of the world's electricity needs by 2050. To materialize this transition, however, this envisioned scale-up in the use of solar PV requires a more comprehensive understanding of economic and social structures related to the *deployment* of this technology. Such knowledge will be important to support the design of policy and business initiatives and to effectively manage the transition.

Pursuant to a number of knowledge gaps that were identified in the scientific literature, the objective of this thesis is to analyse deployment-related socio-economic structures and understand how these structures can contribute to increasing the competitiveness of PV, vis-à-vis other energy sources. The thesis compiles the assessment of selected experiences gained in several pioneering countries in the deployment of PV, primarily Germany, as well as Japan and the United States. In addition, it comprises an analysis of the international collaboration network on PV deployment, involving 55 countries. The analysis is system-oriented and interdisciplinary, building on various concepts such as innovation system theory, network theory and business model theory.

The thesis analyses the evolution of the German market for distributed PV installations, starting from around 1990 until the present. In particular, the findings show how the deployment of PV depends on the collaborative work of a variety of actors. These include various types of firms such as wholesalers, planners, architects, consultants, installers and maintenance firms. In addition, a variety of other types of organizations (e.g. utilities, banks, insurers, standardization bodies, solar initiatives, governmental bodies, local authorities) are involved in different functions. The research analyses how these actors gradually gained knowledge

about PV, how they engaged in various learning processes, and how they interacted with each other in various forms.

The research particularly highlights the presence and importance of networks, including inter-firm networks in the value chain, public-private networks, and firm-user networks. For example, in the installation of residential-scale PV systems, the ad-hoc collaboration of local firms from different professions, such as roofing and electro-technology, enabled mutual learning. Overall, networks served as important learning platforms where different stakeholders contributed with their respective resources to the creation of a comprehensive body of so-called *deployment knowledge*. Developing this knowledge was important in order to successfully plan and install solar PV systems, finance them, and comply with different regulatory requirements. The thesis shows furthermore how these processes were shaped by the broader institutional and social context.

The research underlines the critical role of a multitude of different types of public policies, as well as business initiatives for PV deployment. The findings reemphasize the critical role of public policy for the creation of demand and formation of PV markets. Findings show how policies supported the formation of collaboration networks related to the creation and exchange of deployment knowledge. The backing of these networks was particularly critical during the early phases of market development, at a time when knowledge-generating interactions between firms (and other actors) were still underdeveloped. These findings demonstrate the importance of systematic and integrated policy approaches that require customization to different phases of local market development, as well as different stages in the technology cycle. For example, publicly supported research partnerships during early stages of deployment were important for gaining knowledge and experience about technical, economic and social aspects of the use of PV on residential buildings. The experience gained in these field tests was succeeded by long-term policies that supported market growth, subsequently triggering stronger engagement of solar businesses in further developing knowledge and establishing network structures.

Results show how governments, authorities, utilities and standardizing bodies engaged in streamlining a variety of processes related to PV deployment. This involved amendments in building and tax law, as well as the development of technical codes and standards to enable the integration of solar-generated electricity into the power grid. The findings also show how various procedures related to the financing and administration of PV systems became streamlined over time, as stakeholders gained experience of the various aspects of PV. In general, the removal of excessive bureaucratic barriers is important for facilitating the adoption of PV and contributes to the reduction of the so-called soft costs associated with deployment. Soft deployment costs include, for example, labour costs, permit and insurance fees, as well as a variety of transaction costs related to business transactions and compliance with different legal-administrative requirements.

With regard to the role of the business sector, findings from the cases of Germany, Japan and the United States show how private firms started engaging in the deployment of PV by exploiting the opportunities that opened up through policies. In particular, firms from different sectors took initiatives by creating business models that facilitated the adoption of PV by private customers. Examples of business models analysed in this thesis include the leasing of solar PV systems in the United States and the turnkey integration of PV in pre-fabricated homes in Japan. The analysis also elaborates how these innovative business models contribute to the reduction of customer-sited barriers to the adoption of PV. The cross-country comparison also revealed how PV business models depend on different contextual, country-specific factors. These include parameters such as homeowners' savings rates, consumer preferences, transaction costs associated with PV deployment, as well as the design of the electricity market and the policy framework.

As a final aspect, the research aimed to establish understanding of the relation between the accumulation of local experience in deployment and a potential decline in soft deployment costs and other barriers. In essence, soft costs mirror the activities carried out in deployment. Conversely, *hard costs* reflect the costs for technology components, such as PV modules, inverters and mounting systems. Findings show that soft deployment costs declined with growth in local experience. For example, evidence from Germany shows that the soft costs for planning and installation decreased by 65–85% between the early 1990s and 2012. This decline in deployment costs can be explained as resulting from a variety of factors, such the development and standardization of PV technology components, the streamlining of legal-administrative and business procedures and through the effects of learning gained among stakeholders involved in PV deployment. The research also illustrates the international dimension of learning about PV deployment, specifically by analysing knowledge collaborations that were initiated under the auspices of the European Union and the International Energy Agency.

The thesis holds several implications for the design of *public policies* that aim to catalyse the deployment of PV. Most importantly, the thesis calls for a holistic understanding of deployment-related processes and structures. This knowledge is critical for policy assessments in order to enable systematic and effective approaches to policy intervention. Depending on the state of the technology lifecycle and of local market development, deployment policies may be directed at demand creation, network formation, knowledge and awareness, streamlining of legal-administrative regulations, and a variety of other measures that contribute to the formation of well-functioning local PV markets. It is also emphasized that the anticipated effects in learning and soft cost reduction can better support the use of public resources in supporting PV deployment at more local levels. The analysis of the experience of pioneering countries in PV deployment is also of value to stakeholder in countries with little or no prior experience in PV deployment. Finally, the findings are relevant to further develop methods and analytical tools for the evaluation of policies that aim to boost the use of solar PV.

Executive summary

Background & problem

Solar photovoltaic technology has considerable technical and economic potential to become a key building block of the urgently needed global transition towards low-carbon energy systems. This envisioned scale-up of the use of PV requires, however, a comprehensive and more in-depth understanding of structures and processes related to the *deployment* of PV. Knowledge about deployment-related activities is needed in particular for distributed applications of PV, specifically in relation to the competitiveness and wider geographic diffusion of PV.

The point of departure for this doctoral thesis is grounded in the observation that a number of questions related to the deployment of PV are unsatisfactorily addressed in the broader literature on energy technology change. Firstly, in the domain of scholarship related to innovation, system-oriented research approaches focusing on the deployment stage of energy technologies have been relatively scarce, as opposed to the upstream-centred studies. In particular, knowledge about deployment-related structures and processes, including the nature and interplay of actors, networks, institutions and knowledge, is inadequately developed. Such knowledge is critical as a foundation for the sound management of PV deployment through policy and business initiatives.

Secondly, from an analytical point of view, there is a need for more integrated perspectives between different fields of research that developed in relative isolation from each other. For example, in the conceptualization of technology change, linkages between innovation system concepts and the literature on cost reductions and experience curves hardly prevail. This isolation of related research streams is problematic as it constrains more holistic insights into patterns of technology change and cost reduction, including transaction costs.

Thirdly, notions of the competitiveness of PV have often focused on financial aspects and the questions of cost-competitiveness vis-à-vis other energy sources. Broader perspectives that also consider non-economic motives of adopters and deployment-related barriers and transactions are relatively poorly understood in discussions about PV competitiveness. This aspect links up closely with the observation that academic and public debates on renewable energy support are often dominated by techno-economic approaches and cost debates. As a consequence, the debate on policy instruments often centres on a limited number of specific instruments for market creation, such as feed-in tariff schemes, renewable energy quotas and subsidy programmes. However, this debate may not fully account for the real-life complexities in the deployment of PV.

Fourthly, a review of the literature revealed an overall lack of understanding about the role of *deployment structures and processes* in relation to the competitiveness of PV. While prior research has shown that soft deployment costs[i] can be a critical factor in the economics of PV, there is scarcity of empirical evidence as to whether and how these soft costs decline as a function of cumulative experience in deployment. Nor is it well understood how solar firms, through dedicated business strategies, are able to reduce barriers typically associated with the adoption of PV[ii].

Fifthly, the predominance of the techno-economic paradigm is also reflected in a bias of *policy assessment frameworks and studies* in leaning towards upstream aspects (R&D knowledge, technology, manufacturing) and in emphasizing the role of economic parameters (e.g. cost-competitiveness) in the diffusion of PV. Other factors of potential relevance for effective PV deployment, such as stakeholder learning, creation of deployment knowledge, and removal of non-economic barriers have not received much consideration in frameworks that are commonly used for the assessment of PV policies. This disregard of deployment-related aspects in assessment frameworks is, however, a limiting factor in effectively informing the decision-making process towards more integrated and holistic PV policies.

In sum, the review unveiled the need to obtain a more comprehensive, system-oriented understanding of PV deployment, thereby providing the rationale for this research. The thesis denotes this system-oriented perspective with the notion of *socio-economic structures of the deployment system of PV*, in short a *PV deployment system*.

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[i] Soft deployment costs include labour costs, permit and insurance fees, as well as a variety of transaction costs associated with business transactions and compliance with different legal-administrative requirements. In essence, soft costs mirror the activities carried out in the deployment system. Conversely, “hard costs” reflect the costs for technology components, such as modules, inverters, and mounting systems.

[ii] Typical barriers to the adoption of PV include consumer inertia, high up-front cost, long payback periods, efforts associated with the planning and installation steps, various informational gaps, and customer concerns about PV reliability.

Research objective and approach

Pursuant to the knowledge gaps, the objective of this research is to advance knowledge about the emergence of socio-economic structures related to PV deployment and how the development of these structures contributes to the enhanced competitiveness of PV. By focusing on this objective, the research aims to support policy development and business management processes in relation to the scale-up of PV in the context of a global low-carbon energy transition.

To address the objective, the following research questions (RQ) were chosen to investigate specific aspects of the research. These questions were approached through the analysis of experiences in PV deployment in several countries, with a focus on Germany as well as Japan and the United States.

RQ1: How have the emergence of deployment-related inter-agent relations, knowledge base and institutional context formed a PV deployment system?

RQ2: How have public policies and business initiatives shaped these processes?

RQ3: How has the formation of a deployment system contributed to a decline in (soft) deployment costs, transactions costs and other barriers?

A multi-level analytical framework that draws on concepts from innovation system theory, network theory, business model theory and the experience curve approach has guided the research. This interdisciplinary approach was critical in obtaining complementary insights into particular aspects of the PV deployment system. The notion of a deployment system does not imply the presence of a single global system, but rather the conceptualization of a patchwork of national-scale systems that are interconnected with each other.

The empiric part of the research is primarily based on case study methodology. Data was collected by a variety of methods, including documentary analysis, interviews, observations and databases. The analysis of data relies on a combination of quantitative and qualitative methods, including text analysis, comparative analysis, social network analysis and statistical methods. Overall, the approach of theoretical and methodological triangulation aimed to enhance the validity of the findings.

The thesis is based on a collection of four research papers, three of which are already published. These compile the analysis of selected empirical experiences gained in several countries, primarily Germany (Papers I, II, III, IV), as well as Japan and the United States (Papers III and IV). Paper IV comprises an analysis of inter-organizational knowledge interactions on PV deployment involving 55 countries, mostly from Europe and the OECD.

Main findings

The results of this thesis enrich insights about the emergence of socio-economic structures related to PV deployment and how the development of these structures contributed to the enhanced competitiveness of PV.

Responding to *research question 1* and primarily based on the case of Germany, the research has characterized and conceptualized the PV deployment system in terms of its key actors, its knowledge base, its networks and interactions, and its institutional context. Actors involved in the deployment of PV include firms in the downstream segment of the value chain as well as private, public and non-profit organizations with auxiliary functions. The research has particularly highlighted the presence and importance of actors' inter-organizational interactions, which took place in a large variety of formats. Interactions occurred as part of inter-firm networks in the value chain, public-private interactions, and firm-user interactions. Networks formed at local and national levels as well as internationally. Overall, interactions involved heterogeneous stakeholder groups that contributed with their respective resources to the creation of a comprehensive body of knowledge that has been pivotal for the effective deployment of PV.

In addition, the research illustrates how a comprehensive knowledge base related to PV deployment formed over the course of three decades. PV deployment involves a variety of knowledge areas including technology, planning and installation, legal-administrative compliance, business models and marketing, and finance. Overall, the research shows how the actors, networks and knowledge base associated with PV deployment are embedded into the specific socio-economic and institutional structures of different geographies. Despite its local rooting, findings indicate the presence of the transnational spillover of deployment knowledge, a process that has partially been driven through policy-initiated networks.

In response to *research question 2,* the research underlines the critical role of a multitude of different types of public policies, as well as business initiatives for PV deployment. Firstly, the findings reemphasize the critical role of policy support for the creation of demand and formation of PV markets, in particular during earlier phases of the technology lifecycle. This research provides complementary and more granular insights into how demand creation is instrumental in shaping the deployment system. In addition to forming the local value chain, demand growth enabled specialization of firms' value proposition and their workforce. Evidence shows how demand and market expansion have been conditional for numerous other processes in the deployment system, including agents' interactions, knowledge generation, learning, diversity creation and other scale-effects. Collectively, these processes contributed to the reduction of soft deployment costs.

Secondly, the research shows how public policy supported the formation of collaboration networks related to the creation and exchange of deployment knowledge, both at national and international levels. Networking was triggered both through market mechanisms ("pull/demand mechanisms") as well as through push mechanisms, such as publicly funded collaboration projects. The support of these networks was particularly critical during the early phases of the formation of the deployment system, at a time when knowledge-generating interactions between firms (and other actors) were still underdeveloped. These findings demonstrate the importance of systematic and integrated policy approaches that require customization to different phases of local market development, as well as different stages in the technology cycle.

Thirdly, the research revealed how a variety of legal-administrative processes related to building law, grid integration, policy instruments, finance and tax law contributes to the composition of soft deployment costs and constituted additional barriers to deployment. In particular, local governments can streamline local permit procedures, a process that can be facilitated by higher-level governance rules, standardizing bodies and other solar advocacy coalitions. Based on cross-case analysis, the findings also show how policies shape the contextual environment for PV business models and thereby partially determine which models are viable in their jurisdictions.

Fourthly, findings from the research re-emphasize the need for policies to anticipate and timely respond to market developments, in particular cost developments. Dynamic support policies that frequently adapt to market and cost developments are important for reducing the risk of over-subsidizing PV and to incentivize continuous efforts in innovation and more cost-effective deployment.

With regard to the role of the business sector, findings from the cases of Germany, Japan and the United States show that private firms started engaging in the deployment of PV by exploiting the opportunities that opened up through demand-side policies. In particular, firms from distinctively different sectors took initiatives in forming the downstream segment of PV value chains, creating coalitions with business partners and collaboratively engaging in the creation of a value proposition towards (prospective) users of PV. Findings show how solar firms can reduce customer-sited perceptions of risk associated with the adoption of PV by engaging in long-term relationships with their clients. Evidence primarily obtained from the German case shows that solar firms also engaged heavily in the formation and diffusion of PV deployment knowledge, in particular via learning and interacting in deployment, by arranging workshops and training courses for business partners and by participating in international knowledge collaboration networks.

With regard to *research question 3*, the research aimed to establish understanding about the relation between the formation of the deployment system and a potential decline of (soft) deployment costs, transactions costs and other barriers. In response to this question, this research suggests that the formation and advancement of a PV deployment system resulted in a decline in soft deployment costs. For example, evidence from Germany shows that soft deployment costs for planning and installation decreased by 65–85% between the early 1990s and 2012. Using the experience curve approach, this decline was found to correspond to a learning rate of 10–12%. The findings also show how innovative business model configurations, embodying different attributes of product-service-systems, in principal contribute to the reduction of customer-sited transaction costs and other barriers.

Conclusions and implications

In conclusion, the results reveal the emergence of the PV deployment system in terms of inter-agent relations, the growth and diffusion of the knowledge base and related learning, as well as the development of the institutional context. These processes and dimensions are found to be complex, highly interdependent, and they evolve over time. The research approach of using a number of different conceptual frameworks proved to be valuable for characterizing and assessing the deployment system at different analytical levels of analysis, ranging from more myopic perspectives towards system-oriented levels. Due to its empirical focus on deployment-related structures and processes, the research enriches prior perspectives in the broader literature on renewable energy innovation.

The thesis holds several implications for the design of *public deployment policies*. Most importantly, it calls for a holistic understanding of the deployment system as such, in which knowledge is critical in enabling more integrated and systematic approaches to policy intervention. Depending on the state of the technology life cycle and of local market development, deployment policies may be directed at demand creation, network formation, knowledge and awareness, streamlining of legal-administrative regulations, and a variety of other measures that contribute to the formation of well-functioning local PV markets. It is emphasized that the use of public resources in supporting deployment at more local levels can be justified with the anticipated effects in learning and soft cost reduction. The stronger inclusion of deployment-related aspects, as investigated in this thesis, into future policy assessment frameworks can potentially support decision-making towards more integrated PV policies.

List of papers

This thesis is based on the following papers, which will be referred to by their Roman numerals in the text. The papers are appended at the end of the thesis (printed edition only).

Paper I: Strupeit, L., Neij, L., 2017. *Cost dynamics in the deployment of photovoltaics: Insights from the German market for building-sited systems*. Renewable and Sustainable Energy Reviews 69, 948–960. doi:10.1016/j.rser.2016.11.095

Paper II: Strupeit, L., 2017. *An innovation system perspective on the drivers of soft cost reduction for photovoltaic deployment: The case of Germany*. Renewable and Sustainable Energy Reviews 77, 273–286. doi:10.1016/j.rser.2017.04.011

Paper III: Strupeit, L., Palm, A., 2016. *Overcoming barriers to renewable energy diffusion: business models for customer-sited solar photovoltaics in Japan, Germany and the United States*. Journal of Cleaner Production, Advancing Sustainable Solutions: An Interdisciplinary and Collaborative Research Agenda 123, 124–136. doi:10.1016/j.jclepro.2015.06.120

Paper IV: Strupeit, L. *International collaboration on deployment knowledge for the diffusion of solar photovoltaics: A network analysis*. Submitted

Other publications by the author

The following is a list of other publications by the author and research colleagues that are of relevance to the thesis work:

Strupeit, L., Neij, L., 2014. *The role of local learning to support emerging energy technologies: the case of photovoltaics in Germany*. 5th International Sustainability Transitions Conference, 27–29 August 2014, Utrecht, The Netherlands (conference paper)

Strupeit, L., 2016. *Streamlining Photovoltaic Deployment: The Role of Local Governments in Reducing Soft Costs*. Energy Procedia, CUE 2015 - Applied Energy Symposium and Summit 2015: Low carbon cities and urban energy systems 88, 450–454. doi:10.1016/j.egypro.2016.06.023

Neij, L., Heiskanen, E., Strupeit, L., 2017. *The deployment of new energy technologies and the need for local learning*. Energy Policy 101, 274–283. doi:10.1016/j.enpol.2016.11.029

Figures and tables

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1 Introduction

1.1 Background

1.1.1 Perspectives on renewable energy innovation

For millennia, energy has been a key driver of the socio-economic development of mankind. In recent decades, however, society has increasingly recognized the environmental downsides of using ever-increasing quantities of non-renewable sources of energy. In particular, climate change has been a centrepiece of scientific and political agendas. The conclusion of the Paris Agreement in November 2016 is considered a milestone in international climate policy and expected to have far-reaching implications for the transformation of the global energy system. In this on-going transition, renewable energy (RE) is a fundamental and growing building block in the collective efforts to hold the increase in the global average temperature to below 1.5–2°C above pre-industrial levels.

In addition to its potential in climate change mitigation, the scale-up of renewable energy use has implications on a variety of further environmental, economic, social and geo-political dimensions. In particular, renewable energy use can reduce the rate of depletion of non-renewable resources and mitigate the environmental impacts associated with their use (Emberson et al., 2012; Turkenburg et al., 2012). The economic opportunities of RE have also been discussed as part of debates on green economic growth (Dai, Xie, Xie, Liu, & Masui, 2016; Pahle, Pachauri, & Steinbacher, 2016), employment creation (e.g. Lambert & Silva, 2012; Lehr, Nitsch, Kratzat, Lutz, & Edler, 2008), and industrial policy (Zhang, Andrews-Speed, Zhao, & He, 2013). Due to its distributed nature, renewable energy can contribute to enhanced energy security (Escribano, Marín-Quemada, & San, 2013; Valentine, 2011), and in particular to reduced energy poverty in the developing regions of the world (e.g. Bhide & Monroy, 2011; Yadoo & Cruickshank, 2012). Distributed RE technologies are also viewed as an opportunity to democratize energy supply and empower energy consumers by enabling them to produce their own electricity (Foxon, 2013).

Given the multiple opportunities associated with the use of RE technologies, comprehensive efforts are being made in supporting their diffusion. Academic debates have emphasized that understanding and managing the scale-up of renewable energy use requires system-oriented and interdisciplinary analytical perspectives, nested into broader debates on energy transitions and technology change. From a disciplinary point of view, energy scholarship has drawn from a broad range of knowledge fields that include engineering, economics, history, sociology, political science and psychology (Sovacool, 2014). Different lines of research have also focused in their enquiries on different analytical levels. These can be distinguished broadly between (1) micro-level concepts that focus on the individual, (2) meso-level concepts between individualistic and structural approaches, and (3) macro-level concepts that investigate social structural contexts (Edomah, Foulds, & Jones, 2017).

Amongst the meso-level approaches in energy scholarship, a significant amount of system-oriented research has focused on the take-up of emerging energy technologies. Key notions and concepts in this literature are technical, organizational and institutional innovation, knowledge creation and learning (Grubler et al., 2012; Sagar & Zwaan, 2006). In particular, innovation is theorized as a collaborative process across a variety of actors that is embedded in and shaped by the institutional context (C. Freeman, 1987; Lundvall, 1992; Nelson, 1993). The role of inter-organizational networks as platforms for resource pooling and learning is widely acknowledged in this field. Innovation pathways have been conceptualized as the result of an iterative and co-creative process that nourishes on the resources of multiple actors and involves multiple dimensions of learning, while recognizing that these pathways are far from linear and easily predictable (Karnøe & Garud, 2012).

The notion of innovation as a collective process is also evident in the broader field of business management and organizational studies. In these more firm-centred perspectives of scholarly enquiry, the concept of customer value creation as a collaboration of a network of firms plays a central role (Teece, 2010). Literature from this field has also recognized the role of dedicated business strategies and business models in the commercialization of cleaner technologies (Boons & Lüdeke-Freund, 2013).

More abstract conceptualizations of innovation and technology change have focused on the economic dimension of learning and innovation. In particular, numerous empirical studies have illustrated the cost dynamics of technologies as a function of experience that accumulates with their diffusion (Arrow, 1962; Wilson, 2012). While the role of *learning* as a driver of cost reduction is widely acknowledged in this literature field, it has also been pointed out that more contextualised and qualitative accounts related to cost reduction are still weakly developed (Winskel et al., 2014). Overall, perspectives related to learning are not very well integrated into the more economics-minded literature on energy technology change.

Energy technology innovation is a multi-step process. It involves the research, development and manufacturing of technology hardware and the subsequent deployment and operation of this hardware in society. However, it is important to note that scholars and policy makers incline to relate innovation processes primarily to the upstream segments of technology value chains, and to science and technology forms of knowledge that is created in formal processes of R&D (Jensen, Johnson, Lorenz, & Lundvall, 2007). In the innovation literature on renewable energy, this affinity with manufacturing and hardware-centred studies is reflected in empirical studies that employ a variety of conceptual perspectives. Examples are studies of innovation systems (Klitkou & Coenen, 2013; Vasseur, Kamp, & Negro, 2013), research about inter-organizational networks between R&D organizations and manufacturing firms (e.g. Choe, Lee, Kim, & Seo, 2016; Zhou, Zhang, Zou, Bi, & Wang, 2012), and enquiries about cost reduction as a function of cumulative experience (e.g. de La Tour, Glachant, & Ménière, 2013; Neij, 1997; Watanabe, Wakabayashi, & Miyazawa, 2000). In comparison, and with a few exceptions[1], system-oriented perspectives on the deployment of technologies and the related downstream segment of technology value chains are still relatively few.

Public policies have played a pivotal role in supporting innovation, learning, market growth and cost reduction of novel energy technologies. The use of public resources for the support of RE technologies has, amongst others[2], been justified with the phenomenon that market growth enables learning and results in the reduction of costs. This in turn may induce cycles of further growth and cost reductions (Sandén, 2005). The debate as to how the rate and direction of technological change can be influenced has centred on the interactions of science and technology push efforts with demand pull initiatives (Nemet, 2009a; Taylor, 2008)[3]. In this context, it is noteworthy that debates on assessments of RE

[1] With regard to PV value chains, some notable exceptions include Dewald and Truffer's (2011) research on the formation of PV markets and Shum and Watanabe's (2008) work on a local learning model of PV deployment.

[2] Other rationales commonly put forward in advocacy for the public support of renewable energy relate to sustainability goals, industrial policy, regional development, and employment creation.

[3] Examples of supply side policies include R&D policies (Ragwitz & Miola, 2005) as well as support of field trials and public demonstration projects (J. Brown & Hendry, 2009). The broad portfolio of demand side policies include, amongst others, feed-in tariff schemes (Couture & Gagnon, 2010; Hoppmann, Huenteler, & Girod, 2014), renewable portfolio standards (Espey, 2001; R. Haas et al., 2011), direct subsidies (Reinhard Haas, 2003), tax credits (Coffman, Wee, Bonham, & Salim, 2016), and a variety of financing programmes (Deng & Guo, 2017).

demand-side policies are often dominated by rational choice theory and traditional assumptions from neoclassical economic theory. This has led to a situation where descriptors to assess RE technologies are typically condensed to economic parameters, such as levelized-cost-of-electricity, return-on-investment, and payback time. Given the complexity of the energy technology innovation process, advocacy for the recognition of multiple social science concepts in energy scholarship is, however, on the rise. In particular, there have been calls for more integrative energy policy making and the broader engagement of non-economic social and behavioural sciences in the design and assessment of policies (Stern, 2017; Stern et al., 2016).

To sum up, despite the rich literature on innovation, learning and cost reduction, and the variety of policy mechanisms that support these processes, relatively limited attention has been dedicated to the *downstream segment* of RE value chains. In particular, non-technology aspects of knowledge, learning and related processes of organizational and institutional innovation are not well understood. Also, the drivers and dynamics of non-technology costs associated with the *deployment* of RE remain a research area that requires more profound exploration and understanding.

1.1.2 Solar photovoltaics: past, present and potential future

As stated above, the continued diffusion and scale-up of renewable energy technologies will be critical to meeting pressing sustainability challenges. In the portfolio of RE technologies, solar photovoltaics (PV) is considered one of the most promising options with regard to its theoretical and economic potential. Therefore, this thesis focuses thematically on the deployment of PV.

Amongst the different energy technologies, the direct conversion of solar radiation into electricity through PV technology exhibits some unique features. Compared to established and centralized power generation technologies PV is considered a *radical architectural innovation* (Awerbuch, 2000) and *disruptive technology* (Schleicher-Tappeser, 2012) as it (1) benefits from the economies of scale and learning in industrial mass production, (2) has much shorter implementation cycles, (3) is extremely scalable with flat economies of scale in terms of technical and financial performance, and (4) can generate electricity “behind” the utility meter at the point of consumption, with minimal maintenance, zero emissions and a low-noise profile. The modular nature of PV and its flat scale-economies have enabled a broad portfolio of applications. Typical capacities of grid-connected PV applications range from the single-digit kilowatt range installed on buildings to utility-scale multi-megawatt solar farms[4]. In line with the diversity of applications, ownership structures of PV systems are wide-ranging and include building owners, farmers, local citizen initiatives, municipalities, as well as utilities and investment funds.

Since the discovery of the photovoltaic effect at the end of the 19th century, the deployment of PV technology has come a long way. The first silicon mono-crystalline cell was created in 1941, opening the path initially to space applications and subsequently to a multitude of terrestrial applications from the micro-scale to large solar farms. PV technology has made significant technological advancements and the manufacturing and deployment of PV systems has become a multibillion-dollar business. Since the 1990s, the global PV market has expanded exponentially at growth rates previously unanticipated and underrepresented in even the most optimistic projections by the International Energy Agency (Haegel et al., 2017). By end of 2016, the globally installed capacity exceeded 300 GW, which is 50 times higher than in 2006 (IEA, 2017a). This capacity contributes about 1.8% of global electricity production (IEA, 2017a) and reduces global CO_2 emissions by 200-300 million tonnes annually (IRENA, 2017). Adoption of PV is geographically highly uneven, with China (78 GW), Japan (43 GW), Germany (41 GW), the United States (40 GW), and Italy (19 GW) collectively hosting almost three quarters of the cumulative installed capacity, as of the end of 2016 (IEA, 2017a).

PV is expected to continue to grow and become a key building block in the global energy transition, although the anticipated pace of diffusion is unclear. A review of eleven prominent energy transition scenarios shows that the expected global PV capacities range from 950–3725 GW by 2030, and 6745–32 700 GW by 2050. According to these scenarios, PV could account for 4.1%–15.9% (2030) and 19.9%–29.0% (2050) of worldwide electricity generation (Breyer et al., 2017).

Since the first use of PV in space in the 1960s, the foremost type of terrestrial applications evolved initially from off-grid applications (1970s-1980s), towards distributed grid-connected applications (1990s), and today's large-scale PV power plants (as of 2000). In 2016, utility-scale PV installations accounted for about 72% of new PV capacity additions, with the remainder being rooftop and off-grid systems (REN21, 2017). In spite of some of the drawbacks occasionally associated with utility-scale PV[5], this market segment is projected to continue to flourish

[4] In 2017, China's Yanchi project in Ningxia was reported to be the world's largest PV plant, at 1 GW capacity (REN21, 2017).

[5] At the regional level, challenges to the growth of utility-scale PV may include grid integration, land shortage (REN21, 2017), public acceptance (Carlisle, Solan, Kane, & Joe, 2016) and environmental impacts (Hernandez et al., 2014).

along with a diverse range of distributed PV applications in the residential, commercial and industrial sectors, as well as in rural areas and in various niche markets (IRENA, 2017). In particular, the scope of building-sited applications is expected to expand, with PV increasingly being integrated into buildings and gradually becoming an integral part of new architectural concepts in urban planning. The global technical potential of solar rooftop PV in cities alone is estimated at 5400 GW. This capacity could meet 30% of the electricity needs of cities in 2050 (IEA & OECD, 2016). Rooftop PV can also make a significant contribution to national electricity systems. For example, the technical potential of PV systems installed on existing roofs within the United States has been calculated to amount to about 39% of national electricity demand (Gagnon, Margolis, Melius, Phillips, & Elmore, 2016).

A key driver behind market development has been the declining costs of PV technology, in particular the rapid fall in the costs of PV modules. Nowadays, utility-scale projects have become economically competitive with new fossil fuel-based generation in a number of regions (IRENA, 2017). On the other hand, small-scale rooftop PV has higher specific upfront costs than utility-scale installations. However, the ability of households to substitute higher-priced utility power with self-generated solar electricity has made distributed PV cost-competitive in a number of regions, such as Australia, Denmark, Germany, Italy, Spain, parts of the US and many island states (IRENA, 2017).

It is expected that continued innovation of PV technology hardware (modules, inverters, mounting systems) will be a key feature and driver of future market growth and diversification. Present technologies will further advance incrementally and new concepts, such as new types of PV cells, may become commercialized (Arvizu et al., 2011; Subtil Lacerda & van den Bergh, 2016). Importantly, the costs of different PV hardware components are expected to decline further (de La Tour et al., 2013; Haegel et al., 2017; IEA/OECD, 2014; Mayer, Philipps, Hussein, Schlegl, & Senkpiel, 2015; Ringbeck & Sutterlueti, 2013), thereby enhancing the competitiveness of PV versus other energy technologies.

1.1.3 The need to advance knowledge in relation to deployment

Despite the prospects for continued development of PV technology hardware, the scale-up of PV around the world involves particular challenges in relation to the deployment phase at more local levels. The central point of departure for this thesis is the observation that *downstream* segments of the PV value chain and related processes of deployment are less well understood, in particular from a system-oriented perspective.

Before moving on and reviewing the specific challenges associated with the deployment of PV, some clarification of what actually comprises "*deployment*" will be useful. Various related terminologies have been used in the literature to describe the development and implementation of new technologies. The term *innovation* is typically used to describe the entire process of developing a new technology and putting it into widespread use. *Diffusion* of technology typically describes the increased uptake of an invention without pointing to any particular part(s) of the value chain. The term *adoption* generally refers to the implementation of technologies from the perspective of users at the downstream end of the value chain. The *deployment* of a technology essentially refers to the activities associated with its diffusion at the downstream segment of the value chain, building the link between manufacturing of technology hardware and its operational phase.

On a descriptive level, PV deployment can initially be characterized by the related activities, the knowledge base and the composition of actors involved. Key activities include distribution of PV components, planning, installation, compliance with legal-regulatory requirements, finance, insurance, customer acquisition and the integration into grid and building infrastructure. Furthermore, the integration of distributed, intermittent renewable resources into the electricity system and associated power markets requires amendments in electricity market designs and the provision of reserve and storage capacities (Mateo, Frías, Cossent, Sonvilla, & Barth, 2017). These activities link up to a variety of knowledge fields related to planning, installation, grid integration, electricity market design, building law, finance, operation and maintenance. Although the role of these forms of non-technological *deployment knowledge* for the effective deployment of RE technologies has in principle long been recognized in concepts such as "*software*" and "*orgware*" (Dobrov, 1978), empirical and more system-oriented research enquiries are relatively rare and fragmented.

In terms of actor structure, the composition of stakeholders directly or indirectly involved in PV deployment differs fundamentally from structures in (conventional) centralized modes of electricity generation and distribution. This can be explained by the specific nature and modularity of distributed PV (see 1.1.2). In particular, deploying distributed PV relies on the engagement of actors that traditionally have not been associated with the production of electricity. Figure 1 provides an overview of the principal landscape of actors along the PV value chain. Core firms in the downstream segment of the PV value chain typically comprise a variety of firms such as wholesalers, planners, architects, consultants, installers and maintenance firms. In addition, PV deployment involves a range of actors with auxiliary functions. These include utilities, financiers, insurers, standardization bodies and solar initiatives as well as various governmental bodies and local authorities[6]. Last but not least, users of distributed PV such as households, farmers, commercial building owners and municipalities start engaging as *prosumers* in the generation of electricity.

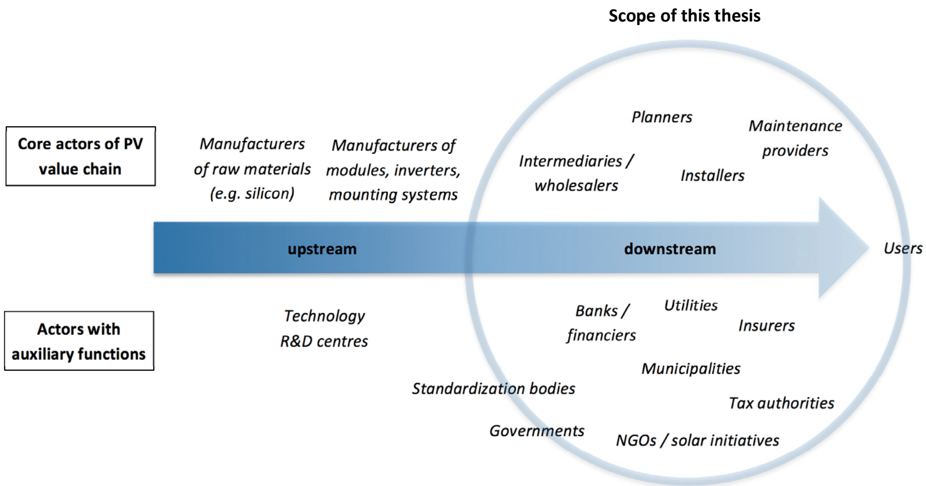

Figure 1: Landscape of core and auxiliary actors along the PV value chain[7]

[6] A key actor group in the downstream segment of the value chain are installation firms that plan and install PV systems on buildings. Installation firms can also be the actor that actually sells the PV system to the building owner and final user. In some markets, other types of firms such as so-called solar service firms, housing manufacturers or utilities market PV systems and serve as the key focal point for customers. Being located at the downstream end of the PV value chain, these firms are critical in offering the value proposition to customers and users. Furthermore, local utilities or distribution system operators that connect PV systems of third-party operators to their grid play an important role in the integration of PV systems to existing electricity grid infrastructures. Local governments have responsibilities to ensure compliance with public health, safety and design standards, and are thereby involved in the permission and inspection processes for new PV systems. Finally, another important stakeholder group are financers, such as banks, that issue loans to homeowners for the purchase of PV systems.

[7] It is noteworthy that the role and positioning of actors along the PV value chain may vary significantly across different geographies and market segments. Nor is there any clear-cut delineation between the upstream and downstream segments. While physical artefacts such as PV system components are primarily channelled towards the downstream end of the value chain, knowledge flows can be bi-directional. For example, knowledge and learning gained in the deployment of PV is fed back to upstream producers who may incorporate experience from the field into product innovation.

As elaborated earlier in Chapter 1.1, energy scholarship has directed less attention to intermediary links and associated deployment processes between the manufacturing and use of PV technology. There may be various reasons that can explain this inclination towards upstream parts of the value chain. Deployment of PV involves a highly heterogeneous and fragmented actor landscape, typically having attributes that are specific to distinct geographies (Neij, Heiskanen, & Strupeit, 2017), jurisdictions and market segments. This fragmentation generally impeded empirical enquiries, in particular in comparison to the more concentrated actor landscape in manufacturing and R&D. Furthermore, methods and frameworks in the traditional innovation literature are biased towards the analysis of R&D organisations, manufacturing firms and the related science and technology knowledge base. In particular, methods to approximate scientific R&D knowledge via patents are well established, while on the other hand the techniques to account for the different types of deployment knowledge are still in an infant stage.

Other methodological challenges occur in the quantification and assessment of soft deployment costs and in disentangling their drivers. Soft costs vary significantly in their nature and order of magnitude by country, by market segment and by the size of PV systems. Techniques to track and benchmark soft deployment costs over time and across different geographies are demanding and have not received much attention for long. For decades, research on the cost reductions of PV has focused on the single biggest cost item, i.e. PV cells/modules, where cost data have been more readily available. As a result of these conceptual and methodological issues, deployment processes and the assessment of soft cost dynamics have largely been beyond the radar of the broader technology change literature. Only recently, and along with the decline in hardware costs, more attention has been directed to the significance of soft deployment costs (Garbe, Latour, & Sonvilla, 2012; Seel, Barbose, & Wiser, 2014). This also involved efforts to establish more consistent methods and routines for the quantification of soft costs. The significance of soft costs and the need to address them is increasingly recognized in academic and policy debates, however. Recent assessments by the International Renewable Energy Agency emphasized in particular the need to understand the drivers of soft cost reductions (IRENA, 2016), with the aim to enhance the competitiveness of PV across a wider group of countries. Responding to these contemporary needs, this thesis explores and further opens up the knowledge field about the downstream segment of the PV value chain and associated processes of deployment. Greater analytical insights and a diagnostic understanding of deployment systems are critical for policy and managerial efforts to enhance the competitiveness of PV and accelerate its international scale-up. This also involves the development and testing of analytical tools for the study of these systems.

In this thesis, key deployment-related challenges that were initially identified relate to (1) the role of actors and associated learning in deployment, (2) the role of soft costs and other barriers in relation to deployment, and (3) the geographic widening of the market base. Firstly, and as elaborated above, the deployment of distributed PV relies primarily on the engagement of a multitude of firms, public actors and users. The engagement of diverse societal groups in the deployment and adoption of novel technologies has previously been brought in connection with various dimensions of learning related to technical change (e.g. Markusson, Ishii, & Stephens, 2011; Williams & Edge, 1996). Learning processes have been found to link to the shaping power of discourses (Rohracher, 2001), the construction of meaning of technical artefacts by social actors (Rohracher, 2001), how innovation is communicated among the members of a social system (Dearing, 2009; Rogers, 2003), how consumers integrate new technologies in their practices, organizations and routines (Lie & Sørensen, 1996), and how users lead and participate in innovation processes (Ornetzeder & Rohracher, 2006).

The outcomes of learning have been conceptualized from various angles. Whereas higher-order learning leads to the modification of values, attitudes and underlying convictions (H. S. Brown, Vergragt, Green, & Berchicci, 2003; Kamp, 2007), the concept of first-order learning captures the optimization of existing routines, practices and systems (Sol, Beers, & Wals, 2012). For example, first-order learning captures performance improvements and cost reductions of the production, installation and operation of the technology itself (Sagar & Zwaan, 2006). Learning related to technology implementation has multifaceted outcomes including reduced uncertainty, increased customer awareness, clarification of institutional barriers, provision of technical credibility to customers, increased public acceptance and reduced stakeholder opposition (J. Brown & Hendry, 2009). Building on these perspectives, this thesis considers deployment-related learning and knowledge creation to be of vital importance in the quest for the wider diffusion of PV.

Secondly, broadening the portfolio of applications of PV and increasing its global uptake will also require continued enhancements of the competitiveness[8] of PV vis-à-vis other energy sources. For distributed PV applications in particular,

[8] Originally used for the analysis of firms, the notion of competitiveness has become a prominent concept in the assessment of countries, regions and locations (Aiginger, 2006). A widely used definition refers to competitiveness as “the ability and performance of a firm, sub-sector or country to sell and supply goods and services in a given market, in relation to the ability and performance of other firms, sub-sectors or countries in the same market” (Hasan & Hacioglu, 2013). The term competitiveness has also been used with regard to renewable energy technology, primarily in the meaning of cost- and economic competitiveness (Fu et al., 2015; Gowrishankar, Hutton, Fluhrer, & Dasgupta, 2007; Tinker & Jones-Albertus, 2016) and the ability of RE technologies to compete with established modes of electricity generation in terms of levelized cost of electricity.

deployment-related factors critically determine the level of soft (deployment) costs, as opposed to the *hard costs* for PV components (module, inverter, mounting system, cables, etc.)[9]. Soft deployment costs include labour costs, permit and insurance fees, as well as a variety of transaction costs associated with business transactions and compliance with different legal-administrative requirements. In essence, soft costs mirror the activities carried out in the deployment system.

As PV deployment is subject to many local factors, their level (per kW) can vary significantly depending on the geography, such as a country. They can also differ significantly by market segment and system size (IRENA, 2015). Importantly, soft costs can make up a major share of the upfront cost of PV. For example in the United States in 2016, soft costs accounted for a significant portion of total installed PV system prices: 58% of the total residential system price, 49% of the price for medium-sized (10 kW – 2 MW) commercial systems, and 34% of utility scale (>2 MW) system prices (Fu et al., 2016). In Europe, deployment-related soft and transaction costs have been found to vary by several orders of magnitude between different countries (Barth et al., 2014; Garbe et al., 2012). Figure 2 illustrates the significant differences in costs that arise due to various legal-administrative processes in deployment across 13 European PV markets.

Considerable opportunities remain to reduce the levelized cost of PV electricity with and across regions, specifically by reducing soft costs. In particular, it has been highlighted that reducing the current differentials between markets for these costs presents a significant cost reduction opportunity (IRENA, 2015). If soft costs remain unaddressed, their proportion in the economics of PV will continue increasing as technology costs continue to decline. Excessively high soft costs are likely to hamper the global scale-up of PV, partly because incentive schemes in policy-driven markets need to offer overly high rates of support in order to compensate for prohibitive soft costs. It is therefore critical to understand how best-practice levels have been achieved.

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[9] Prior work has not delimited and labelled soft costs very consistently, a situation that may be explained by their heterogeneity and complexity. In the literature, these “soft costs” – together with the costs for inverter, mounting system and cabling – are commonly referred to as “balance-of-system (BOS) costs” or “non-module costs”. However, the concept of the BOS is not uniformly defined and therefore “BOS costs” are not comparable across different studies.

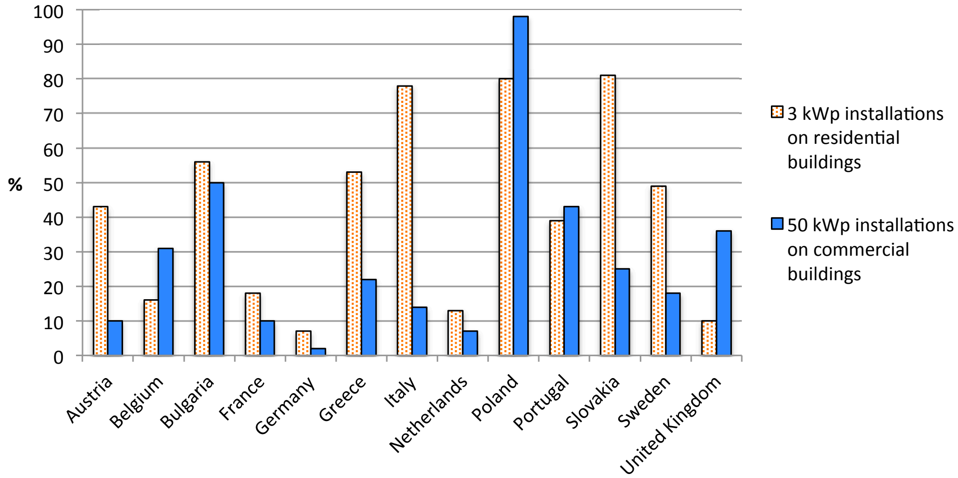

Figure 2: Share of legal-administrative costs as a proportion of deployment costs (excluding PV hardware) in ca. 2013 (Barth et al., 2014)

In addition to focusing on the nature and dynamics of soft deployment costs, this research emphasizes the need for a broader perspective in relation to the notion of PV competitiveness. Prior work has shown that the motives of PV adopters extend beyond economic motives and also involve non-economic instrumental motives, environmental motives and symbolic motives (Bergek & Mignon, 2017). Current and prospective adopters are also highly heterogeneous populations. For example, comparative research on adopters and non-adopters of PV has displayed significant variations in the perception of risk between these two groups (Sonnberger, 2014). Furthermore, literature has pointed to the importance of the removal of various barriers and transaction costs to adoption, such as consumer inertia, high up-front cost, long payback periods, efforts associated with the planning and installation steps, various informational gaps and customer concerns about PV reliability (Rosoff & Sinclair, 2009; Shih & Chou, 2011; Yang, 2010). In terms of adopter groups, the mobilization of mainstream consumers will be particularly important, as early adopter markets already appear to become saturated in some countries (REN21, 2017). It has been argued that mainstream consumer groups particularly appreciate aspects such as affordability, visual attractiveness, low maintenance, provision of added value to the property and a simple installation process (Faiers & Neame, 2006).

Thirdly, another set of challenges to the scale-up of PV in the context of a global energy transition relates to the geographic widening of the market base. At present, a significant share of globally installed PV capacity is located in a relatively small number of countries and deployment remains geographically highly uneven. While PV met a substantial share of electricity demand in several countries throughout 2016, including Honduras (9.8%), Italy (7.3%), Greece (7.2%) and Germany (6.4%) (REN21, 2017), the rate of deployment has remained marginal for most countries. Currently installed capacity only accounts for a fraction of what could be possible in the future.

In this regard, it is a promising signal that the political interest in renewable energy has gained significant momentum. By the end of 2016, 176 countries had established renewable energy targets, with 150 of them having set specific targets for renewable electricity (REN21, 2017). Although these commitments are critical and demonstrate the widespread interest to scale up renewable energy, they can only provide the initial foundation for the formation of national RE deployment systems. This will require the enactment of dedicated policies and the regulatory framework, the development of deployment-related stakeholder and knowledge capacities, and the formation of value chains for deployment[10]. For follower countries, significant opportunities prevail to benefit from the experience of pioneering countries in PV deployment. Unlike codified forms of science and technology knowledge, deployment knowledge does not diffuse as easily across borders. Skills and knowledge associated with deployment are often of a more tacit nature (Neij et al., 2017) and actors engaged in the deployment of small-scale energy technologies often have fewer ties to international partners. Overall, however, the experience in the international co-creation and exchange of PV deployment knowledge remains inadequately understood.

1.2 Problem definition

The review, as elaborated in the previous sections, clearly demonstrates that a number of questions related to the deployment of PV are unsatisfactorily addressed in the broader literature on energy technology change. Particularly for distributed applications of PV, understanding and managing deployment-related activities are critical in order to support the technology's competitiveness and its wider geographic diffusion. Overall, the research in this thesis has its point of departure in the following gaps in knowledge.

Firstly, in the domain of scholarship related to innovation, system-oriented research approaches that focus on the deployment stage of energy technologies have been relatively scarce, as opposed to the upstream-centred studies. In

[10] Nowadays, standardized PV system hardware components are commercially traded and widely available, principally eliminating the need for follower countries to build up their own manufacturing capacities.

particular, knowledge about deployment-related structures and processes, including the nature and interplay of actors, networks, institutions and knowledge is inadequately developed. Such knowledge, however, is critical as a foundation for the sound management of PV deployment through policy and business initiatives.

Secondly, from an analytical point of view, there is a need for more integrated perspectives between different fields of research that developed in relative isolation from each other. For example, in the conceptualization of technology change, linkages between innovation system concepts and the literature on cost reductions and experience curves hardly prevail. This isolation of related research streams is problematic as it constrains more holistic insights into patterns of technology change and cost reduction, including transaction costs.

Thirdly, notions of the competitiveness of PV have often focused on financial aspects and the questions of cost-competitiveness vis-à-vis other energy sources. Broader perspectives that also consider non-economic motives of adopters and deployment-related barriers and transactions are relatively poorly understood in discussions about PV competitiveness. This aspect closely links up with the observation that academic and public debates on renewable energy support are often dominated by techno-economic approaches and cost debates. As a consequence, the debate on policy instruments often centres on a limited a number of specific instruments for market creation, such as feed-in tariff schemes, renewable energy quotas and subsidy schemes. However, this debate may not fully account for the real-life complexities in the deployment of PV.

Fourthly, a review of the literature revealed an overall lack of understanding about the role of *deployment structures and processes* in relation to the competitiveness of PV. In particular, there is scarcity of empirical evidence as to whether and how the softer costs associated with PV deployment decline as a function of cumulative experience in deployment. Nor is it well understood how solar firms, through dedicated business strategies, are able to reduce barriers typically associated with the adoption of PV.

Fifthly, the prominence of the techno-economic paradigm is also reflected in an overall tendency of *policy assessment frameworks and studies* to focus on upstream aspects (R&D knowledge, technology, manufacturing) and economic parameters of PV. In general, assessment of public policies is critical for understanding their actual effects (via ex-post assessments) or expected effects (via ex-ante approaches) (Fischer, 1995), with the aim to support decision-making. Any policy assessment is grounded on a conceptual framework, which determines methodological procedures as well as the types of effects that are captured. For the evaluation of renewable energy policy, a variety of conceptual approaches exist, including quantitative, qualitative and hybrid models that all have their respective strengths and weaknesses (Horschig & Thrän, 2017). In the empirical assessment of PV policies, upstream-centred studies have often focused on the effects of policy on R&D knowledge and technological advancements (Curtright, Morgan, & Keith, 2008; Park et al., 2013; Watanabe et al., 2000). In addition, diffusion-oriented evaluations have often addressed questions about how demand-side policies affect economic performance of PV (Campoccia, Dusonchet, Telaretti, & Zizzo, 2014; Dusonchet & Telaretti, 2015; Sarasa-Maestro, Dufo-López, & Bernal-Agustín, 2013) and to which degree they effectively boost PV diffusion (Hafeznia, Aslani, Anwar, & Yousefjamali, 2017; Sarzynski, Larrieu, & Shrimali, 2012). Often, there is a tendency to assess the isolated effects of single policy instruments, such as feed-in tariff schemes or net-metering policies, as opposed to investigations of more comprehensive policy packages. Overall, aspects related to downstream structures in the PV value chain and associated processes in deployment are not given much attention in current policy assessment frameworks. Consequently, empirical enquiries into the effects of policy on deployment-related aspects, aside from the diffusion rate and economic parameters, are relatively few. In particular, critical underlying drivers that are potentially important for the effectiveness of deployment policies are typically not part of the investigative questionnaire of the frameworks that are commonly used for the assessment of PV policies. These drivers may include various factors, such as stakeholder learning, creation of deployment knowledge, removal of non-economic barriers, as well as cost reduction. The disregard of deployment-related aspects in standard frameworks for policy assessment is a limiting factor in effectively informing the decision-making process towards more integrated and holistic PV deployment policies.

In sum, the review unveiled the need to obtain a more comprehensive, system-oriented understanding on PV deployment, thereby providing the rationale for this research. The thesis denotes this system-oriented perspective with the notion of *socio-economic structures of the deployment system of PV*, in short a *PV deployment system.* It is important at this point to note that the notion of a PV deployment system does not imply the presence of a single global system, but rather a conceptualization of a patchwork of national-scale systems that are interconnected with each other. Presumably the internal dynamics of domestic deployment systems are shaped by influences external to the nation state. In particular, exchange and spillover of deployment knowledge from other countries may be important in this respect. As another gap in knowledge, the research identified the need to better understand the international dimension of learning in relation to PV deployment.

1.3 Objective and research questions

Pursuant to the knowledge gaps, the *objective* of this research is to advance knowledge about the emergence of socio-economic structures related to PV deployment and how the development of these structures contributes to the enhanced competitiveness of PV. By focusing on this objective, the research aims to support policy development and business management processes in relation to the scale-up of PV in the context of a global energy transition.

To address the objective, the following *research questions* (RQ) were chosen to enquire specific aspects of the research. These questions were approached through the analysis of experiences in PV deployment in several countries, with a focus on Germany, as well as Japan and the United States.

RQ1: How have the emergence of deployment-related inter-agent relations, knowledge base and institutional context formed a PV deployment system?

RQ2: How have public policies and business initiatives shaped these processes?

RQ3: How has the formation of a deployment system contributed to a decline in (soft) deployment costs, transactions costs and other barriers?

The research uses an interdisciplinary, multi-level and system-oriented research approach to assess selected empirical experiences of socio-economic structures related to PV deployment. In addition to its value for the scientific community, the outcomes of the research offer various implications to decision makers. As such, the research is applied and policy-oriented. It follows along the traditions of evaluative forms of research, regarding the analysis of past experiences to serve as a useful learning arena and source of knowledge for future decision-making. In the energy and technology domain of evaluative research, an underlying belief is that energy markets and technology are susceptible to human manipulation through various causal factors, such as policy and business decisions. In particular, it is believed that policy and business decisions can influence the innovation and market adoption of new technologies, such as PV. Knowledge provided by applied forms of science, as presented in this thesis, is regarded as having instrumental value to support decision-making.

1.4 Research scope and delimitations

In addressing the overall research objective, the scope of the research is delimited in a number of dimensions, such as technology, applications and market segment, value chain section, geography, temporal scale and unit of analysis.

In terms of the *technological scope*, the four research papers consistently deal with the deployment of photovoltaic technology, regardless of any specific cell or module technology. With regard to *applications*, the research focuses on distributed, grid-connected PV. Grid-connected PV, as opposed to stand-alone applications, has accounted for the large majority of all PV installations and in recent years it made up more than 99% of new capacity (IEA, 2016). Grid-connected PV is also expected to remain the dominant application in the foreseeable future. Pursuant to the overall research objective, the thesis focuses on deployment-related aspects, of which the *downstream* segment of the *PV value chain* is of central relevance.

In terms of the *market segment*, Papers I–III focus on building-sited PV. Particularly in densely populated high-income regions, building-sited PV is the preferred application as it allows building owners to make use of existing building surfaces and does not require additional land. Paper IV exhibits a somehow broader thematic scope, as the empirical data sets used in this study were of relevance to both building-sited as well as on-ground PV applications. As elaborated in Chapter 1.1, knowledge about deployment-related aspects is particularly needed for distributed applications of PV, such as building-sited PV.

In terms of *geographical scope*, Papers I–III examine the experience gained in a number of pioneering countries that have demonstrated an extensive and relatively long experience in the deployment of PV. Paper IV has a broader geographical scope, involving organizations from 55 countries with most of them being members of the European Union (EU) and/or the Organization for Economic Development and Co-operation (OECD). The choice of this geographically broader data set was critical for exploring the international dimension of deployment-related knowledge creation and exchange.

One pioneering country in PV deployment that has received particular attention in the research is Germany. The German experience serves as a single-case study in Papers I and II, and as one out of three cases in Paper III. It is also part of Paper IV. The selection of Germany as a prominent case in this thesis is justified by a number of reasons. Firstly, Germany has been one of the true pioneers in deploying distributed, grid-connected PV, and it has gained substantial experience over the years[11]. While some countries with larger populations (China, the United States, Japan) have – due to the rapid deployment of utility-scale on-ground PV – gained higher cumulative capacities, Germany still remains a country with a high proportion of and significant experience in distributed *building-sited* PV (IEA, 2017b; SolarPower Europe, 2015). Secondly, the soft deployment costs of PV in Germany are amongst the lowest in comparison to other major PV markets (IRENA, 2016), which justifies this empirical choice in relation to the objectives of the research. The choice of the United States and Japan as additional case studies in Paper III is justified with their experience in distinct PV business models. In all, the geographical scope of the research represents some of the largest and most experienced PV markets (Papers I, II, III), as well as the network interactions between countries with different levels of deployment (Paper IV).

Pursuant to the research objective, the research takes a retrospective vantage point. The use of longitudinal research designs (Papers I, II, IV) allowed the study of temporal developments, while a snapshot approach (Paper III) enabled greater descriptive thickness and analytical depth in a comparative research design. The longitudinal studies stretch over periods of two to three decades, covering developments from the inception of distributed, grid-connected PV around 1990 up to the present. The temporal perspective is closely related to distinct phases of the technology lifecycle[12] of grid-connected, distributed PV, covering demonstration, early adoption and the growth phase.

In terms of the social unit of analysis, the four research papers have different foci on different aspects relating to PV deployment. The units of analysis comprise a cost model of a PV project (Paper I), an innovation system related to PV deployment (Paper II), a business model (Paper III), and inter-organizational network ties (Paper IV). The combination of a variety of analytical units enabled the assessment of experience in PV deployment through complementary investigative perspectives.

[11] Germany has for a number of years been the market with the highest cumulative capacity in the world and still had the highest installed wattage per capita in 2016 (IEA, 2017a).

[12] The concept of the technology lifecycle describes the consecutive phase a technology passes through its lifecycle, from basic research towards large-scale commercialization. Generally, it is broadly distinguished between the phases of basic research, applied development, demonstration, early adoption, growth phase and maturation.

1.5 Research process and papers

In this thesis, the experiences gained in the deployment of PV systems have been examined in a collection of four research papers; see Table 1. The papers were sequenced in a distinct order, where findings obtained in the earlier research studies triggered new questions that affected the design of subsequent studies. In this sense, the order of papers is a reflection of the actual research process.

Firstly, the research in Paper I gives an overview of the scale and composition of costs for the deployment of distributed PV systems. The results gained in this paper provided the knowledge foundation for subsequent stages of the research. Specifically, Paper I maps the processes and associated costs of PV deployment, and shows that an increase in *cumulative experience* resulted in reductions of deployment-related soft costs. These findings triggered a set of new questions about what actually comprises cumulative experience in deployment, how it can be conceptualized, and how it drives reductions in soft cost. Obtaining these more granular insights was considered critical knowledge that is required for the targeted management of deployment-related processes, for example via public policies. Next, and building on the findings of Paper I, Paper II offers an explanatory, theory-based perspective on processes and drivers of soft cost reduction. In essence, Paper II conceptualizes the formation of a selected national PV deployment system and offers an explanatory perspective how various processes in this system contributed to the reduction of soft costs.

In addition to the mapping of upfront costs, the results of Paper I also charted a set of other deployment-related barriers and non-monetary transaction costs. These barriers and transaction costs arise primarily at the interface between users, firms and other organizations. Yet the research in Paper II dedicated limited attention to firm-user interactions in the value chain, and in particular it did not explore how solar firms employ various strategies to reduce customer-sited barriers to the adoption of PV. Therefore, the research design of Paper III directed the analytical focus towards the firm-user segment of the value chain. Specifically, the study assesses the role of various business models in overcoming barriers to PV adoption.

Papers I, II and III analyse experiences gained towards more competitive PV deployment at domestic levels. Germany, Japan and the United States served as cases, representing pioneering countries in PV deployment. During the research process of the thesis, questions emerged about the international, trans-border dimensions in the creation and exchange of deployment knowledge. These questions were further inspired and reinforced after reviewing prior research on global innovation processes and international knowledge collaboration in module manufacturing (Choe et al., 2016; Wu & Mathews, 2012). They eventually led to the design of Paper IV, focusing on the analysis of international collaboration on PV deployment knowledge.

Table 1: Research papers and contributions by the author of this thesis

Publication	Title	Contribution
Paper I	Strupeit, L., Neij, L., 2017. *Cost dynamics in the deployment of photovoltaics: Insights from the German market for building-sited systems*. Renewable and Sustainable Energy Reviews 69, 948–960. doi:10.1016/j.rser.2016.11.095	The researcher (first author) contributed to the design of the research framework, conducted all data collection, carried out the majority of the analysis and wrote most of the article.
Paper II	Strupeit, L., 2017. *An innovation system perspective on the drivers of soft cost reduction for photovoltaic deployment: The case of Germany.* Renewable and Sustainable Energy Reviews 77, 273–286. doi:10.1016/j.rser.2017.04.011	The researcher (single author) conducted all of the research and analysis, and wrote the entire article.
Paper III	Strupeit, L., Palm, A., 2016. *Overcoming barriers to renewable energy diffusion: business models for customer-sited solar photovoltaics in Japan, Germany and the United States*. Journal of Cleaner Production, Advancing Sustainable Solutions: An Interdisciplinary and Collaborative Research Agenda 123, 124–136. doi:10.1016/j.jclepro.2015.06.120	The researcher (first author) designed the research framework and literature review, conducted data collection for two of the three case studies, and carried out the majority of the analysis. The researcher wrote most of the article.
Paper IV	Strupeit, L. *International collaboration on deployment knowledge for the diffusion of solar photovoltaics: A network analysis* (submitted)	The researcher (single author) conducted all of the research and analysis, and wrote the entire article.

1.6 Target audience

The findings of the thesis are of value for a variety of stakeholder groups interested in understanding socio-economic structures and processes in relation to the deployment of solar PV. The research follows along the lines of system-oriented and interdisciplinary traditions, and is therefore of value to an academic audience with an interest in gaining more holistic insights into processes of innovation, deployment and technology change. Furthermore, scholars with specific interests in technology learning, business model innovation, technology transfer, and energy policy-related questions also belong to the intended audience of this research.

The research is applied and aims to generate knowledge for intentional action with the aim to catalyse the scale-up of PV diffusion as part of a global transition towards low-carbon energy systems. As such, and in addition to the academic community, the research aims to provide diagnostic knowledge for action for practitioners in policy making and business. In particular, policy makers that engage in the design of deployment policies for PV may benefit from the system-oriented research approach. Findings may be of particular value to policymakers who seek to purposefully reduce the levels of soft deployment costs in their jurisdictions. As such, the research can be of use to municipalities as well.

The findings of the research are also of value to business practitioners, in particular managers of firms that – directly or indirectly – engage in the deployment of PV. This group of firms can include PV distributors and installation firms, solar service firms, utilities, and financers.

1.7 Thesis outline

This thesis is organized around six chapters and a compilation of four appended research articles.

Chapter 1 primarily outlines the broader field of study, the definition of the research problem, as well as the objective and overall scope of the research.

Chapter 2 presents the theoretical and conceptual background to the research developed in this thesis. Specifically, it summarizes four different concepts and elaborates how the combination of these approaches forms an interdisciplinary, multi-level framework applied to pursue the research objective.

In *Chapter 3*, the design of the research and methodological choices made are explained. Specifically, the chapter explains the ontological and epistemological position of the research, describes methods of reasoning, the units of analysis, as well as the methods for data collection and analysis. It also discusses parameters to judge the validity and reliability of the findings.

Chapter 4 presents a summary of the main findings from the four research articles, organized on a paper-by-paper basis. In addition to the presentation of findings from the individual papers, the chapter also elaborates how the papers are inter-related and build upon each other.

The aim of *Chapter 5* is to highlight the main results and contributions of the thesis as a whole. Based on the collective results of the research papers, the chapter presents answers to the research questions of the thesis. Furthermore, the chapter summarizes the conceptual and methodological contributions of the research, it presents implications for policy makers and business practitioners, and it identifies issues for further research.

The thesis finishes off in *Chapter 6* with a brief summary of key conclusions derived from the research.

2 Theoretical and conceptual perspectives

This chapter presents the theoretical and conceptual background to the research developed in this thesis. Recognizing the rich portfolio of theories and concepts in the scholarship of technology change, and bearing in mind the research objective and questions of this research, several conceptual choices were made that were intended to improve a systemic understanding of experiences gained in the deployment of PV. Specifically, four different conceptual approaches served as the guiding framework. This chapter starts off with an elaboration of how these different analytical perspectives are interrelated and complement each other. Subsequently, the four chosen conceptual approaches are introduced in greater detail.

2.1 An interdisciplinary, multi-level and system-oriented framework

The research is guided by a number of different theoretical and conceptual perspectives that provide analytical insights into multiple levels of the socio-economic system for the deployment of PV. In Paper I, a key objective was to understand the nature, scale and dynamics of costs associated with the deployment of PV. Pursuant to this objective, a bottom-up cost model is developed and applied to illustrate the composition of upfront costs that arise in deploying turnkey PV systems. Here, the unit of analysis is denoted as the *deployment cost of a PV project*. Cost data is not derived from a single project but is intended to reflect a representative average across an entire market segment, i.e. distributed building-sited PV. In order to investigate the development of costs over time, a temporal dimension is added to the bottom-up cost model. Subsequently, the cost dynamics are put in relation to the cumulative experience gained, using the concept of the experience curve. The conceptual framework of Paper I essentially relies on the modelling of costs. It portrays an abstract conceptualization of technology learning, thereby disregarding the dimensions of agency (actors), knowledge, learning and social context as drivers of cost reductions.

The framework used in Paper II draws on notions of the sectoral innovation system concept to analyse the drivers of soft cost reduction. Based on the findings from Paper I, it became clear that deployment not only depends on firms in the downstream segment of the PV value chain, but also involves a range of other actors. In particular, findings from Paper I display a variety of transaction costs for the conduct and coordination of activities across solar firms, governmental actors, utilities, banks and users. Given this complexity, a system-oriented approach was needed to enable a comprehensive understanding of the factors that shape the nature and dynamics of deployment costs. The point of departure for the choice of the analytical framework in Paper II was that soft cost reductions as a function of cumulative experience are essentially the result of a set of incremental technological, organizational and institutional innovation processes. Hence, the unit of analysis is the level of an *innovation system* in relation to deployment. Innovation system theory conceptualizes innovation processes through qualitative narratives that involve a variety of constituents, such as actors, networks, knowledge, learning and institutional embedment. The choice of the innovation system concept in Paper II added a qualitative, interdisciplinary perspective to the cost modelling approach of Paper I.

Although system-oriented approaches can offer more holistic perspectives, their drawback is that their analytical capacity is less granular than more myopic concepts. The latter offer more powerful analytical lenses at lower levels of enquiry and can therefore be more appropriate to illuminate distinct aspects for which more system-oriented frameworks are not designed. In Papers III and IV, the chosen analytical perspectives allow zooming in to specific aspects of the PV deployment system.

In Paper III, business model theory served as the analytical tool. This concept has a more firm-centred perspective, while still recognizing the network of interactions with partners in the value chain, as well as users. This meso-level approach focuses on firm-internal aspects as well as inter-organizational networks and how these factors relate to the collective creation of customer value. The analytical perspective used in Paper IV is grounded in network theory. Although network theory is also one of the concepts inherent to innovation system theory and the business model concept, the exclusive use of network concepts in Paper IV offered more granular insights into the structure and composition of a deployment-related large-scale, international network.

In sum, although the analytical concepts employed across the four research papers share some common theoretical roots, it is emphasised that they operate at different levels of analysis. The unit of analysis of the mapping of cost structures and cost dynamics is primarily set at the level of a PV project, aggregated across a certain market segment. The framework of network theory has the inter-organizational level as its focus of analysis. Traditionally, the business model concept focuses in its analysis on a firm or group of firms in a sector. In this research, this perspective was further expanded by recognizing the embedment of business models in a set of contextual conditions. Finally, the unit of analysis of innovation system theory is at a higher system level, which in this research gave additional insights on the role of policy, governance and institutions for the deployment of PV. The collective use of these perspectives forms an interdisciplinary, multi-level and system-oriented framework for the research as a whole. The triangulation of theories and concepts enables complementary insights into the PV deployment system, aiming to enhance the validity of the research.

An additional novelty in this thesis relates to the empirical application of this framework to *deployment* processes. As elaborated in Chapter 1, system-oriented research approaches focusing on the deployment stage of energy technologies have been relatively scarce in the wider innovation literature. It is the intention of this thesis to partially fill this gap with the compilation of the appended Papers I–IV. Following, the four chosen conceptual approaches, as applied in this research, are introduced in greater detail.

2.2 Cost dynamics in technology change studies

In the literature on the economics and competitiveness of new energy technologies, the investment or upfront costs of renewable energy technologies for electricity generation have always received considerable attention (OECD, IEA, & NEA, 2015). For non-combustible sources of renewable power[13] operating costs are, due to the absence of fuel costs, relatively low and, as a consequence, upfront investment and associated finance costs determine the levelized cost of electricity production. In the economics of PV, modules typically represent the single biggest cost item and traditionally account for about half of the upfront cost of a turnkey PV system. Given the significance of modules for the cost-competitiveness of PV, extensive research has been dedicated to the investigation of sources of costs in module manufacturing (Nemet, 2006) and the decline of these costs as a function of cumulative experience. In general, the conceptualization of cost dynamics using experience curve concepts has been applied for a wide range of technologies (Argote & Epple, 1990; Arrow, 1962; BCG, 1972; Wright, 1936), including energy technologies (e.g. Grübler, Nakićenović, & Victor, 1999; Junginger, Sark,

[13] These include wind, solar, geothermal, hydro, wave and tidal energy.

& Faaij, 2010; Neij, 1997, 2008). In these studies, empirical observations have shown that the unit cost decreases by a constant percentage with each doubling of the total number of units produced. This cost decline is expressed in the so-called learning rate.

The experience curve concept has been used for the analysis of past cost trends and future cost projections, thereby serving as guide for firm strategy, for technology foresights, in energy system modelling studies (Bhandari & Stadler, 2009; Breyer & Gerlach, 2013; Mattsson & Wene, 1997) and for policy analysis (Neij, 2004; Nemet, 2009b; Zwaan & Rabl, 2004). From a policy point of view, experience curves have offered justification to support initial market formation in order to provide opportunities for learning, which in turn can lead to cost reductions. Despite a number of critiques, uncertainties and methodological issues (Nemet, 2009b; Söderholm & Sundqvist, 2007; Yeh & Rubin, 2012), the experience curve concept has gained widespread application, which may be explained by its empirical simplicity. In particular, PV modules have been a popular subject of research (Nemet, 2006; Nemet & Husmann, 2012; Parente, Goldemberg, & Zilles, 2002) with an observed learning rate of 16–30% for global scale studies (de La Tour et al., 2013).

Given the significance of non-module costs in the economics of turnkey PV systems, the analysis of these other cost items has received little attention in the literature. In particular, only marginal efforts (e.g. Schaeffer et al., 2004) have been made to investigate the cost dynamics of more deployment-related aspects of technology learning. The review of the literature shows that the accounting of soft deployment costs is faced with numerous methodological challenges. In particular, their heterogeneous nature, limited data availability and problems with transaction cost accounting complicate the consistent mapping of historical deployment costs. Although a number of bottom-up and top-down methods exist, the different approaches all have their advantages and drawbacks. In addition, this research identified distinct methodological aspects that are critical to the study of soft deployment cost trends, which have not yet been given much attention in the hardware-centred technology learning literature. In particular, scale-effects at the project level should be accounted for when studying soft deployment cost trends.

In Paper I of this thesis, a framework for the accounting and development of soft deployment costs of PV was developed. The framework served as a guide to gain a contemporary and more comprehensive understanding of the relevance of soft deployment costs in the economics of PV, as well as of their development as a function of time and experience. Gaining this knowledge was critical and provided the foundation for subsequent stages of the research. In order to account for the impact of project-scale effects on the level of soft costs, the framework distinguishes between different capacity classes. Further analysis relied on the experience curve concept, which in the domain of PV had primarily been used for the study of module costs. This required consideration of some of the specifics in relation to deployment. In particular, the research highlights the need to understand the effects of different indicators that can be used as a proxy for experience in *deployment* processes. This research proposes that in addition to the use of "cumulative capacity", the parameter of "cumulative number of installed systems" should be considered as an alternative variable in *deployment cost studies*, as it may better reflect the actual *inter-project learning* (Shum & Watanabe, 2008) gained in the planning and installation of PV systems.

In sum, analysing the composition and dynamics of deployment costs is critical to gain a more holistic understanding on the economics of PV. Although soft deployment costs and their dynamics can be accounted for with similar methods to those used for technology hardware, a number of distinct methodological aspects should be recognized. Furthermore, two additional aspects about the spatial scope of the systems under study and about the experience curve concept as such need to be pointed out. The first observation relates to the geographic scope of *experience*. While the learning system for the R&D and manufacturing of PV modules tends to exhibit more global characteristics, deployment processes and the associated soft costs are rather rooted at national and local levels (Candelise, Winskel, & Gross, 2013; Shum & Watanabe, 2008). As a consequence, the empirical analysis of soft costs is most meaningful at the national or even the sub-national level. Secondly, and as pointed out in the previous technology-centred literature, it also becomes clear for the case of soft deployment costs that the experience curve concept should be primarily regarded as a correlation method. It is recognized that the concept itself does not offer insights into the actual drivers of cost reduction, which to some extent limits its value for more targeted policy analysis and intervention. Opening up the black box around deployment processes and softs costs could, however, provide vital knowledge to support more holistic energy and innovation policies. This requires complementary methodological and conceptual toolkits. In this thesis, innovation system theory was therefore subsequently used as a conceptual approach to shed more light onto the actual drivers of soft deployment cost reductions.

2.3 Innovation system theory

The term "innovation" is typically used to describe the entire process of developing a new technology and putting it into widespread use. As such, innovation is a central building block in processes of technology change, including major transitions in energy systems. The deployment of technologies is essentially a subset in the innovation process and refers to the "putting-into-use" phase. Understanding and purposely managing innovation processes in a larger societal context has been the core objective of the broader literature on *innovation systems*. Scholars in innovation system theory (e.g. Carlsson & Stankiewicz, 1991; C. Freeman, 1987; Lundvall, 1992; Nelson, 1993) introduced a more holistic view on the role of policy, governance and institutions for innovation, in particular in regard to the creation of knowledge and the selection of technologies, firms and people (Lundvall, 1998). Overall, innovation system theory combines and bundles principles from several theories of the organizational field, including economic, sociological and political disciplines (Hudson, Winskel, & Allen, 2011).

Various branches of the concept were developed for national (Nelson, 1993), regional (Cooke, Gomez Uranga, & Etxebarria, 1997), technological (Bergek, Jacobsson, Carlsson, Lindmark, & Rickne, 2008; Jacobsson & Johnson, 2000), and sectoral (Malerba, 2002) levels. While the fundamental role of the innovation system concept is to give insights into the set of factors and mechanisms that drive and direct innovation processes (Grubler et al., 2012; Hekkert & Negro, 2009; Hekkert, Suurs, Negro, Kuhlmann, & Smits, 2007), the rationales to study innovation and technological change have been diverse and evolved over time. The early versions of the concept had predominantly economically oriented goals, including accelerating the speed of innovation (Hekkert et al., 2007), improving competitiveness and inducing economic growth (Coenen & Díaz López, 2010). Much of the more recent work has focused on the understanding of innovation processes of sustainable or "cleaner" technologies, including RE technologies.

The underlying reasoning behind the concept is that technological innovations are human-made resources that can be generated and expanded as a matter of social choice (Grubler et al., 2012). Consequently, innovation is not an autonomous process, but it can be purposefully managed. In this sense, the concept has been adopted for guiding science and innovation policy by numerous public organizations around the world (Hekkert & Negro, 2009). It is seen as a more appropriate alternative to guide policy action than the market failure approach of classic economic approaches. Unlike the static equilibrium and utility-maximization assumptions of the neoclassical economics perspective, the evolutionary perspective emphasizes the dimensions of learning, cooperation and competition of inter-firm relations (Cooke et al., 1997). This evolutionary perspective is grounded in an understanding of knowledge as a fundamental basis of economic activities, with the continuous accumulation and diversification of the knowledge base regarded as a key driver of continual, decentralized and self-organized change (Nishibe, 2006).

A major motivation for scholars in the field of innovation systems has been to inform policy making (Markard & Truffer, 2008). Following the identification of systemic problems that hinder innovation, innovation policy is seen as a means to consciously influence the innovation process (Edquist, 2011) through different regulatory, economic and "soft" instruments (Borrás & Edquist, 2013). Innovation policy concepts refrain from simple policy recipes, rooted in classic-economic approaches, such as "getting the prices right" (Lovio & Kivimaa, 2012). Rather they emphasize the need for combinations of policy instruments that address systemic failures in the innovation system (Borrás & Edquist, 2013).

As pointed out in the problem definition of this thesis (Chapter 1.2), perspectives on innovation systems have developed relatively isolated from the more economic-minded literature on cost reductions and experience curves (Winskel et al., 2014). Yet, while it is widely acknowledged that the diffusion of emerging technologies into mass markets is closely intertwined with its price/performance ratio (Jacobsson & Johnson, 2000), innovation system studies have not given much analytical consideration to unpacking the drivers of cost reduction. Cost reductions are essentially the result of many small incremental and cumulative innovations along the value chain (Mathews & Reinert, 2014).

In response to this gap in knowledge, a novel framework has been developed in the appended Paper II of this thesis to illuminate the drivers of soft cost reduction associated with PV deployment. The framework draws on notions of the sectoral innovation system (SIS) concept (Malerba, 2002). Similar to other branches of innovation system theory, the SIS concept abstracts the structure of the innovation system as a set of actors, networks, institutions and knowledge. A distinct feature of Malerba's theorizing on innovation is the concept's stronger rooting in evolutionary theories[14]. In particular, specific evolutionary notions of the SIS concept involve diversity generation, selection and competition. Empirically, SIS concepts have been employed mostly for the investigation of relatively established sectors (Malerba, 2004) where innovation is rather of incremental than radical or disruptive character. Due to these particular features, this research proposes that the SIS concept lends itself as an appropriate concept for studying a dispersed set of incremental innovations along the downstream segment of the PV value chain. These incremental technical, organizational and institutional modes of innovation are assumed to collectively translate into lower specific costs of PV deployment.

Operationalizing the framework, it is useful to distinguish between structure and processes of the sectoral system. Following earlier criticism by innovation system scholars (Hekkert et al., 2007) that studying the (static) structure of an innovation system only gives limited insights into its performance, the framework developed in this thesis takes a process-centred perspective instead. Specifically, the framework focuses on the identification of a number of processes that serve as

[14] See Coenen and Díaz López (2010) for a comparison of three systematic approaches to innovation.

intermediate variables between the system's structure and its performance, explicitly cost reductions. The processes under investigation are:

- demand and market expansion;
- interactions across firms, other organizations, and consumers, including competition;
- knowledge generation and learning;
- diversity generation and selection; and
- institutional development.

Paper II elaborates in more detail how these processes are linked to cost reductions. Furthermore, it is emphasized that these stylized processes do not operate in isolation but are closely intertwined with each other. The framework was applied for the PV deployment system in Germany with the aim to explain key drivers of soft cost reduction.

System-oriented approaches, such as the proposed variant of the SIS concept, can offer more holistic perspectives on innovation and associated deployment pathways. They are less suited for the study of concepts that are closer to the meso-level, however. Hence, business model theory was chosen as a complementary framework in this thesis, with the aim to advance knowledge on the role of selected businesses initiatives in the deployment of PV.

2.4 Business model theory

In the conceptualization of innovation systems, firms are a central actor group. In particular, in the downstream segment of the PV value chain, distributors and installers serve as the intermediary link between manufacturers of PV system components and the final users. The deployment of PV and its competitiveness is fundamentally dependent on these firms and on the way they package technology hardware into offerings that provides value to investors and users. A widely used model that conceptualizes how firms create value for themselves and for their customers is the business model concept. Therefore, and in accordance with the overarching objective of the thesis, business model theory has been used as the analytical framework in Paper III.

Building on central ideas in business strategy, the business model[15] concept draws on a variety of theories, including the value chain concept, resource-based theory, strategic network theory, cooperative strategies, transaction cost economics and industrial organization strategy (Hedman & Kalling, 2003; Morris, Schindehutte, & Allen, 2005; Porter, 1985). In particular, the creation and capture of value are central in most business model definitions (Boehnke & Wüstenhagen, 2007; Shafer, Smith, & Linder, 2005). Recently, the concept of the *business model* as an analytical and operational tool has become increasingly popular for the management of cleaner technologies and sustainability-related innovation (Boons & Lüdeke-Freund, 2013). Pursuant to the research objective of this thesis, the business model perspective is a particular useful analytical approach to understand how firms were able to catalyse the deployment of PV, by focusing on the reduction of customer-sited transaction costs and other barriers. The review of barriers to the adoption of PV (Chapter 1.1.3) illustrates the significance of various hurdles that (prospective) users of PV can face. Key barriers can include consumer inertia, high up-front cost, long payback periods, efforts associated with the planning and installation steps, various informational gaps, and customer concerns about PV reliability.

Prior work in other technology markets has described how firms were able to address such kinds of barriers through different strategies that focus in their value proposition on the customer problem that their product can solve. Generally, in successful business models the firm takes a high responsibility and focuses on ensuring functionality, durability and reduced complexity for the customer (Bocken, Short, Rana, & Evans, 2014; Reim, Parida, & Örtqvist, 2015). Furthermore, in use-oriented models, customers pay on a fee-for-service basis for the service provided by a product, rather than purchasing the product themselves (Mont, Dalhammar, & Jacobsson, 2006). Such types of models are particularly attractive to customer segments that may not have the financial resources to purchase a capital-intensive technology such as PV. On the other hand, in business models where customers purchase and own costly and complex equipment with a long operational life, such as PV systems, a key strategy of firms can involve a strong focus on complementary customer services. Offering additional services, such as maintenance, consultancy, financing, and extended warranties or advice, was found to lower customer-sited barriers (Chattopadhyay & Rahman, 2008; Tukker, 2004). These features of business models illustrate the potential of

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[15] A business model perspective can serve various functions including (1) understanding and sharing, (2) analysing, (3) managing and execution of strategy, (4) prospect and business scenario creation, and (5) patenting of businesses process (Osterwalder, Pigneur, & Tucci, 2005). As a tool for communication, business models can in particular facilitate firm internal management and as such execution of strategy (Magretta, 2002).

different business strategies in addressing customer-sited barriers to the adoption of PV. In this research, the choice of the business model concept as an analytical tool was critical to understand the process of value creation through (solar) firms in collaboration with their partners.

As an analytical tool[16], the business model concept aims to represent similarities between the model and those aspects of firms that are associated with value creation and value capture. Hence, following Knuuttila's (2009) classification on models, the business model concept can be characterized as a credible construction, comprising of a number of stylized pillars and elements. Following Osterwalder's et al. (2005) morphology, the four pillars of the model are the value proposition, the customer interface, infrastructure, and the financial model. The pillar of the customer interface describes (1) the customer segments to which a focal firm wants to offer value, (2) the various means the firm has to get in touch with its customers, and (3) the type of links a company establishes between itself and its customers. The infrastructure describes the architecture that is necessary to create and deliver the value proposition. It outlines (1) the firm's core competencies and resources, (2) the firm's partner network, and (3) the arrangement of key activities. Finally, the financial model with its elements of the revenue model and cost structure is another pillar of the concept.

In this morphology, the system boundaries of the business model are loosely delimited by the value chain of the focal firm. Aspects external to the value chain, such as the institutional framework, the market context, and other cultural factors are basically isolated and sealed off from the model. Prior research has shown, however, how business models emerge or change in response to technological opportunities (Johnson, Christensen, & Kagermann, 2008; Johnson & Suskewicz, 2009), institutional change (Casper & Kettler, 2001; Provance, Donnelly, & Carayannis, 2011) and changing consumer preferences (Linder & Cantrell, 2000). The contextual environment for the emergence of new business models can be shaped in particular by the national context (Birkin, Polesie, & Lewis, 2009; Budde Christensen, Wells, & Cipcigan, 2012). Recognizing these aspects on context dependency, a number of country-specific conditions specific to the deployment of PV are identified in Paper III. These contextual conditions include the policy framework, transaction costs, the electricity market, the building sector

[16] Whereas the business management and strategy literature applies the business model concept primarily to the organizational level of the firm and the inter-organizational aspects of a value network (Zott, Amit, & Massa, 2011), scholarship in the area of sustainable innovation further expanded the system boundary to the societal level (Boons & Lüdeke-Freund, 2013). In the same direction, Johnson and Suskewicz (2009) highlight the relevance of the business model concept to entire industries and infrastructure such as energy and mobility sectors, and the contributions it can make in system transformation.

and consumer-related factors. Although not yet part of the conventional business model conceptualization, the research argues that these conditions were critical in shaping the choice and design of PV business models in the analysed geographies.

In conclusion, the particular strength of the business model concept is its analytical capacity in understanding how downstream solar firms can create customer value, thereby catalysing the deployment of PV. Furthermore, it is recognized that business models and the firms that shape and execute them are embedded in different socio-economic contexts that are often specific to a certain country. This probably has important implications for the transferability of business models across different countries.

It is noteworthy that the conceptual frameworks presented in Chapters 2.2, 2.3 and 2.4 have distinct national or sub-national dimensions. As such, they offer limited capacity to unveil the role of transnational processes related to PV deployment, in particular the international creation and exchange of deployment knowledge. Therefore, and in order to analyse the international network for PV deployment knowledge, network theory is introduced as an additional, complementary framework in this thesis.

2.5 Network theory

Networks play a central role in the conceptualization of innovation and deployment. As such, notions of network theory are pivotal constituents in innovation system and business model theory, and they are implicitly used in Papers II and III of this thesis. In these studies, the analysis of networks is delimited by the geographic scope of the respective national case studies, however. Furthermore, in the innovation system and business model frameworks, networks are just one parameter of enquiry amongst others, and therefore empiric descriptions remain at moderate levels of descriptive thickness. Furthermore, the empirical investigation of large-scale network structures that involve several hundreds of organizations is from a practical perspective challenging with the qualitative methods typically employed in these frameworks.

One of the identified knowledge gaps in this thesis is the need to better understand the international dimension of deployment-related learning; see Chapter 1.2. Considering that networks play a key role as arenas of learning, knowledge generation and knowledge exchange, the objective of Paper IV is to map and assess the international policy-driven network for PV deployment knowledge. Given the limitations of the qualitative methods typically used in the application of the innovation system and business model concepts in their capability in framing the analysis of large-scale networks, a different approach and a dedicated framework were required. Consequently, network theory and the related method of social network analysis were chosen as the conceptual framework for the research presented in Paper IV.

In general, network theory has implicitly been a key pillar in the conceptualization of innovation as a collective process. A central and widely recognized concept in network theory is the catalytic function of networks in pooling complementary resources and capabilities across different organizations, knowledge fields and geographies (Bosetti, Carraro, Massetti, & Tavoni, 2008; Liu & Liang, 2013; Ru et al., 2012; Zhou et al., 2012). In particular, knowledge collaboration networks have been found to play a key role in international knowledge exchange, which is critical to accelerating the diffusion of low-carbon technologies (Bento & Fontes, 2015; Gosens, Lu, & Coenen, 2015; Wieczorek, Hekkert, Coenen, & Harmsen, 2015). In order to assess the performance of inter-organizational networks in their capacity to influence the generation and diffusion of knowledge, different strands of literature have identified attributes for the characterization of networks. In this research, the two prime dimensions used to characterize networks are their structure and composition.

Firstly, network structures have been found to influence knowledge diffusion (Cowan & Jonard, 2004; Fritsch & Kauffeld-Monz, 2009; Kim & Park, 2009) and thereby may affect the innovative performance of networks (van der Valk, Chappin, & Gijsbers, 2011). In addition to knowledge diffusion and absorption, networks structure have also been found to relate to aspects of prioritization and coordination (Provan, Fish, & Sydow, 2007), leadership (Newig, Günther, & Pahl-Wostl, 2010), susceptibility to change (Newig et al., 2010), and power asymmetries (Bodin & Crona, 2009; Ernstson, Sörlin, & Elmqvist, 2008). Principally, network structures can be characterized from the perspective of whole networks and from the perspective of individual network nodes. For the examination of whole network structures, key concepts proposed in the literature include *cohesion* (van der Valk et al., 2011), the *presence of cohesive subgroups* (Cowan & Jonard, 2004) and *network centralization* (Crona & Bodin, 2006; Leavitt, 1951; Scott, 2000). In this thesis, these concepts have been used to analyse the longitudinal development of the international policy-driven network on PV deployment knowledge.

In addition to the characterization of whole networks, network theory can also be used to investigate the position of individual nodes in a network, and thereby explain variations in the performance of different nodes based on their position. The fundamental concept in network analysis to describe a node's position in a network is *node centrality* (Bonacich, 1987; Borgatti, 2005; L. C. Freeman, 1978). The concept of node centrality essentially characterizes the degree of ties an actor has with other actors in the network. A simple measure of node centrality is *degree centrality*, which describes the number of ties a node has with adjacent nodes. High degree centrality means that, for example, an organization is well connected to other organizations. In the field of inter-organizational studies, node centrality has been used to characterize the degree of access an organization has to external (knowledge) resources and capabilities (Powell, Koput, & Smith-Doerr, 1996; Zaheer & Bell, 2005). This access to external resources may partially explain why actors who maintain central network positions exhibit innovative performance (Chiu, 2009; Powell et al., 1996; Tseng, Lin, Pai, & Tung, 2016) and are likely to adopt innovations earlier (Becker, 1970; Coleman, 1966; Peng & Dey, 2013), as opposed to actors with more peripheral positions in a network (Pittaway, Robertson, Munir, Denyer, & Neely, 2004; Rogers & Kincaid, 1981). Based on this understanding of the relationship between node centrality, knowledge access and adoption rate, the method of network analysis was selected in this thesis to explore the possible role of international collaboration on PV deployment knowledge in relation to the actual rate of PV adoption in different countries.

The second key dimension to characterize networks is their composition in terms of number and characteristics of participating actors, the resources and strategies they contribute to the network (Markard & Truffer, 2008), and actors' absorptive capacity (Cohen & Levinthal, 1990; Tsai, 2001). Network composition and in particular the diversity of knowledge resources, behaviours and habits of thought within a network are critical for its ability to generate new knowledge (Grubler et al., 2012; Pittaway et al., 2004). In the same line, prior research about the deployment of new energy technologies emphasizes the benefits of recombining diverse knowledge resources and strategies from a variety of stakeholders, such as different kinds of firms, universities and R&D organizations, financiers, associations, consumers and public bodies (Musiolik, Markard, & Hekkert, 2012). For the research presented in Paper IV, the diversity of knowledge resources has been approximated by the variety of different types of organizations that participated in the network.

In conclusion, network theory served as the framework for the analysis of the structure and composition of the international network on PV deployment knowledge. The framework facilitates the characterization of networks with regard to a number of parameters. This allows drawing implications on a number of different levels, such as the ease of knowledge flows, susceptibility to newness, knowledge diversity, resilience to internal and external changes, leadership, power and legitimacy. Understanding the implications of the topology of networks on their performance is particularly relevant for networks that are initiated and supported through public policies. While prior research has applied similar frameworks primarily to the investigation of networks related to R&D and science-and-technology modes of knowledge, this thesis uses network theory for the analysis of a specific network related to PV *deployment* knowledge. The framework is therefore of relevance for the analysis and design of policies that seek to support networks for the creation and exchange of deployment knowledge.

3 The design of the research

Chapter 2 summarized the theoretical perspectives that formed the conceptual framework applied to pursue the research objectives. In this chapter, the methodological choices are explained. Specifically, the chapter explains the ontological and epistemological position of the research, describes the methodology applied, and discusses parameters to judge the validity and reliability of the findings.

The research takes an applied approach to address a contemporary problem of societal relevance. The research is framed in the wider context of technology and innovation management, which considers the development and adoption of technologies to be the result of social choice. In an increasingly popular subset of this school, in particular cleaner technologies can and should be purposely promoted in order to pursue long-term societal goals with regard to pressing sustainability challenges.

In general, it has been widely acknowledged that the complex challenges associated with ecological and societal systems implies the need for new methods of scientific research that generate applied knowledge, for the purpose of both understanding and action. This includes knowledge of relevance for policy and business managerial action with the designated aim to trigger transitions toward a low-carbon energy system. In this paradigm, energy markets and technology are susceptible to human manipulation through various causal factors, such as policy and business decisions. Knowledge provided by applied science is expected to have instrumental value to support informed decision-making.

Furthermore, it is widely recognized that the understanding and management of complex sustainability challenges, including the management of cleaner technologies, benefit from research designs that are interdisciplinary, employ a comprehensive system's perspective, and use multiple methods. Credible findings can only be generated using research designs that allow the empirical testing and verification of claims. In addition, given the need to produce knowledge for action to tackle global sustainability challenges, it is imperative that the findings obtained from distinct empiric cases can, to some degree, be generalized and thereby have more universal value for a wider audience.

3.1 Meta-theoretical considerations

Every scientific investigation is framed by a set of beliefs that capture the researcher's position in thinking about the world. These beliefs are reflected in meta-theoretical perspectives or research paradigms that embody ontological, epistemological and methodological assumptions. This scientific position is closely interrelated and it entails implications for how the research was designed and how its results can be interpreted. In the philosophy of science, there is a broad distinction between the antagonisms of realism and relativism that take fundamentally different positions on questions about reality and truth, and the ability to measure these objectively. Stretching between these poles, Guba and Lincoln (1998) distinguish between four major philosophical research paradigms, positivism, post-positivism, critical theory and social constructivism. This research primarily follows along the lines of post-positivist traditions.

In line with the post-positivist paradigm, the author acknowledges the existence of a real world but it is difficult fully and objectively to observe and measure, due to its complexity. As such, the ontological position of the research embodies the perspectives of critical realism in which reality can only imperfectly and probabilistically be apprehended (Guba & Lincoln, 1998). In this thesis, the scale and complexity of the socio-economic system related to PV deployment is perceived to comprise multiple levels of reality. In addition to the physical world, it involves social, political, cultural and cognitive behavioural dimensions that stretch from the level of individuals towards the societal scale. In its ontological understanding of PV deployment, this research follows along Nishibe's (2006) perspectives on economic activity as a dynamic and evolutionary process, as opposed to a static, functional one as in neo-classical economics. In this perspective, knowledge and associated processes of learning are considered a fundamental basis for economic activities. In particular, knowledge is embodied in physical artefacts and in the practices of how these artefacts are deployed into existing and evolving physical, institutional and social structures. The ontology is system-oriented, and it is characterized by a large number of heterogeneous agents such as individuals and organizations, who engage in a wide variety and number of linear and non-linear interrelations. Furthermore, actors' activities are embedded in a social, political and cultural context. The system is viewed to undergo continual, decentralized and self-organized change, driven by the continuous accumulation and diversification of the knowledge base. In this ontological perspective, the deployment of PV relies on the existence of a social world that is being constructed by a large set of agents with heterogeneous knowledge, experience and preferences.

The ontological position dictates *epistemological beliefs* and the relationship the researcher has with the knowledge. In this research, the author had the possibility to define how the reality is scoped, studied and interpreted. Driven by the nature of the problem and the aim of the research, this thesis is of normative character and is thus not value-free. Similar to other problem-oriented forms of research in sustainability and innovation, it aims intentionally to produce knowledge that directs societal actions in a desired direction. This normative nature of the research is in line with the post-positivist view, where it is accepted that the used concepts and theories have a direct impact on the research as every theory is for a particular normative purpose. Similarly, the choice of the empirical object of enquiry is guided by normative views. For example, the chosen case studies in the research papers essentially represent "successful" PV markets that are generally considered as "role models" in the PV community. The predictive and explanatory findings from these case studies are thereby implicitly legitimized and recognized as "how things ought to be" in order to attain the goal of effective PV diffusion. According to Niiniluoto (1993), this normative element of "how things ought to be in order to attain goals" is a key characteristic of *design science.*

3.2 Key methodological choices

The design of the research is characterized by different methodological choices that were made throughout the entire research. Generally, the research methodology is framed by the research objectives, the theoretical perspectives and the ontological and epistemological positions (Bryman, 2012). These considerations also determine the empirical nature of the research and the methods applied. The analysis of the socio-economic system of PV deployment requires a combination of different interdisciplinary theories, with some of them forming the conceptual framework for this thesis. Since no theory can consider all relevant factors in any particular economic context, there is a strong case for theoretical pluralism. Different theories will often be complementary rather than alternative. The complexity of economic reality necessitates the complementarity, rather than substitution, of different theories. As elaborated in Chapter 2, theories used in this thesis include experience curve theory innovation system theory, business model theory and network theory. Concepts applied are knowledge development and learning (sociology, economics), market development (economics), diversity generation and selection (economics), technology development (technical studies), actors and networks (sociology, economics), value creation and business strategies (organizational studies), as well as policy concepts (policy-oriented research). These concepts derived from theories have guided the methodological choices in terms of methods of reasoning, research design, unit of analysis, case selection, and the methods for data collection and analysis.

With regard to the *method of reasoning*, the research is based on a combination of both deductive and inductive techniques. Using a deductive approach, the research employed established theories and concepts (see Chapter 2) that were used earlier to study upstream segments of value chains. Concepts such as the experience curve approach, innovation system theory and network theory offered orientation to frame and guide the research. This approach was complemented with inductive modes of reasoning. The use of the existing frameworks for the systematic analysis of the deployment segment of PV value chains is rather novel, and efforts to conceptualize and theorize this segment have been relatively few. Furthermore, some frameworks were used for the study of different aspects than in earlier research. For example, prior use of innovation system concepts focused primarily on the diffusion rate of new technologies as the dependent variable of the investigated system. This research, however, sought to investigate the relationship between the development of the innovation system and deployment cost reductions. Therefore, the review and recombination of theoretical concepts as well as observations from the field were used in an inductive mode of reasoning to guide the research, and eventually develop and apply a modified version of the sectoral innovation system concept (Paper II). Similarly, observations resulting from the research were critical, by means of inductive reasoning, to establish a set of contextual conditions that embed PV business models (Paper III). In all, the inductive approach led to the advancement of existing theoretical concepts and their application to the downstream segment of the PV value chain.

The research has descriptive, explanatory and predictive elements in relation to patterns in the socio-economic system for PV deployment. In the quest of inferring explanations from observations, two different logics have been used. To start with, it is helpful to distinguish between two fundamental modes of reasoning that have been used in explanatory research related to organizational change. These dimensions have been labelled variance and process methods (Van de Ven & Poole, 2005). While variance approaches seek explanations of change to be the result of deterministic causation between independent variables acting upon dependent variables, process approaches investigate change through rich longitudinal narratives of a causally interrelated succession of events. Variance approaches typically use research designs that are grounded on linear models and they focus on variables that represent the key attributes of the subject under investigation. On the other hand, process approaches are characterized by more eclectic research designs, incorporate several different types of events, use multiple data sources, and explore multiple interwoven themes (Van de Ven & Poole, 2005). In this research, process theory is the underlying logic of reasoning in studying the longitudinal evolution of the PV sectoral innovation system, as presented in Paper II. Conversely, the more quantitative studies in Paper I and Paper IV rather follow the logic of variance theory. In comparison with these three papers, the multiple-case study presented in Paper III is of more static nature and does not seek to explain changes over time. Rather, it offers a qualitative comparison and contrasting of three cases that produce similar results. Since variance and process methods provide a different – but partial – understanding of organizational change (Van de Ven & Poole, 2005), their complementary use as performed in this research offers a more holistic understanding of change in the socio-economic system for PV deployment. The choice of the process vs. variance approach also determined subsequent choices of research design and methods.

In terms of *research design*, the research is primarily based on case study methodology. Case study design is an empirical inquiry that allows the investigation and understanding of complex social phenomena over which the researcher has little or no control. Specifically, case study methodology is useful to answer "how" and "why" research questions in explanatory studies (Yin, 2013). Case studies have also advantages in the identification of new variables and hypotheses, and they can thereby contribute to the development of analytical generalizations and, eventually, theory (George & Bennett, 2005). Case studies rely on multiple sources of evidence and they may include both qualitative and quantitative approaches to investigate reality by triangulating both data and methods (Yin, 2013). Although there is no single-best method in social science research, case study methods have been widely used to generate knowledge and foster a broad understanding of technology change processes, including the understanding of how new technologies diffuse in society and how innovation processes can be conceptualized as the interplay between actors, networks, institutions, and technology.

This research encompasses both *single-case study approaches* (Papers I, II, IV) and a *multiple-case study design* (Paper III). Generally, single-case research designs are useful for longitudinal studies that involve studying the same single case over different points in time, thereby giving insights into the dynamics of certain conditions and underlying processes over time (Yin, 2013). In Papers I and II, the case is delimited by the geography of a national PV market; in Paper IV it is framed by the organizational boundaries of a policy-driven international knowledge collaboration network. A potential drawback of single case designs is misrepresentation of the selected case, limiting the ability to generalize the findings to a wider population or setting (Bryman, 2012). Multiple-case research designs allow drawing cross-case conclusions. The particular value of the cross-case approach is its potential to enhance the generalizability of findings to other contexts (Miles, Huberman, & Saldana, 2013). Multiple-case designs should follow a replication logic, such as literal replication in which the cases are characterized by similar results (Yin, 2013). The multiple case study design in

Paper III adheres to this logic, as all three cases represent business models that were effective in overcoming barriers to PV deployment and thereby catalysed the diffusion of PV.

The overarching *social unit of analysis* are socio-economic structures and processes in the deployment system of PV. The specific levels of analysis differ across the four research papers, however. They include the project level (Paper I), the inter-organizational level (Papers III and IV), and the innovation system level (Paper II). This multi-level approach was chosen as it allowed the investigation of the research problem from a variety of perspectives, and contributed to enhancing the validity of the research outcomes (see Chapter 3.5). Generally, it is emphasized that policy-relevant research can benefit from multi-level analysis, as opposed to research designs with a single unit of analysis only (Hakim, 2000).

The *selection of cases* was made based on the relevance of the cases and their potential for providing pivotal insights in response to the research objective (see Chapter 1.4). As such, they were selected along the logics of theoretical sampling (Eisenhardt, 1989). In Papers I, II and III, the three national PV markets of Germany, Japan and the United States were chosen on the grounds of their significant, long experience of PV deployment. In particular, the case of Germany as a major market for building-sited PV with exceptionally low deployment costs offered unique opportunities to enhance understanding in relation towards more competitive PV. In Paper IV, the selection of the knowledge network on PV was chosen as a critical case for the efforts of two major supranational policy institutions (EU & OECD/IEA) in supporting international collaboration on PV deployment. Pursuant to the research objective, it was critical to understand processes of change in the PV deployment system and therefore a retrospective longitudinal perspective was taken in Papers I, II and IV. Generally, for the understanding of organizational change processes, it is considered vital to understand how they unfold over time (Van de Ven & Poole, 2005) and in this respect longitudinal studies have the ability to answer questions about the sequence of causes and effects (Hakim, 2000). Table 2 provides a summary of the geographic and temporal scope, and of the focal social units of analysis in the four research papers.

Table 2: Units of analysis in the four research papers

Paper	Geographic scope	Focal social unit of analysis		Temporal scope
		Structural	Thematic	
I	Germany	PV project	Deployment costs	Longitudinal (1991–2015)
II	Germany	Innovation system	Deployment / downstream value chain	Longitudinal (ca. 1990–2015)
III	United States, Japan, Germany	Business model and its contextual embedment	Deployment / downstream value chain	Static
IV	Japan, United States, Germany, Switzerland, Italy, Spain, Korea, France, Netherlands, Austria, China, United Kingdom, Australia, Belgium, Greece, Canada, Czech Republic, Thailand, Romania, Bulgaria, Denmark, Israel, Slovakia, Portugal, Russia, Algeria, Turkey, Slovenia, Mexico, Malaysia, Malta, Cyprus, Lithuania, Hungary, Sweden, Poland, Croatia, Macedonia, Norway, Finland, Serbia, Latvia, Albania, Ireland, Estonia, Morocco, Egypt, Mongolia, Singapore, Lebanon, Tunisia, Jordan	Inter-organizational network ties	Deployment knowledge	Longitudinal (1989–2017)

Case study designs can rely on multiple *methods* for data collection and analysis, and in this research a variety of techniques have been used for the purpose of data triangulation, and to increase the validity of the findings.

3.3 Methods for data collection

Data collection was guided by the research objective and the conceptual frameworks, and it was framed by the research design of the cases study approach and the empiric nature of the respective cases. Data collection was closely interweaved with data analysis. Specifically, data was essentially collected in an interactive cyclical process with data analysis, and analytical choices were made throughout this process. This enabled a reflective process, combining deductive and inductive modes of reasoning.

The ontological and epistemological position of the research argues for triangulation in data collection in order to approximate objectivity and reduce inevitable uncertainty. Specifically, case study methodology calls for multiple sources of evidence, a technique that allows the development of converging lines of inquiry (Yin, 2013), thereby strengthening the validity of the research.

The data collection methods included literature review, interviews, database research and participatory observations, see Table 3 for an overview. Depending on the specific objective of the different papers, the depth of the case and feasibility, these methods were applied to varying extents. Throughout the research an extensive review of academic literature was carried out to investigate the state-of-the-art knowledge in the field. Academic literature was systematically searched in scientific databases and consisted of articles published in peer-reviewed and specialized journals, as well as books and conference papers. This literature provided information about the research background and the context of the topic of investigation (Chapter 1). Furthermore, academic literature was critical for building the conceptual foundations concerning soft deployment costs, innovation system theory, business model theory and network theory (Chapter 2). Finally, the academic literature complemented some of the findings for the empirical cases studies (Chapter 4).

In addition to the academic literature, an important source of documentary information was the collection and review of industry-related literature as well as literature related to the institutional framework of PV deployment. Textual information was a particularly critical source to track historical developments, back to the early years of the formation of PV markets in the early 1990s. Industry-related textual data comprised a large number of sources such as trade journals about the PV sector and deployment, handbooks on PV installation, market surveys, research and project evaluation reports (non-peer reviewed), and a variety of websites. Furthermore, websites and sales brochures targeting PV users were important textual sources to identify the customer value proposition offered by solar firms. Reviewed literature that was related to the institutional framework of PV deployment included legislative documents, technical codes and standards, as well as technical and quality management guidelines.

Interviews are one of the most important sources of evidence in qualitative research (Roulston, 2010), including case study research (Yin, 2013). In this research, interviews with stakeholders in the downstream segment of the PV value chain played a critical role in the gathering of information about the PV deployment system, and in complementing and confirming information obtained from the documentary sources. Due to the focus of the research, interviewees were selected based on professional occupation and expertise in the field of study. Most chosen interviewees had professional affiliations to the private sector and the downstream segment of the PV value chain. For the longitudinal studies in Papers I and II, interviewees were selected primarily on the basis of their long professional experience in the field of study, dating back to the early or mid-1990s. The author carried out a total of 20 interviews with installation firms, architects, PV system component producers, and intermediaries such as wholesalers and system integrators. The interviews were carried out in a semistructured manner and were based on interview protocols, which on request were sent out to the interviewees before the interview. Interviews lasted typically 30–60 minutes and were conducted via telephone or in person. Handwritten notes from interviews were transcribed into electronic format directly after the interviews. For the investigation of the case study of Japan in Paper III, co-author Alvar Palm carried out interviews (using an interpreter) with stakeholders from five Japanese companies in the prefabricated housing sector. Across all interviews, data was collected until – in combination with other data sources – converging lines of evidence emerged (cf. Eisenhardt, 1989; Yin, 2013) and the possible prevalence of rival explanations could be minimized.

For Paper IV, data sampling for the network analysis relied on an event-based strategy (Knoke & Yang, 2008) and, in particular, on a multi-event approach which, by aggregating participants across all events, generally yields a more inclusive network than the study of single events. Events included 197 international collaboration projects on PV deployment, about which information was sourced from number of databases and programme websites. In total, organizations from 55 countries participated in these projects; these countries accounted for more than 97% of globally installed PV capacity in 2015. Following project sampling, a total of 1256 organizations participating in these 197 projects were identified, and their interrelations served as key input for the network analysis.

Finally, participatory observations and a number of informal conversations took place on a number of occasions such as study visits, trade fairs, conferences and other seminars. Furthermore, prior private-sector experience of the author (from 2002 to 2004) in the project management of renewable energy deployment (including PV) in Germany has been vital for creating contextual understanding about the sector as a whole. These participatory observations, informal conversations and first-hand professional experience provided a fundamental knowledge base and understanding of a large number of aspects related to deployment, including industry structure and culture, technology, project finance, legislative aspects and grid integration, as well as supplier and customer interrelations. This experience thus helped during the targeted phases of data collection with the interpretation of textual information, engagement in interview conversations, and triangulation of observations made.

Table 3: Overview of conceptual frameworks and key data sources employed in the four papers

Paper	Conceptual framework	Data		
		Type	**Data source**	**Quantity**
I	Cost mapping / experience curve concept	Price / cost data	Installer surveys (derived from documentary sources), project evaluation reports	3370 PV systems
		Interviews	Installers, architects, experts, manufacturers	20 organizations
II	Innovation system theory	Other documentary data	Trade journals	188 issues
			Project reports, academic literature, ISO and DIN standards, technical codes, legislative documents, quality management guidelines, websites	n/a
III	Business model theory	Interviews	Prefab-housing manufacturers (Japan)	5 companies
		Marketing data	Marketing brochures (Japan)	
			Websites (US solar service firms)	20 companies
			Websites (Germany installer firms)	50 companies
		Other documentary data	Project reports, academic literature, websites	n/a
IV	Network theory	Databases Programme reports	European Union programmes, International Energy Agency programmes	197 projects with 1256 organizations involved

3.4 Methods for data analysis

Data analysis involves the management, analysis and interpretation of the data (Bryman, 2012). In this research, methods for data analysis comprise both qualitative and quantitative approaches. In Papers II and III, primarily qualitative approaches were used. The studies of Papers I and IV rely primarily on more quantitative data sets and were complemented with a smaller set of qualitative data.

The process of qualitative data analysis can be broadly classified into three flows of activity, i.e. data condensation, the use of data displays, and the process of drawing and verifying conclusions (Miles et al., 2013). *Data condensation* involves processes of selecting, focusing, simplifying, abstracting and transforming raw data (Miles et al., 2013). Overall the primary technique for data analysis was qualitative content analysis (Flick, 2006) and it involved the systematic identification of themes (Bryman, 2012), which were initially guided by the categories of the analytical frameworks used in this thesis. For example, in Paper II, in a deductive approach, concepts of the sectoral innovation system framework served as a guide to organize data and identify themes from the documentary sources and interview transcripts. In Paper III, primary and secondary data obtained from the investigation of the three cases were iteratively condensed and then used to systematically chart the morphology of the case-specific business model. In situations where data could not easily be classified into the initial framework, inductive approaches to reasoning were used for the identification of novel themes and regularities that offered complementary insights into the research subject.

In the analysis of qualitative data, the creation of *displays* is useful for an organized and condensed assembly of information that allows the drawing of conclusions (Miles et al., 2013). In the multi-case study of Paper III, matrix displays (Gale, Heath, Cameron, Rashid, & Redwood, 2013; Miles et al., 2013) and comparative analysis techniques were used to systematically identify variations across the cases. The creation of the initial matrix was guided by ontological themes derived from the business model framework. The matrix was, in a cyclical process with data collection, iteratively expanded with additional headings that captured novel themes of interest in relation to the research objective. This process involved multiple tactics of analysis, such as identification of patterns and themes, as well as comparison and contrasting. The combination of deductive and inductive modes of reasoning in the research presented in Paper III enabled the identification of regularities, and eventually allowed the drawing of conclusions about the specific contextual environment of PV business models.

Finally, data analysis involves the *drawing and verification of conclusions* from the condensed and organized data (Miles et al., 2013). In Paper II, primary and secondary data were used to systematically trace the key processes and their interrelations in the sectoral innovation system, based on the indicators, event types and facilitating conditions provided by the conceptual framework. This approach involved several tactics, such as the noting of patterns and causal flows, in order to reach towards explanation. In the interpretation of the data, logics of the process approach (Van de Ven & Poole, 2005) were used to create a rich narrative and sequence of events, and to establish causalities between different constituents and processes in the analysed innovation system. In Paper III, a cross-case analysis (Miles et al., 2013) generated a thematic narrative derived from the systematic comparison of within-case causal displays.

The analysis of qualitative data should be closely interweaved with data collection in order to facilitate a reflective and open-minded research approach (Miles et al., 2013). Throughout this research, new data were iteratively collected alongside the analysis of data obtained during earlier stages of the research. Data analysis continuously triggered new questions, which required the gathering of data about new thematic aspects of the research subject. This cyclical approach was also essential as a mechanism to follow up on surprises, to triangulate, and to check out rival explanations, thereby strengthening the validity of the findings.

Quantitative approaches to data analysis were primarily used in Papers I and IV. Throughout the process of data collection, a comprehensive database using the Excel spreadsheet software was built for each of the two studies. These databases served for overall data management and subsequent quantitative analysis. In Paper I, specific methods employed for processing cost data involved standard statistical methods (Bryman, 2012), including regression analysis as it is commonly practised in the experience curve approach (Yeh & Rubin, 2012). Subsequently, a *mixed method approach* was used to explain findings from the quantitative analysis of costs by using qualitative data obtained from documentary sources and interviews. Generally, explanatory techniques in mixed method analysis are a tactic to infer causal relationships between quantitative and qualitative variables (Bryman, 2012).

In Paper IV, data analysis is based on social network analysis methods (Scott, 2000). This quantitative approach was selected due to its ability to practically chart the structure of interactions between a large number of organizational nodes. As such, this network analysis method proved to be useful for the investigation of the international knowledge collaboration network on PV deployment knowledge, which comprised 1256 organizations. Specifically, the use of dedicated software packages for social network analysis generated a number of graphs as well as results on various parameters that characterize interrelations between organizations, sectors and countries. In order to explore change in the network over time, the data set was divided into three subsets, each covering an approximately equally long period. Logics of variance methods (Van de Ven & Poole, 2005) were used to infer conclusions about changes in the analysed network over time. Finally, a combination of clustering tactics, pattern matching and regression techniques were used to explore relations between variables obtained from the network analysis and countries' deployment rates in PV. Here, the conclusions drawn in the final step of the data analysis rely on models and theories from the field of network and diffusion research (Hedström & Wennberg, 2017).

To sum up, the analysis of data in this research rests upon a multitude of methods and approaches, including quantitative, qualitative, and mixed methods. A circular and iterative process between data collection and data analysis allowed for a combination of deductive and inductive modes of reasoning and thereby generated new insights into the PV deployment system, and additionally pushed and expanded the boundaries of the initial frameworks and concepts used in this research.

Generally, research can be affected by several sources of uncertainty, including unreliable and incomplete data, issues of causality and non-linearity, as well as aspects related to the analytical lenses and the choice of system boundaries (Persson & Sahlin, 2013). Although uncertainties are always inherent to the research process, methodological pluralism in data collection and analysis aim to strengthen the validity of the research outcomes in this thesis.

3.5 Validity, reliability and replicability

Three prominent criteria for the evaluation of social research are validity, reliability and replicability (Bryman, 2012). In particular, case study designs have been exposed to discussions about their internal and external validity. In this research, a variety of techniques have been used to enhance and judge the validity, reliability and replicability of the research.

Firstly*, measurement validity (*also referred to as *construct validity)* relates to the question about how adequately a measure represents a concept that it is assigned to (Bryman, 2012). Measurement validity in case studies requires the identification of correct operational matters for the concepts being studied, in order to minimize the effects of subjective judgments by the researcher (Yin, 2013). In this research, the use of established theories and concepts served as a strategy to enhance measurement validity. Furthermore, the use of thick empiric descriptions in the more qualitative studies (Papers II and III) is based on multiple sources of evidence, which enhances the measurement validity.

The criterion of *internal validity* primarily concerns explanatory case studies, and the causal relationship between two variables that research may attempt to establish in this type of study (Yin, 2013). The possible prevalence of spurious effects requires various tactics, such as pattern matching, explanation building, addressing rival explanations and the use of logic models (Yin, 2013). As regards the understanding of causality, there are, according to Persson and Sahlin (2013), two major lines of reasoning about cause-effect relations. The first line associates cause-effect relations with strong associations and regularities, with constant conjunction being the ideal type. The cause is sufficient and guarantee for its effects. In the second line of reasoning, the cause makes a difference and causes are in one way or another a necessary condition for their effects. Without the cause, the world would be different. Counterfactual analyses of cause-effect relations belong to this category. In this research, the understanding of cause-effect relations rather tends to be along the lines of regularities and (more or less) strong associations. This view aligns with the post-positivist ontology of the research.

In this research, the ontological understanding of the socio-economic system related to PV deployment is characterized by a complex set of interactions, including the presence of multiple causal factors, multiple effects, various interaction effects such as two-directional causality or feedback loops, non-linearity and, presumably, equifinality, where many different paths can lead to the same outcome. In the field of organization and innovation studies, a simplified representation of this complexity involves the use of mechanism-based models. For the analysis of relationships between phenomena across micro-macro levels, Hedström and Wennberg (2017) distinguish between situational mechanisms, action-formation mechanisms, and transformational mechanisms. These types of mechanisms conceptualize the mutual effects between contextual factors at the macro-level, such as the institutional and cultural environment, and the beliefs, goals and actions of actors at the micro-level. In this research, the understanding of cause-effect relationships follows along the thinking of this mechanism-based approach.

In this thesis, a number of strategies were used to enhance the confidence into the cause-effect linkages. In particular, triangulation and methodological pluralism and the use of theory, as well as external review, served as key techniques to strengthen the internal validity of causal claims. Firstly, using triangulation tactics, the research relies on multiple conceptual frameworks and multiple methodologies, thereby enabling a variety of analytical foci on different parts of the PV deployment system. Furthermore, the use of multiple sources allowed crosschecking of information in order to assess the consistency of the results. For example, findings obtained from the documentary analysis were verified and complemented during interviews with experts. A second approach to enhance internal validity has been theory-oriented explanation and the use of the congruence method. The key area of application of the congruence method as described by George and Bennett (2005) is to elucidate the causal processes that may be hidden in a black box between an independent variable and a case outcome. Although congruity by itself does not ensure that a causal relationship exists, and researchers need to guard themselves against spurious correlation, support by a strong and precise version of a general theory can attach more confidence to claims of causality (George & Bennett, 2005: 189). In this research, the use of various established theories and concepts strengthen the internal validity. Thirdly, external scrutiny of the use of methods and the reliability of the results occurred through the research. In particular, the internal validity was externally examined during presentations at international conferences and seminars as well as during the peer-review process of scientific journals in which the appended papers were published.

The concept of *external validity* refers to the issue of whether a study's findings are generalizable beyond the specific research topic such as the chosen case. In general, due to the context specificity of case studies, generalization of the research outcomes should be approached with caution (Yin, 2013). Given the applied and problem-based approach of this thesis, it has been the explicit aim of the research to generate knowledge that is of relevance to contexts, other than the investigated empiric cases themselves. Given the ontological perspective on the socio-economic system related to PV deployment, a number of aspects need to be discussed with regard to the generalizability of the findings of this research. In general, it has been argued that the use of appropriate theory in the research design can form the groundwork for starting to address the external validity of case studies (Yin, 2013). From this point of view, the use of established theories and concepts in the research design provides the foundation to generalize findings and apply them to a different (geographic) context, and possibly other applications of renewable energy technology. It is important to note that key concepts employed in this research, such as knowledge as a foundation of economic activity, learning, network theory, value creation, and the role of institutional embedment are of more universal character. Hence, it can be expected that these more universal concepts apply across different geographies and technology fields. In turn, the grounding of the research outcomes of this thesis in established concepts enhances in principle the external validity of the findings.

Still, the context-bound character of the cases needs to be carefully acknowledged. In particular the embedment of the socio-economic system related to PV deployment in the distinct social and cultural settings of certain geographies implies that caution needs to be taken into account when judging the external validity. This view aligns with the perspective on the limitations of design science in being able to guide decision-making. Niiniluoto (1993) refers to the arguments of Hubert L. Dreyfus, who elaborates on the importance of absorptive capacity and "intuitive intelligence", thereby essentially claiming that the effective use of design rules requires an experienced decision maker who is able to appropriately interpret the rules to the respective situation. This perspective on the ability of theory and generic knowledge to act as a guide to policy design is echoed in the literature. George and Bennet (2005) emphasize the need for scholars as well as policy makers to have a realistic understanding of the limited and often indirect impact that scholarly knowledge, theory and generic knowledge can have on policy making. They argue that theory and generic knowledge are best understood as a source of inputs to policy analysis of specific problems. They are an aid but not a substitute for case-specific policy analysis (George & Bennett, 2005).

In the assessment of external validity, another aspect that requires consideration are the dynamics of the economic system studied and, in particular, the evolution of the technology cycle in relation to PV. Findings obtained from the case studies are based on historical experiences that stretch back to around 1990. Since then, and as analysed in this research, the technology cycle of PV has evolved significantly. This also includes the advancement and accessibility of a codified knowledge base related to many aspects of deployment. This implies that follower countries in PV deployment are likely to be able to leapfrog through some of the phases of the technology cycle that pioneer countries went through earlier. Hence, the findings from this research need to be interpreted in the light of these dynamics of the PV technology cycle and the advancement of the associated deployment knowledge base.

Finally, the criteria of *reliability and replicability* are related to the quality of a study to be repeated by a later investigator who should arrive at the same findings and conclusions (Yin, 2013). The concept of *reliability* is closely related to the aspect of measurement validity (Bryman, 2012). As replicability is dependent on the consistent application and interpretation of measures across studies, it is closely related to the notion of reliability (Bryman, 2012). In this thesis, critical tactics to enhance the reliability and replicability are the use of case study protocols and case study databases that document the procedures followed throughout the research. Furthermore, all the materials collected and produced throughout this research serve as auditable documentation that would allow later investigators to replicate the research. Given the ontological understanding of the economy as a continuously evolving system, replicability of findings in future research will depend on the temporal unit of analysis chosen in such investigations.

4 Key findings and analysis

This chapter presents a summary of the main findings from the four research papers, which comprise assessments of selected empirical experiences in the deployment of PV. Based on the case of Germany, Papers I & II characterize and explain the dynamics of deployment-related costs. The comparative case study presented in Paper III is based on experiences in the United States, Japan and Germany, and shows how PV deployment has been catalysed through different business models. Paper IV presents an analysis of the international policy-driven network on PV deployment knowledge, involving organizations from 55 countries.

4.1 Paper I: Mapping the cost dynamics of photovoltaic deployment

4.1.1 Objective and approach

The objective of Paper I was to provide new insights into the long-term dynamics of deployment-related costs of PV. Using the case study of building-sited PV systems in Germany, the study aimed specifically to give an updated review of the nature and scale of deployment costs and illustrate the longitudinal development of major cost items since the inception of the market in the early 1990s. By focusing in the analysis on non-module deployment costs, the study fills a gap in the research literature and contributes to a more holistic understanding about the cost dynamics of PV.

The approach used in the study comprised three main steps. Firstly, using a bottom-up model, the composition of deployment cost was illustrated. Secondly, in order to identify the historical trajectory of hard and soft deployment costs, a comprehensive review of the literature (academic, industry journals, project evaluation reports, etc.) was carried out. Thirdly, the correlation between longitudinal soft deployment costs and cumulative capacity, and cumulative installed number of PV systems respectively, was illustrated with an experience curve model.

The analysis of the scale and dynamics of deployment costs served as the groundwork and guide for subsequent papers in this thesis. Specifically, the case re-emphasizes the significant proportion of deployment costs in the economics of PV and also shows the scale of cost reductions that have been achieved in one of the pioneering and largest PV markets in the world.

4.1.2 Main findings

The review of the composition of upfront cost for the deployment of a turnkey PV system shows the significance of costs that arise in the downstream segment of the value chain. These soft deployment costs arise from a variety of activities, such as

- processes related to choice of business partner and technology, as well as customer acquisition;
- processes related to technical planning;
- processes related to legal-administrative planning, permitting, and grid connection;
- installation work; and
- processes related to financing and support schemes.

Findings show that for a 5 kW_p residential system, soft deployment costs accounted to about 38% of the upfront cost in 2013. It is noteworthy that these are, by international comparison, still exceptionally low numbers[17]. Besides, additional transaction costs arise from the time that prospective PV investors need to spend on information search, interactions and negotiations with the installer firm as well as other administrative processes. Quantitative empiric data on these customer-allocated transaction costs were scarce, however. PV modules (38%) and other hardware components (24%), such as inverters, mounting systems and cabling account for the remainder of costs.

The results of the review of the historic development of deployment costs of building-sited photovoltaics show that, similar to cost reductions for PV system hardware, the soft deployment costs have decreased significantly over time and with cumulative experience. In Germany, soft deployment costs for planning and installation have decreased by 65–85% since the formation of the market for residential PV systems in the early 1990s. Despite this impressive rate of cost

[17] For example, soft deployment costs for residential systems in the US accounted for 58% of system prices in 2016 (Fu et al., 2016); in Japan they accounted for 44% (Friedman, Margolis, & Seel, 2014). In Europe, soft costs and transaction costs can vary by several orders of magnitude between different national PV markets (Barth et al., 2014; Garbe, Latour, & Sonvilla, 2012).

reduction, results also show that soft costs declined at a slower pace than the costs for major hardware components. For example, costs for crystalline silicon PV modules decreased by about 92–94% from the early 1990s to 2015, and inverter costs have decreased by about 85–87% since the early 1990s. As a consequence, results show that the even greater cost reduction of hardware components entailed that the share of soft deployment costs for PV deployment increased from 10–15% in the early 1990s to more than 35% in 2013. Using the experience curve method, a learning rate in the range of 10–12%[18] was identified for soft deployment costs. This learning rate is lower than the corresponding rate for hardware components, such as modules. The slower pace of cost reduction for deployment-related activities re-emphasized the need to better understand the sources of costs as well as opportunities for cost reduction in the downstream segment of the PV value chain.

The study generated initial insights that part of the reduction in soft deployment costs has been the result of more sophisticated PV hardware components. For example, the advancement of mounting system and inverter technologies, as well as an increase of module conversion efficiencies and larger module dimensions contributed to shorter planning and installation times. In addition, processes of technology standardization, integration and modularization facilitated easy replication of PV system designs and reduced the labour time required for planning and installation. Furthermore, findings from the interviews revealed that stakeholders with auxiliary functions for the deployment of PV, such as utilities and banks, gradually gained significant experience with PV, which reduced the (transaction) costs associated with processes related to grid connection and finance. Due to data limitations, long-term trends in transaction costs could often only be assessed in qualitative terms however.

The study revealed a number of methodological aspects that are critical to the study of soft deployment cost trends. Notably, the research exposed the very limited availability of longitudinal soft cost data, in particular transaction costs. For future work, therefore establishing international, standardized data collection routines could help to track and benchmark soft cost trends across different geographies, and also facilitate the ex-post evaluation of policies that seek to reduce soft costs. The study also highlights the need to consider multiple indicators (incl. “cumulative number of installed systems”) as a proxy for experience in deployment cost experience curve studies in order to better account for inter-project learning effects.

[18] Two experience curves were created by using two different approaches using (1) *installed capacity* and (2) *number of installed systems* as a proxy for experience.

4.1.3 Concluding reflections

The results of the study re-emphasize the significance of deployment-related activities for the economics of PV. While the primary aim of the study was to map cost structures and cost trends, it also identified a number of technology developments that have contributed to the reduction of soft costs. However, it also became clear that technology advancements could only offer a partial explanation about the sources and drivers of reductions of soft and transaction costs. The research gave early indications about the presence and significance of numerous organizational and institutional processes that affect these types of deployment costs. As the approach and method used in Paper I were not suitable to fully explore these processes, it became clear that further research was needed. Thereby, the findings from Paper I triggered the rationale for the design of subsequent papers in this thesis, in particular Paper II and Paper III.

For policymakers, a key implication of this study is the need to direct their attention to the learning rate of soft costs, which proved to be lower than the respective rate of PV modules, for instance. If unaddressed, this disparity in the learning rates between soft and hard costs will lead to a situation in which soft deployment costs continue to gain importance in the economics of PV. The findings are also of relevance for decision makers in other geographies, and in particular for early PV markets where the expected decline of deployment costs as local experience is built up can justify the launch of dedicated PV deployment policies. Given the fact that the soft costs of PV deployment vary extensively across different markets and jurisdictions, the study furthermore emphasizes the principal potential to converge excessively high costs towards best-practice levels as a result of cumulative, local experience[19].

[19] In fact, on a global scale, the convergence of balance-of-system costs towards best-practice levels is seen as the key opportunity for reducing the costs of PV deployment until 2025 (IRENA, 2016).

4.2 Paper II: Explaining the cost dynamics of photovoltaic deployment

4.2.1 Objective and approach

The objective of the research carried out in this study was to shed light onto the organizational and institutional aspects that drive the dynamics of soft deployment costs. Thereby, the research in Paper II responded to the relative negligence in the majority of technological change models in considering the impact of organizational and market aspects on the upfront costs of renewable energy technologies. Drawing specifically on notions of the sectoral innovation system concept, the paper proposes a new framework for the study of deployment-related cost reductions. The framework considers cost reductions to be the result of various processes in the innovation system, including cooperation, competition, specialization, knowledge formation, learning, diversity creation, selection and institutional alignment. The framework was empirically tested and applied in a case study, which is the downstream segment of the PV value chain in Germany. As shown in Paper I, soft deployment costs have decreased considerably in Germany since the early 1990s, and they are at present significantly lower than in most other countries.

4.2.2 Main findings

The analysis of the German PV sectoral innovation system was structured around its key processes of (1) demand and market expansion, (2) agents' interactions, (3) knowledge generation and learning, (4) diversity generation and selection, and (5) institutional alignment[20]. Furthermore, the analysis suggests that a set of crosscutting enabling conditions have facilitated and driven these processes across the sectoral system.

Firstly, *demand and expansion* of the German PV market was critical to enable various processes in the sectoral system. Demand growth triggered the market entry of a large number of firms that operated across various segments of the value chain. Downstream, thousands of small businesses engaged in the planning and installation of PV systems. In the upstream part of the PV value chain, demand growth triggered market entry of numerous manufacturers of complementary products that are needed to integrate PV systems into the local infrastructure.

[20] In Paper II, institutional alignment refers to the creation and amendment of formal institutions (standards, technical codes, legislation) in relation to PV deployment.

Market growth enabled specialization of firms' value proposition and their workforce, last but not least, as smaller firms were able to grow. This has likely contributed to the decrease in soft costs along with market expansion. Furthermore, market development towards larger PV systems clearly resulted in project-scale effects, and partially explains the decrease in soft costs per kW. Market growth has resulted in denser distribution networks, and has thereby probably contributed to the decrease in soft cost. Additionally, demand and market expansion have been conditional for numerous other processes in the sectoral system, including agents' interactions, knowledge generation, learning, and diversity creation.

Secondly, demand provided conditions for a wide range of *interactions* between firms, consumers, authorities and other organizations. Across the PV value chain, producers and distributors of PV system components established formal and informal networks and alliances, which served as platforms for interactions with the aim to gain access to the end-user, ensure quality of installations and build credibility for PV. Among local installation firms, a horizontal form of interaction involved temporary coalitions of firms from different trades, which enabled the recombination of knowledge and experience from different professions. These networks serve as critical platforms for training, as well as bilateral exchange of knowledge and experience with regard to products, planning, installation and regulatory requirements. Furthermore, interactions between non-commercial solar initiatives and firms and users were instrumental platforms for the advocacy of solar energy. The formation of networks and cooperation across standardizing committees, legislators and courthouses, producers and industry associations, solar advocacy associations and R&D organizations were vital in developing the institutional framework. The research also discusses the role of non-commercial networks and solar initiatives that served as focal points for learning and raising awareness about PV deployment.

Another form of interaction was *competition*. As a result of growth in demand and of number of firms (installers, intermediaries, producers), market concentration declined and competition increased. Competition was also facilitated by the relatively homogenous nature of the product offering (increasingly standardized PV systems), low entry thresholds[21] for new firms to engage in the installation market, increased market transparency, and a relatively uniform institutional framework across the country. Although not empirically investigated in the research, competition has likely resulted in pressed margins.

[21] Low appropriability conditions exist due to the advancement and standardization of PV technology, the small-scale nature of many PV projects, and the absence of significant legal-administrative barriers to engage in the market.

Thirdly, *knowledge generation and learning* related to deployment were found to be present across the entire value chain. Upstream, the advancement of *science and technology knowledge* resulted in increasingly sophisticated PV system components, such as modules, inverters, mounting systems and cabling. Technological advancements facilitated easy replication of PV system designs and significantly reduced the labour time required for planning and installation. Initially, during the inception phase of the PV market in the early 1990s, the experience gained during the government-run 1000-roofs programme was vital in building a knowledge base for the deployment of grid-connected, distributed PV. Due to the low entry thresholds in the PV deployment market, small and medium-sized installer firms were able to try out and learn about PV technology at a low level of risk and subsequently benefit quickly from learning-on-the-job. Gradually, the knowledge base related to the planning and installation of building-sited PV expanded greatly. Central blocks of deployment knowledge include (1) climate data, (2) orientation of the module pane and assessment of potential shading effects, (3) technical configuration of PV system components, (4) attachment or integration into the building shell, and (5) integration into the electricity grid. Results show that since the early 1990s, the body of deployment knowledge and its accessibility has increased considerably. An ever-growing variety of information channels such as books, magazines, websites, planning software and training courses became available and provided comprehensive learning opportunities on various aspects of planning, installation, maintenance, safety, marketing and sales, finance and legal matters. Similarly, accessibility of information for (prospective) users about the various aspects of PV increased significantly. Banks and insurers gradually gained the knowledge to assess the opportunities and risks of PV, and in turn administrative processes related to the finance and insurance of PV systems became streamlined.

Fourthly, another set of processes found in the sectoral innovation system included *diversity generation and selection*. The research findings show that the sectoral system comprised an increasingly versatile and diverse knowledge base, which also became reflected in more diverse technology portfolios. Furthermore, it can be assumed that the huge increase in the number of firms (producers, intermediaries, installers) in the PV market also resulted in a greater diversity of strategies, agents and structure. On the other hand, the *selection environment* in the sectoral system has gradually become more stringent. For solar firms, the decline in industry concentration likely resulted in increased competition. The selection environment was also tightened as a consequence of incrementally declining feed-in tariff rates for newly commissioned PV systems. Based on evolutionary principles, it was proposed that the combination of greater diversity with an increasingly stringent selection environment was one of the drivers behind the incremental sophistication and lower costs of PV technology and deployment services in the market.

Fifthly, *institutional development* was found to be another factor that contributed to the decline of soft deployment costs. Demand growth and market expansion have been enabled through a variety of different support schemes that have been enacted and provided by federal and state governments, municipalities, utilities and citizen initiatives. Furthermore, both in Germany and internationally, various schemes for standardization, quality management and safety of PV system components were developed. The advancement of technical rules and standards and their actual use overall increased the quality of PV system components and their installation, and they provided important guidance for installers, users and banks as they reduced uncertainties and the risk of liability claims. Furthermore, the development and clarification of rules related to the grid connection process, the Renewable Energy Sources Act, building law and tax law overall led to streamlined routines, shorter planning times, reduced uncertainty and a decline in transaction costs.

The findings show that *public policies* at various levels had a central role in the evolution of the sectoral system, and they indirectly incentivized processes related to soft cost reductions. Policy programmes focused primarily on the support of niche experimentation, provision of conditions for demand growth, and financing initiatives. The iterative decrease of support levels thus ensured a continuous tightening of the selection environment, thereby incentivizing further innovation and cost reduction. Furthermore, results show the development and streamlining of legal-regulatory institutions, standards and technical codes.

Finally, the study acknowledges that the evolution of the sectoral innovation system needs to be interpreted in the context of broader societal developments that provided the breeding ground for PV. Prior literature has discussed the role of public discourses on energy and sustainability in Germany, which triggered a social movement that created a sense of urgency and vision to transform the energy system (Bruns, Ohlhorst, Wenzel, & Köppel, 2011; Jacobsson & Lauber, 2006; Mautz, 2007; Hake, Fischer, Venghaus, & Weckenbrock, 2015). The research in this thesis confirms the significance of this earlier work. Observations made during interviews and in the review of documentary sources revealed how firms and individuals ascribed PV technology a variety of meanings. For example, interviewees referred to aspects of perceived business and employment opportunities, to the desired role of PV in society as a means for a more secure and sustainable energy source, as well as for gaining independence from incumbent utilities. It is important to recognize the embedment of the sectoral innovation system in this wider societal context when judging the external validity of the findings (see Chapter 3.5 for a discussion on this matter).

4.2.3 Concluding reflections

The process-centred analysis of the sectoral innovation system offers insights into key mechanisms associated with PV deployment and the reduction of soft deployment costs. In terms of conceptual appropriateness, the SIS framework offered sufficient flexibility to be populated with an expanded dataset, tied to the deployment of technology as opposed to the concept's conventional use in production-centred studies[22]. Based on the identification of theoretical mechanisms in the framework, it is argued that the above-described processes have contributed to soft cost reductions in the sectoral system. At the same time, it is acknowledged that their relative contribution could not be established in this research due to data issues, interrelatedness of process and other feedback effects.

This study holds various implications for policy makers. By disclosing various processes in the PV deployment system, the study emphasizes primarily the importance of stable or growing demand for the generation of deployment knowledge, learning, network formation, specialization and other scale-effects. These processes are, alongside with evolutionary-based principles in demand-side policies, vital drivers of soft cost reduction. The presence of different types of deployment policies and their relation to processes in the sectoral innovation system demonstrate that dedicated, well-targeted policy intervention has the potential to reduce soft deployment costs and thereby boost the competitiveness of PV.

The results confirm and refine prior views that the organizational and institutional processes of PV deployment are deeply embedded in national and sub-national settings. As present experience in PV deployment is distributed highly unevenly across the world, it can be concluded that significant potential for the international exchange of deployment-related knowledge does prevail. This observation triggered interest to further explore experiences gained in the international collaboration on PV deployment knowledge, and it eventually shaped the research design of Paper IV.

[22] According to Malerba (2005), a sector can be defined and delineated by a shared body of knowledge, which still may involve multiple, interrelated technologies. Deployment and operation of turnkey PV systems involves a shared body of *deployment knowledge*, while relying on a variety of interrelated technologies (PV modules, inverters, mounting systems, cabling). Hence, deployment of PV can be defined as a distinct sector, which is delineated (though not isolated) from the upstream manufacturing of PV system technologies, based on *science and technology forms of knowledge*.

4.3 Paper III: Business initiatives to catalyse photovoltaic deployment

4.3.1 Objective and approach

The aim of the research presented in Paper III was to advance knowledge about how downstream firms were able to catalyse PV deployment through dedicated business strategies. The specific objective was to analyse how these strategies addressed commonly recognized barriers to PV adoption. Overcoming barriers has been considered as central to catalysing PV diffusion, particularly in the mainstream consumer segment. Using business model theory as the analytical framework, the study analyses and compares the deployment of customer-sited PV systems in Germany, Japan and the United States. A secondary aim of this comparative study was to understand how the respective business models are dependent on the national context in which they emerge.

The research in Paper III focuses on a distinct segment of the sectoral innovation system that was introduced in Paper II. In terms of actors, the unit of analysis involves solar firms at the downstream end of the value chain and their adjacent ecosystem of suppliers and partners, who collectively engage in the delivery of the customer value proposition.

4.3.2 Main findings

The multiple-case study displays the prevalence of distinctly different PV business models in three major markets, i.e. the United States, Japan and Germany. In the *United States*, third-party ownership (TPO) models became the dominant business model for commercial, institutional and residential end-customers. The focal actor group in the TPO model is so-called solar service firms that act as the coordinating hub between a variety of actors in the deployment system (PV manufacturers, installers, utilities, authorities, financiers) and the end-user of PV. Solar service firms, in collaboration with their partner network, plan, install, own and maintain PV systems on the properties of their clients. A third party generally provides financing. Solar service firms also secure necessary building permits, negotiate grid interconnections and file applications for incentives and tax breaks. Essentially, the model has been described a full-service concept, as all the transactions typically associated with the deployment of a PV system are provided by the solar service firm. Building owners sign up for a power purchase agreement (PPA) and buy the electricity produced by the PV system that is installed on their premises. Terms agreed in the PPA typically guarantee a predictable price over a

15–20 year period, at a level that initially is generally 15–20% below utility rates. A variant of the TPO model are leasing models in which the building owner (as lessee) pays to use the PV system instead of purchasing the generated power via a PPA agreement. In sum, the TPA model offers immediate financial benefits to users, eliminates the need for users to provide upfront finance, and shifts transaction costs and operational risks towards the solar service firm.

In *Japan*, firms from a variety of sectors have engaged in the cross-selling of PV systems since the 1990s, although the majority have been in the construction sector and in particular the prefabricated homes industry. In 2011, about 60% of all prefabricated homes were sold with a PV system, with some house producers selling up to 85–90% of their homes with PV. PV systems are marketed as eliminating all of a household's electricity expenses and as enhancing its energy security, particularly if combined with batteries. Further elements of the customer value proposition are the aesthetic appeal, competitive price, and the low transaction costs involved in purchasing a turnkey home with a PV system already integrated. Furthermore, the expenses for the PV system are generally integrated into the home mortgage, reducing transaction costs and interest rates. In sum, the Japanese cross-selling model particularly addresses issues related to consumer inertia, financing, transaction costs and operational risks.

In *Germany*, the so-called "host-owned feed-in model" was the dominant business model throughout the first decade of the 2000s. Central to the model is that customers purchase and own a PV system, with all electricity generated fed to the grid and reimbursed by the utility according to a regulated feed-in tariff rate. Core elements of the customer value proposition are a green, low-risk financial investment offering a competitive rate of return and some degree of (perceived) independence from utilities. Installer firms can be regarded as the "focal firm" in the analysis, although the PV manufacturing industry has actively shaped the design of the business model and its value chain. Since installer firms are the key focal point for building owners, they play a crucial role in tackling various barriers to customer PV adoption. In all, the German model is characterized by low financial risk, low transactions costs, and the presence of local installation firms that can mitigate user concerns about operational reliability.

The cross-case comparison revealed notable insights about the heterogeneous design and functioning of PV business models in three major PV markets. Findings show that all the business models investigated serve as important catalysts for PV deployment. In all three cases, the customer value proposition inherent to the business model is on a par with or superior to existing offers, reduces complexity and transaction costs and is compatible with existing consumer practices. However, the comparative analysis also shows that PV business models across different geographies differ significantly with respect to the customer value proposition and its creation and delivery. For example, in the US and Japan, key parts of the value proposition involve an easy adoption procedure with low consumer transaction costs, minimal technical risk during installation and operation, and immediate electricity bill savings. On the other hand, PV systems sold in Germany typically were offered with the value proposition of a “green”, low-risk financial investment that promises a competitive rate of return.

Despite these differences across the cases, the findings show how solar firms enhance the customer value proposition through a variety of mechanisms and firm strategies. These involve full-service offerings, the collectivization of risks, as well as turnkey product solutions in combination with advisory support, finance, insurance and various warranties. Also, the use of certification schemes and the building of a trust relationship with customers helped to reduce the degree of perceived risk.

The diversity of the value propositions and the heterogeneity of business model configurations can be explained with the prevalence of different contextual conditions and consumer preferences across the three countries. For example, the research emphasizes that variations in specific national parameters such as homeowners' savings rates, familiarity with leasing schemes, moving rates, transaction costs associated with PV deployment, electricity market design and the policy framework are all factors that have shaped the design of the respective business models. This embedment of business models in geographic settings and jurisdictions implies that models cannot easily be transferred from one context to another. It also implies that PV business models may evolve in response to a changing context.

4.3.4 Concluding reflections

This study shows how solar firms in the US, Japan and Germany employ distinctively different business models for the effective deployment of customer-sited PV systems. These models essentially embody several attributes of product-service systems (PSS) and their configuration responds to case-specific barriers to the adoption of PV. While the US model employs use-oriented (leasing model) and result-oriented (PPA model) PSS strategies, the models in Japan and Germany rather follow the product-oriented category of PSS models. In the latter, firms combine product-sales with a bundle of product-related services in order to reduce customer transaction costs, such as perceptions of risk and uncertainty commonly associated with PV systems.

The evidence gained from the cross-case analysis suggests that the full-service approach of use-oriented and result-oriented business models is likely to prevail in markets where the level of transaction costs barriers to PV adoption are particularly high. The case of the U.S. solar service firms illustrates how third-party firms can handle such barriers more efficiently. PV business models that rely on this full-service approach may be particularly suitable during the earlier phases of market development. During this more formative phase of a PV deployment system, solar service firms can serve as pivotal coordinators and deal more efficiently with market imperfections. However, when PV markets develop gradually, as observed in Germany, the effects of local learning, declining transaction costs and lower PV system prices may undermine some of the rationale for third-party owned models. Furthermore, cost analysis suggests that customer-owned models can offer higher financial returns due to the absence of extra costs such as the solar service firm's margin and transaction costs for business-to-business processes (Feldman, Friedman, & Margolis, 2013). In these situations, customers may direct their attention towards models where they purchase and own the PV system.

Despite its focus on business models and firm strategies, the study carries several implications for policy making as well. In particular, it challenges prevailing policy perspectives and related policy assessment frameworks that have often focused on micro-economic parameters as the key parameter affecting PV diffusion. This study emphasizes, however, that for the case of private users, value is not solely created through financial incentives but also benefits from the removal of various barriers and transaction costs. It can be assumed that successful solar firms generally have a good understanding about the "true" needs of their clients. The design of PV deployment policies may therefore benefit from this more holistic knowledge about user needs. Findings across the cases suggest that users cherish the easing of legal-administrative processes, the presence of financing solutions and the minimization of risks during the operational phase of the PV system. These findings are relevant for the design of integrated policy packages that centre on a more holistic understanding of user needs, beyond the sole considerations of economic aspects.

4.4 Paper IV: International policy initiatives to foster deployment knowledge

4.4.1 Objective and approach

The objective of this study was to map and assess the international policy-driven network for PV deployment knowledge. In order to enhance the understanding of the performance of this network, the research in Paper IV focused on the following questions:

(1) How conducive was the structure and composition of the network to the generation and diffusion of PV deployment knowledge?

(2) How did the network foster interactions between different countries, in particular between groups of countries with different levels of experience in PV deployment?

(3) How did countries' participation in the network correlate with their actual level of domestic PV diffusion?

Pursuant to the overarching aim and objective of this thesis, the point of departure for the research in Paper IV was the presumption that international collaboration on deployment knowledge is considered critical to extending the adoption of PV to a larger group of countries. Broadening the international market base for PV is considered a key contribution to the achievement of global climate targets.

The research in Paper IV builds on the findings of Papers I and II, which clearly demonstrated the importance of the so-called deployment knowledge, involving a variety of knowledge items related to planning, installation, grid integration, finance, operation and maintenance. As shown in Paper II, these heterogeneous groups of actors involved in PV deployment are typically embedded deeply in local contexts and, due to their small size and local operational area, they often have limited ties to international sources of deployment knowledge. Similarly, the findings of Paper III show that PV business models and the knowledge base inherent to these models are distinct to certain geographies. As the Papers I, II and III all comprised in-country case studies, processes and interactions between organisations from different countries remained unexplored. In particular, there was a clear need to investigate inter-country knowledge flows related to PV deployment. The analysis in Paper IV is therefore based on a compilation of 197 international collaboration projects that were established under the auspices of the European Commission and the International Energy Agency from 1989 to 2017. Based on network theory and using social network analysis methods, the study characterizes the topology, composition and longitudinal development of the international network that emerged from these projects.

4.4.2 Main findings

The findings of the network analysis illustrate the development, growth and geographic expansion of the network over a period of three decades, and they bring to light a number of aspects regarding the significance of the network in the deployment of PV. In response to the first question posed in Paper IV, the structure of the network as a whole was characterized by using the social network analysis parameters of *cohesion*, *presence of cohesive subgroups*, and *network centralization*. This analysis showed that the network provided favourable conditions for PV deployment knowledge to flow freely between participating organizations. Furthermore, it was proposed that network centralization and the presence of a relatively established core of organizations and countries likely had positive effects with regard to knowledge transmission, coordination and (opinion) leadership. Furthermore, the findings display effects of path dependency in terms of the geographic composition of the network. For example, the initial core countries of the network maintained their relative central position over the three decades of the analysis, and most countries with more peripheral positions in the network only gained moderate increases in centrality over time.

The review of the 197 projects shows that, over time, the network was made up of an increasingly diverse number of organizations that collaboratively worked on a wide range of technical and non-technical themes related to PV deployment. These included, for example, knowledge on solar resources, planning and installation, standardization, quality management, grid integration and architectural integration, as well as economic, policy and market aspects. The network facilitated the generation of these knowledge resources through project platforms that pooled complementary competencies from a diverse set of actors. Among the 1256 participating organizations, the most common types found were universities and R&D organizations, consulting and engineering firms and manufacturers of PV components, as well as utilities and energy agencies. Additional categories of organizations included business associations, installers, users, municipalities and other government bodies.

In order to answer the second question of Paper IV, the participating countries of the network were categorized, depending on their experience and time of PV adoption, into four groups (*Pioneer, Follower 1, Follower 2, Low-adopter*). The analysis of network ties between these four groups revealed a steadily increasing intensity of interactions between them. It can be concluded that the network facilitated the transfer of PV deployment knowledge from more experienced countries towards less experienced ones. This data suggest that the network could have had a role in contributing to the uptake of PV in follower countries. In fact, the evidence shows that an increasing number of organizations from follower countries joined the network over time. Presumably, this contributed to the build-up of domestic knowledge capacity in these countries and eventually translated into accelerated PV adoption.

Thirdly, in the attempt to assess the relevance of the network in fostering PV deployment, the research investigated the correlation between countries' position in the network and their levels of domestic PV diffusion. A country's position in the network is essentially the sum of the collective participation of organizations based in it. The parameter of *node centrality* was used to characterize the positions of 52 countries in the network. The results of this analysis show a moderate linear correlation between countries' node centrality and their national PV diffusion rates. This correlation needs to be interpreted with caution, however, as the causal relation between a country' centrality in the network and national PV adoption can be of a two-fold nature. On one hand, a country's central network position is the reflection of intense ties with other (experienced) countries, and it thereby grants access to external knowledge resources. These resources can be vital for the build-up of domestic knowledge capacity and the formation of domestic deployment systems. On the other hand, high levels of PV adoption may further reinforce a country's prominent and central position in the network. For example, pioneer countries have been attributed as benefiting from their reputation as forerunners and they are attractive for other countries to partner with (cf. Protogerou, Caloghirou, & Siokas, 2013).

Furthermore, an additional observation made relates to the importance of network centrality in different phases of the technology cycle. The analysis shows that late followers (*"Follower 2 countries")* exhibit rather peripheral positions in the network. This suggests that, in later phases of the technology cycle, effective PV deployment may be less reliant on the follower country's participation in international knowledge collaboration networks. There are several possible explanations for this finding. Firstly, follower countries are likely to benefit from knowledge spillover, in particular from unprotected types of PV deployment knowledge that was initially created and subsequently codified by organizations from pioneering countries. Secondly, follower countries may also have benefited from other technology transfer mechanisms than the policy-driven knowledge collaboration network investigated in this study.

4.4.3 Concluding reflections

The findings of Paper IV provide insights into the structure and composition of a policy-driven international collaboration network on PV deployment knowledge. As such, the study sheds light onto the interconnections between different national-scale deployment systems. It is important to note, however, that policy-driven collaboration networks make up only one layer of a more complex set of mechanisms of international knowledge transfer[23]. Future research may investigate the role of these other mechanisms in tying together national PV deployment systems.

Knowledge about the structure and composition of the policy-driven knowledge network is of particular value to countries with limited or non-existing participation in the network. In particular, policy leaders who pursue scaling up PV in their countries may want to support the engagement of their national resource centres in the international PV community. This research has identified a relatively small number of highly interconnected organizations that have long-standing experience in relation to PV deployment. Newbies to the network may preferably seek to establish ties with these centrally located actors in order to attain access to well-developed knowledge capabilities.

From an analytical point of view, it is important to note that social network analysis method is primarily advantageous for the analysis of large quantitative datasets. The outcomes of the analysis can approximate the structure and intensity of interactions between a large number of organizations. The method, however, is more limited in answering questions about the actual diffusion and assimilation of knowledge, and how this external knowledge effectively and efficiently contributes to the formation of domestic deployment systems. Developing such insights requires complementary methodological approaches and may include the creation of additional intermediary indicators in order to trace processes along various causal chains.

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[23] Prior literature in technology transfer has emphasized the role of a range of mechanisms of international knowledge transfer. These include licensing (Able-Thomas, 1996; Lewis, 2007), trades in goods and services (Brewer & Falke, 2012; Wan, Baylis, & Mulder, 2015), mobility of skilled personnel (Choi & Johanson, 2012), foreign direct investment (Borensztein, De, & Lee, 1998), institutional financiers (Martinot, 2001), global industry platforms (Gosens, Lu, & Coenen, 2015) and technology standards (IRENA, 2013), as well as transnational institutions and institutional transfer programmes (Blohmke, 2014; Gosens et al., 2015; Kang & Park, 2013).

5 Reflections and implications

The aim of this chapter is to highlight the main results and contributions of the thesis as a whole. Based on the collective results of the research, the purpose is to provide answers to the research questions, to indicate the contributions to conceptual and methodological aspects in the field, to draw certain implications for policy makers and business practitioners, and to identify issues for further research.

5.1 Core research contributions

In addressing the research objective, the results obtained from the analysis of the case studies in this thesis enhance insights about the emergence of selected socio-economic structures related to PV deployment. Furthermore, the findings enhance insights about how the development of these structures contributed to the enhanced competitiveness of PV. Three research questions have guided the enquiry of specific aspects of the research:

RQ1: How have the emergence of deployment-related inter-agent relations, knowledge base and institutional context formed a PV deployment system?

RQ2: How have public polices and business initiatives shaped these processes?

RQ3: How has the formation of a deployment system contributed to a decline in (soft) deployment costs, transactions costs and other barriers?

The findings are based on the analysis of selected empirical experiences gained in several countries, primarily Germany (Papers I, II, III, IV), as well as Japan and the United States (Papers III and IV), and to some extent inter-organizational interactions involving another 52 countries, mostly from Europe and the OECD (Paper IV). Using multiple analytical frameworks, the findings from the four research papers offer complementary insights into particular aspects of the PV deployment system. Here, it is important to note that the notion of a deployment system does not imply the presence of a single global system, but rather the conceptualization of a patchwork of national-scale systems that are interconnected with each other. The presentation of the collective results is organized around the three research questions. The research also offers a number of conceptual and methodological contributions.

5.1.1 Contributions in relation to the research objective

Responding to *research question 1* and primarily based on the case of Germany, the research has characterized and conceptualized the PV deployment system in terms of its key actors, its knowledge base, its networks and interactions, and its institutional context. Actors involved in the deployment of PV include firms in the downstream segment of the value chain as well as private, public and non-profit organizations with auxiliary functions. The research has particularly highlighted the presence and importance of actors' inter-organizational interactions, which took place in a large variety of formats. Interactions occurred as part of inter-firm networks in the value chain (Papers II and III), public-private interactions (Papers II and IV), and firm-user interactions (primarily Paper III; also in Papers II and IV). Networks formed at local and national levels (Papers II and III) as well as internationally (Paper IV). The research identified both formalized as well as more ad-hoc and temporary types of interactions. Interactions were found to occur during specific projects in deploying PV (Papers II and III), as well as a part of collaborations in the development of knowledge and regulative institutions (Papers II and IV). It is a key argument in this research that interactions involved highly heterogeneous stakeholder groups (Papers II, III and IV) who contributed with their respective resources to the creation of a comprehensive body of knowledge that has been pivotal for the effective deployment of PV.

The research illustrates how a comprehensive knowledge base related to PV deployment formed over the course of three decades. PV deployment involves a variety of knowledge areas including technology (Papers I, II, IV), planning and installation (Papers II and IV), legal-administrative compliance (Papers II and IV), business models and marketing (Paper III), and finance (Papers I, II, III, IV). The research also shows that there is a significant degree of interplay between the science-and-technology knowledge associated with the hardware components of a PV system and the knowledge involved in deploying this hardware into local physical, organizational and institutional infrastructures. Although these two knowledge domains are not isolated from each other, their creation is located at different spatial levels. Particularly, the deployment-related knowledge base is to a significant degree specific to more local geographies and jurisdictions (Papers II and III). Furthermore, the research indicates the presence of the transnational spillover of deployment knowledge, in particular from pioneer countries towards follower countries in PV deployment (Paper IV).

The research shows how the actors, networks and knowledge base associated with PV deployment are embedded into the specific socio-economic and institutional structures of different geographies. Institutional structures include a wide set of formal policies, regulations and standards, and these shape the activities of downstream actors in the value chain (Papers II and III). Specifically, the research shows how deployment-focused solar firms designed their business models in unique ways and how these models have been moulded by a set of contextual market-based and institutional conditions (Paper III). However, the socio-economic and institutional context is not static and the research illustrates the co-evolution between institutional context, technology and actors as the PV deployment system formed and grew in a pioneering market (Paper II).

In response to *research question 2,* the research underlines the critical role of public policies and business initiatives for PV deployment. It is notable how a multitude of different types of policies were instrumental in shaping the PV deployment system in a variety of ways. Firstly, this thesis reemphasizes findings of the prior literature about the critical role of policies for the creation of demand and formation of markets for renewable energy technologies, in particular during earlier phases of the technology lifecycle. Building on the prior literature, this research offers a complementary and more granular perspective as to how demand and market expansion were instrumental in forming the structure of the deployment system and enabled various processes within this system (Paper II). Demand growth triggered the formation of the value chain for the local deployment of PV and enabled specialization of firms' value proposition and their workforce. Additionally, demand and market expansion have been conditional for numerous other processes in the sectoral system, including agents' interactions, knowledge generation, learning, diversity creation and various other scale-effects, which eventually contributed to the reduction of soft deployment costs.

Secondly, the research shows how public policy supported the formation of collaboration networks related to the creation and exchange of deployment knowledge, both at national (Paper II) and international levels (Paper IV). Networking was triggered both through market mechanisms ("pull/demand mechanisms") (Papers II and III) as well as through push mechanisms, such as publicly funded collaboration projects (Papers II and IV). The support of these networks was particularly critical during the early phases of the formation of the deployment system, at a time when knowledge-generating interactions between firms (and other actors) were still underdeveloped. These findings demonstrate the importance of systematic and comprehensive policy approaches that require customization to different phases of local market development, as well as different stages in the technology cycle. In particular, large-scale deployment policies are likely to substantially benefit from preceding efforts in incubating, nurturing and fine-tuning the deployment knowledge base and institutional parameters at more local levels.

Thirdly, the research revealed how a variety of legal-administrative processes related to building law, grid integration, policy instruments, finance and tax law contribute to the composition of soft deployment costs and constituted additional barriers to deployment (Paper I). Findings show how governments, public authorities and standardizing bodies at various levels clarified and, in many cases, eased legal-administrative procedures in relation to PV deployment. For example, evidence from Germany shows how amendments in local building law, national building codes and tax law were made in order to accommodate the specifics of PV (Paper II). Furthermore, utilities, standardization bodies and quality management initiatives engaged in the development of technical codes, as well as quality and safety standards (Paper II). Cross-case analysis (Paper III) also showed how governments, through various regulations and dedicated PV deployment policies, shape the contextual environment for PV business models, and thereby partially determine which business models are viable in their jurisdictions.

Fourthly, findings from the research re-emphasize the need of policies to anticipate and timely respond to market developments, in particular cost developments. Dynamic support policies, such as incrementally declining feed-in tariff rates for newly commissioned PV systems (Germany, Paper II) are important to reduce the risk of over-subsidizing PV deployment and gradually tighten the selection environment. The research suggests that a reasonably tight selection environment and competitive pressure appear to be important drivers of incremental technological and organizational innovation, and thereby can contribute to the reduction of soft deployment costs.

With regard to the role of the business sector, findings from the cases of Germany, Japan and the United States show that private firms started engaging in the deployment of PV by exploiting the opportunities that opened up through demand-side policies. In particular, firms took initiatives in forming the downstream segment of the PV value chain. In this thesis, cross-country research (Paper III) clearly shows how networks of firms collaboratively engage in the creation of a value proposition that is offered to (prospective) users of PV. The design and functioning of these value networks vary significantly across different geographies, confirming earlier research about the local nature of PV deployment systems. Specifically, the findings show that the leadership in forming the downstream segment of the value chain was taken by firms from distinctively different sectors, including manufacturing, housing development, and intermediary developers and solar service firms. Relations in downstream value chains were found to be both of long-term formal nature as well as of ad-hoc character, where networks reshuffled between different PV projects (Paper II). It is notable that firms across different markets (Paper III) engaged in long-term relationships with their clients and users of PV systems, an approach that was valuable in reducing risks that customers may perceive with the long-term operation of a PV system.

Evidence primarily obtained from the German case (Paper II) shows that solar firms also engaged heavily in the formation and diffusion of PV deployment knowledge, in particular via learning and interacting in deployment (Paper II), by arranging workshops and training courses for business partners (Paper II), and by participating in international knowledge collaboration networks (Paper IV). Furthermore, solar firms engaged in the development of technical codes and guidelines, for example through their participation in standardizing committees (Paper II). Through their membership in solar advocacy associations, firms were also able to shape the institutional context, such as the legal-regulative framework related to PV deployment.

In all, the research has unpacked and added knowledge to the complexity of PV markets and to different processes associated with deployment. These findings underline the need to assess (future) deployment policies in a more comprehensive and integrated manner than is often practised by current rational economic-engineering approaches that typically focus on aspects of cost-effectiveness and return-on-investment from an adopter perspective. It was also found that concepts from the domain of business management, such as customer value creation, can offer more comprehensive insights into the non-economic motives of adopters.

With regard to *research question 3*, the research aimed to establish understanding between the formation of the deployment system and a decline of (soft) deployment costs, transactions costs and other barriers. During the early design phase of the entire research in this thesis, the decision to focus on the downstream segment of the PV value chain was justified by the significance of this segment for the overall competitiveness of PV. In particular, prior research (see Paper I) had shown that soft deployment costs comprise a significant part of the upfront costs. Besides, various other transaction costs and barriers were found to impede the deployment of PV. In response to research question 3, this research suggests that the formation and advancement of a PV deployment system resulted in a decline in soft deployment costs (Paper I). For example, evidence from Germany shows that soft deployment costs for planning and installation decreased by 65–85% between the early 1990s and 2012. Using the experience curve approach, this decline was found to correspond to a learning rate of 10–12% (Paper I). Findings of the experience in the United States, Japan and Germany also show how innovative business model configurations, embodying different attributes of product-service-systems, contribute in principal to the reduction of customer-sited transaction costs and other barriers (Paper III).

Although the research has unpacked the role of various deployment-related processes in the reduction of soft costs, it acknowledges the complexity of the system under study and the associated methodological challenges. Understanding this complexity more fully would deserve further research and the advancement of appropriate analytical toolkits. Despite these limitations, there is compelling evidence that justifies the use of public resources during the formative phase of deployment systems for PV and (possibly other cleaner technologies). Such public spending can be considered learning investments that eventually pay off in the form of reduced costs and higher levels of the technology's competitiveness. Although discussed earlier in relation to PV technology hardware and the associated international innovation system, this research emphasizes that the use of public resources in supporting deployment at more local levels can be justified with the anticipated effects in learning and soft cost reduction.

In conclusion, the results illustrate the emergence of the deployment system in terms of inter-agent relations, the growth and diffusion of the knowledge base and related learning, as well as the development of the institutional context. These processes were found to be complex, highly interdependent, and they evolved over several decades. The research approach of using a number of different conceptual frameworks proved to be valuable for characterizing and assessing the deployment system at different analytical levels of analysis, ranging from more myopic perspectives towards system levels. Furthermore, the use of multiple methods enabled studying networks and associated flows of knowledge in qualitative and quantitative terms, and across different spatial scales.

Due to its empirical nature, the research contributes to the knowledge base on PV deployment, in particular to the literature about long-term longitudinal developments. As the empirical focus is the downstream segment of the PV value chain, the research also adds novel insights to the wider body of the innovation system literature, which has paid less attention to these aspects. In all, knowledge obtained in this research is of high relevance for designing future policies and business strategies for the scale-up of PV.

5.1.2 Methodological and conceptual contributions

The research provides a variety of methodological and conceptual contributions, thereby expanding the frontier of existing frameworks used in the field. The following sections summarize these contributions paper by paper. Table 4 also provides an overview.

Firstly, in Paper I, the experience curve concept is used for the investigation of the dynamics of specifically *soft deployment costs*, as opposed to its prevailing application in the PV technology field for the study of module costs. In doing so, the research emphasizes the need to account for the effects of inter-project learning in deployment. In particular for the market segment of distributed PV, inter-project learning in planning and installation is rapid due to short project implementation cycles, as well as high modularity and standardization. Therefore, the research presented in Paper I proposes that, for the study of cost dynamics in PV *deployment*, the variable of "cumulative number of installed systems" should be considered as a complementary or alternative proxy indicator for experience in deployment.

In Paper II, the development and empirical application of a process-centred perspective of the sectoral innovation system concept for the study of cost reductions offers a conceptual contribution to the wider literature on innovation systems. In prior applications of innovation system theory, the rate of technology diffusion is typically the dependent variable and has been used to assess the performance of the innovation system. The role of cost reductions as an intermediary variable between the development of the innovation system and the rate of technology diffusion in the growth phase of the technology cycle has hardly been investigated. The novel framework developed in Paper II expands the applicability of innovation system concepts by building a link between reductions in deployment costs and technological, organizational and institutional forms of incremental innovation. Drawing on Malerba's (2002) conceptualization of the sectoral innovation system, the framework focuses on the identification of a number of processes that serve as intermediate variables between the system's structure and its performance, explicitly cost reductions. The processes under investigation are (1) demand and market expansion, (2) interactions across firms, other organizations and consumers, (3) knowledge generation and learning, (4) diversity generation and selection, and (5) institutional development. Considering that the diffusion of emerging technologies into mass markets is closely intertwined with its price/performance ratio, the framework further unpacks the innovation process and offers more granular insights. In doing so, the framework seeks to build a bridge between two major streams of the technology change literature, i.e. the abstracted representations of technology learning in experience curve studies and the contextualized accounts of innovation system studies. A second conceptual novelty of Paper II is the use of an innovation system concept for the study of *deployment* processes. Unlike earlier PV innovation system studies that focused on PV manufacturing sectors (e.g. Klitkou & Coenen, 2013; Lo, Wang, & Huang, 2013; Quitzow, 2015), the research in Paper II also demonstrates the applicability and usefulness of innovation system approaches to downstream segments of the PV value chain.

In Paper III, a novel contribution involves the conceptualization of PV business models in a wider set of contextual, region-specific conditions. In the prior business model literature, the primary unit of analysis has been a focal firm (or focal sector) and the investigation of organizational configurations in relation to value creation and value capture. In this literature, aspects external to the value chain, such as the institutional framework, market context and other cultural factors have received little consideration in business model conceptualizations. In the study presented in Paper III, actors of the value chain still remained in the focus of the business model analysis. However, as a conceptual novelty the research identified and acknowledged a number of contextual conditions specific to the deployment of PV. These conditions are distinct to national contextual environments and include factors such as the policy framework, transaction costs, the electricity market, the building sector and consumer-related factors. Understanding the presence and relevance of these contextual conditions for the design of PV business models has important implications for both academics and practitioners. Specifically, the dependence of business models on context implies that they cannot easily be transferred from one geography to another, and that business models may evolve in response to a changing context.

Finally, Paper IV applied and tested some novel data sampling approaches in the field of social network analysis. Conversely to earlier energy network studies, sampling for the network analysis was rather specific and targeted in terms of technology scope, but quite broad in terms of geography and programme scope. By focusing on grid-connected PV only, the sampling strategy allowed the exploration of the correlation between network features and the diffusion rate of a distinct technology. Furthermore, sampling a number of different EU and OECD programmes enabled, in comparison to earlier programme-specific evaluation studies (e.g. Protogerou et al., 2013; Roediger-Schluga & Barber, 2006), a broader geographic coverage of a collective international knowledge network.

Table 4: Overview of conceptual and methodological contributions in the four papers

Paper	Conceptual framework	Conceptual and methodological contributions
I	Experience curve concept	• application of the experience curve concept for the study of the dynamics of *soft deployment* costs • use of the variable of *cumulative number of installed systems* as an alternative proxy indicator for experience to account for the particular effects of *inter-project learning in deployment*
II	Sectoral innovation system theory	• development of *process-centred* perspective of the sectoral innovation system concept • use of innovation system theory for the study of *incremental innovation* and *cost reductions* • empirical application of innovation system concept for the study of the *deployment segment* of a technology value chain
III	Business model theory	• conceptualization of PV business models in a wider set of *contextual conditions* • identified contextual conditions include factors related to policy framework, transaction costs, electricity market, building sector and consumer-related factors
IV	Network theory & social network analysis	• data sampling employs *broad cross-programme approach*, and *targeted focus* in terms of value chain segment (deployment) and technology application (grid-connected PV)

5.2 Implications for policymakers and business practitioners

For those stakeholders interested in enhancing the diffusion of PV, this section elaborates briefly on several policy considerations related to the deployment system of PV. Responding to earlier calls for more integrative energy policymaking that extends beyond the assumptions of neo-classical economics, the findings from this research offer several implications.

In this context, it is emphasized that the deployment of PV is embedded into broader societal discourses related to environment, visions of the future energy system and social learning processes (see Paper II). Policymakers have only limited ability in shaping these discourses, particularly in a short-term timeframe. Therefore, contextual aspects need to be taken into consideration when judging the external validity and the universality of claims that were obtained from the study of specific cases in this thesis. It is therefore accentuated that the implications presented in this section should be interpreted as overarching policy design guidelines and that they cannot substitute the case-specific ex-ante assessment of policies.

The policy implications presented in this section can be of interest for three main target groups: (1) policymakers interested in advocating the deployment of PV in general, (2) policymakers in countries with high soft deployment costs, who wish to converge these towards best-practice levels, and (3) policymakers in countries with presently low adoption rates, who wish to learn from the experiences of pioneering countries in PV deployment. The guidelines are organized according to the following themes and design principles.

Justify local policy intervention. Firstly, this research supports the notion that the use of public resources through PV deployment polices can be justified as an investment into more local forms of learning. To that end, a comprehensive assessment (as attempted in this thesis) is critical. The findings of the thesis show and unpack how such forms of more local experience in deployment is gained among a broad group of domestic actors as national PV markets grow, and how, as a consequence, soft deployment costs decline (Papers I and II). Hence investment in learning and local experience can translate into lower costs for future adopters of PV. Lower costs can translate into higher adoption rates, which will bring along various societal benefits typically associated with the use of renewable energy. Unlike for PV technology hardware, such as PV cells and modules, the spatial scope of this experience gained in deployment is rather of national and local character. Although certain forms of PV deployment knowledge appear to spill over across geographic borders (Paper IV), local actors often only have limited access to international sources of deployment knowledge. Furthermore, PV deployment knowledge needs customization to the climatic, institutional and market context of different geographies. Hence, the research emphasizes the rationale for PV deployment policies to be operationalized at national (and sub-national) levels in order to develop more local experience and stimulate a reduction of (soft) deployment costs.

Recognize the multiple benefits of deployment policies. Secondly, and related to the previous point, the research emphasizes the importance of recognizing the multiple effects of local deployment policies. Such assessments need to extend beyond standard assessment parameters of deployment policies such as PV market growth and economic return-on-investment for adopters. This research shows in particular how growth in demand induces the generation of deployment knowledge, learning related to deployment, the formation of networks, and various scale-effects, such as specialization. Collectively, these processes are critical drivers of soft cost reduction. The research findings show that these processes develop over longer time periods and also depend on anticipation of continued future demand (Papers I & II). Ensuring and legitimizing long-term and predictable deployment policies in a climate of political debates can potentially benefit from a more holistic understanding of the multiple benefits of these policies in terms of deployment knowledge, human capital and soft cost reduction. In this regard it is considered important that analytical tools for the assessment of deployment policies incorporate additional parameters that measure progress of the various dimensions of local experience gained in deployment. Furthermore, recognizing and carefully nurturing these learning investments is particularly critical when transforming policy-induced markets for PV. The more recent experience of the German PV market as of 2012 (Paper II) illustrates the risk of sudden market disruptions and potential loss of competence and skills that have accumulated across a broad range of actors involved in deployment.

Acknowledge the value of systematic policy intervention. Thirdly, the development of local PV deployment systems can benefit from support through a combination of different types of policy intervention. This research clearly illustrates the value of a combination of push and pull approaches, such as the support of niche experimentation, establishment of public-private research partnerships and learning platforms, enabling grid-access, and creation of demand. In particular, findings show the value of deploying different policy approaches in a systematic manner. During the early phase of the technology cycle, publicly supported research partnerships that examine early stages of deployment (e.g. 1000-roofs programme & battery storage evaluation programme in Germany; Paper II) are vital to gain knowledge and experience about technical, economic, institutional and social aspects. Once the foundational knowledge base and actor networks have formed, polices directed at the creation of more large-scale demand – as exemplified through the combination of the feed-in tariff scheme with the 100,000-roofs soft loan programme in Germany (Paper II) – have been found to trigger stronger engagement of businesses in further developing knowledge and establishing network structures.

Streamline legal-administrative procedures. The research emphasizes the presence and significance of soft costs and transaction costs that arise from various legal-administrative rules and processes (Papers I & II). For example, regulatory requirements and bureaucratic processes related to local permitting requirements can substantially add to deployment costs. Equally, administrative processes related to taxation law, corporate law, finance and ease of access to public support schemes exhibit additional (transaction) costs to (prospective) users of distributed PV (Papers II & III). Cross-country findings (Paper III) indicate that customer transaction costs exhibit a barrier to PV adoption and that (solar) firms specifically seek to remove the associated burden from their clients. Given the significance of transaction costs, policy makers also carry responsibility in streamlining excessively complex and burdensome rules and routines in relation to PV deployment. Findings from Germany show how cooperation across a wide range of actor groups, including legislators, authorities, courts, standardizing bodies, utilities, solar advocacy associations and firms, was involved in developing the institutional framework (Paper II). This included the facilitation of rules and routines in relation to building permits, grid connection, and taxation.

Understanding and managing soft cost reductions. The research generated knowledge about the pace of reductions in soft deployment costs as a function of cumulative experience, as expressed in the learning rate (Paper I). This type of knowledge is important in policy analysis, in particular for economic ex-ante assessments of demand-side policies that strive for constant profitability of PV systems installed under future contracts. Conversely, underestimating future cost reductions can result in excessively generous demand-side policies that may deter market actors from striving for more cost-effective PV deployment. Findings in this research propose that demand-side policies that consider evolutionary-based principles can support soft cost reductions. For example, it is concluded that the step-wise decline of feed-in tariff rates in Germany created selection pressure, signalling to actors across the value chain the need for continuous incremental cost reductions (Paper II).

In addition, the research draws attention to the slower pace of soft cost reduction, in comparison with the rate of hardware cost reductions. Evidence from Germany shows that the learning rate for soft costs has been significantly lower than the respective learning rate for PV modules (Paper I). If this divergence in the learning rates between soft and hard cost items persists, the proportion of soft deployment costs in the cost structure of PV systems will increase further. In response to the growing significance of soft costs, policy makers may take dedicated action to manage them. This may involve the benchmarking of soft cost developments against the numbers as identified in this research, as well as against targets of long-term roadmaps that might be established.

Support network formation where no market mechanisms prevail. This research shows that policies can make important contributions to the formation of domestic (Paper II) and international (Paper IV) knowledge collaboration networks. Policy makers may consider to actively supporting deployment-related knowledge networks, particularly in situations where market mechanisms for their formation do not exist. Overall, the research indicates that the large majority of actors involved in the deployment of distributed PV primarily operate in national or sub-national contexts (Papers II & III). This situation stands in stark contrast to the more internationally oriented actor structure involved in the R&D and manufacturing of PV hardware. Given the relative isolation of domestic markets for distributed PV, the research shows the significance of policy-driven initiatives in catalysing network formation for the transnational creation and exchange of deployment knowledge (Paper IV). In this context, it is important to note that most forms of PV deployment knowledge are of a non-proprietary nature, as opposed to the R&D and scientific forms of knowledge associated with PV modules and inverters, for example. Hence, and considering the positive externalities associated with the dissemination of knowledge and experience in PV deployment, the continued and expanded support of international collaboration networks is desirable. In particular, policymakers of countries with limited or no historical participation in these international networks are advised to support stronger engagement of their national resource centres in the international PV community. Research findings show the presence of a core group of organizations with long-standing experience in the international network on deployment knowledge (Paper IV). Countries with no or limited experience in PV deployment may preferably seek to establish ties with these established knowledge resources centres.

Analyse the contextual environment. The research also holds several implications for managers of solar firms. Particularly, comparative cross-country research (Paper III) draws attention to the presence of a broader portfolio of successful PV business models. Despite the diversity of theoretical options available to solar firms, it is important to recognize that different PV business models rely on particular contextual conditions, including jurisdictions, consumer preferences and the presence or absence of various other drivers and barriers. Therefore, business models are unlikely to work equally well in different geographies. Business managers who wish to narrow down the potential business model options in a first step can benefit from analysing a number of region-specific parameters. This thesis proposes a set of contextual conditions that offer initial guidance in facilitating this analysis (Paper III).

Offer comprehensive product-service packages. Furthermore, for solar firms that sell towards mainstream user groups, research findings illustrate the value of comprehensive product-service offerings in reaching this market segment (Paper III). In particular for private consumers, it is emphasized that value is not solely created through financial incentives but also relies on the removal of a range of barriers and transaction costs. This research shows that solar businesses were able to enhance private consumer value by developing comprehensive product-service offerings. These can be designed in fundamentally different ways, such as leasing models, power-purchase agreement models, as well through other types of long-lasting firm-customer relationships. Their joint feature is that the deployment of PV is not a one-off task of planning and installation, but also encompasses services and customer-support throughout the PV system's entire operational phase.

Integrate deployment-related aspects into frameworks for policy assessment. This research has unveiled numerous aspects in the PV deployment system that are critical for a more holistic understanding about potential intervention points for catalysing deployment into a desired direction. In order to operationalize this knowledge, it needs to be integrated into the analytical tools that support decision-making. As discussed previously, the relative absence of deployment-related aspects in standard assessment frameworks is a limiting factor in striving towards more holistic PV policies. Hence, the incorporation of knowledge about the deployment system, such as the knowledge partially investigated in this research, into policy assessment frameworks could potentially catalyse more integrative policy making in relation to the scale-up of PV. This process would benefit from the empiric testing, refinement and mainstreaming of these novel assessment frameworks.

In conclusion, the implications presented in this section echo earlier calls (e.g. Miller, Richter, & O'Leary, 2015) of bringing socio-energy system design into energy policy and governance. The implications particularly challenge present energy and climate policy assessments and debates that are often dominated by neoclassical economic-engineering concepts. For examples, PV deployment policies have often focused on the provision of financial incentives or the setting of targets only (e.g. Moosavian, Rahim, Selvaraj, & Solangi, 2013; Polo & Haas, 2014; Sarasa-Maestro et al., 2013; Zhai, 2013), with the underlying assumption that the internal rate of economic return for the adopter is the key parameter affecting PV diffusion. However, the findings of this research demonstrate the complexity of PV deployment systems and the need for comprehensive policy assessments and packages that intervene at multiple levels and consider context-specific issues.

5.3 Further research

This research analysed selected empirical experiences gained in the deployment of PV. Given the complexity of the identified socio-economic structures in PV deployment systems and their specific local nature and context-dependency, various opportunities for further research exist.

Firstly, the validity of the findings from this research could be complemented through the investigation of additional empirical cases, in particular regions that exhibit different socio-economic parameters than the ones selected in this thesis. Recognizing the potential contribution of PV in meeting growing energy needs in emerging economies as well as other low- and middle-income countries, future research work about the past, present and future of PV deployment systems could be directed at these (prospective) follower markets. This research needs to be conducted in the light that the PV technology cycle, including the body of deployment knowledge, has advanced considerably during the past three decades. Hence, enquiries may explore present and potential mechanisms and forms of inter-organizational cooperation about the transfer and customization of PV deployment knowledge towards follower countries. A related line of research could further investigate the role of policy-driven international knowledge collaboration networks for the formation of domestic deployment systems in follower countries.

Secondly, further work could examine future pathways of PV deployment systems from a variety of angles. This is an important area for future research as the envisioned scale-up of PV and broadening of applications will require continued development of deployment systems. For example, the cost-effective and large-scale integration of intermittent renewable energy sources into electricity grids will critically depend on new forms of knowledge, continued learning and development of the institutional framework. Similarly, jump-starting the market segment of building-integrated PV (BIPV) will require new forms of collaboration between the PV industry and the building and construction sector. Another aspect that has received less empirical attention is how solar firms within distinct geographies adapt their business models in response to changes in their contextual environment. From a policy perspective, exploring these aspects can be important to anticipate possible effects of policy revisions on the business model of solar firms.

Thirdly, this research aimed to explore the links between various processes in the PV deployment system and the dynamics of soft costs. Despite the use of system-oriented approaches and theories, additional research could shed further light onto the detailed mechanisms between different parameters. For this line of research, new methodological toolkits are needed to further establish causality and to understand the relative contribution of different processes in reducing different types of soft costs. Gaining such knowledge would be important in order to further improve and refine the design of various types of deployment policies.

Finally, given the widespread use of assessment tools and energy models in energy and climate policy design, future studies could examine opportunities to integrate the findings obtained in this thesis into the mechanics of these tools. This suggested direction for future research conforms with prior requests to provide more realistic representations of micro-economic decision-making in energy models (Kolstad et al., 2014).

6 Conclusions

This thesis advances knowledge related to the deployment of distributed solar photovoltaics. Based on an examination of the experience in pioneer countries in the deployment of distributed PV (primarily Germany; as well as the United States & Japan; to some degree other EU and OECD countries), the thesis conceptualizes structures and processes related to PV deployment with the notion of the *deployment system.*

In this *system-oriented conceptualization,* PV deployment is illustrated to rely on the collaborative actions of and interactions between heterogeneous stakeholder groups, including solar firms, utilities, banks, governments, users and non-profit initiatives. Furthermore, results show the creation, accumulation and transfer of a comprehensive knowledge base related to deployment, from both domestic and international viewpoints. This PV deployment knowledge involves multiple dimensions (technical, financial, legal-regulatory, quality, marketing, etc.) and processes of local learning were found to be critical for the effective integration of PV technology into the physical, organizational and institutional infrastructures of distinct geographies. In fact, results show that structures, processes and strategies related to PV deployment depend significantly on geographic, institutional and cultural context.

A second key theme of the research relates to the nature, level and dynamics of non-hardware or *soft costs* associated with PV deployment. While prior research has raised attention to the significance of soft costs in the economics of PV, findings from the longitudinal analysis of the German PV market emphasizes that soft costs can decline significantly as a result of the accumulation of local experience in deployment. The research elucidates such forms of experience through various evolutionary concepts, including demand, knowledge creation and learning, inter-organizational interactions, competition, diversity creation and selection, as well as the alignment of regulatory institutions. From a policy perspective, findings about the softer aspects of technology learning and associated cost reductions are important to justify the use of public resources in supporting the formation of more local stakeholder capacities.

The thesis holds several implications for the design of *public deployment policies*. Most importantly, it calls for a holistic understanding of deployment systems, as such knowledge is critical in enabling more integrated and systematic approaches to policy intervention. Depending on the state of the technology lifecycle and of local market development, deployment policies may be directed at demand creation, network formation, knowledge and awareness, streamlining of legal-administrative regulations and a variety of other measures that contribute to the formation of well-functioning local PV markets. The research also emphasizes the need to include deployment-related aspects, as investigated in this thesis, into policy assessment frameworks in order to strengthen their analytical capacity and thereby support decision-making towards more integrated PV deployment policies.

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Solar photovoltaic (PV) technology has the potential to become a central building block in a global transition towards low-carbon energy systems. This doctoral thesis provides a system-oriented perspective of experiences gained in PV deployment in a number of pioneering markets, including Germany, Japan and the United States. The research results show how PV deployment relies on the collaborative actions of a multitude of actors who also engage in the creation, accumulation and transfer of PV deployment knowledge. The build-up of local experience results in a decline of soft deployment costs, thereby enhancing the competitiveness of PV. Furthermore, the thesis investigates how various types of business models of solar firms can catalyse the deployment of PV.

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