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Diffusion of dynamic innovations:

A case study of residential solar PV systems

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Abstract

In the literature on diffusion of innovations, it is widely known that the characteristics and socio-environmental settings of adopters do evolve in space and time. What about innovations themselves? During the diffusion process, don't some innovations continuously alter in space and time? If so, how does the dynamic character of an innovation influence the diffusion process? In previous research, it has been often assumed that innovations do not continuously alter or get modified when diffusing from a source to potential adopters. This assumption may mean that the innovation is invariant as it diffuses in time and space—i.e., the innovation does not have a continuously dynamic character. Is it always the case in practice?

A single form of an innovation is not always necessarily compatible with the preferences, limitations, and residential settings of adopters. The innovation might appear in different forms when it diffuses in space and time, i.e., it is "dynamic". This PhD thesis aims to explore how dynamic innovations diffuse in space and time—a relatively understudied topic in research. In doing so, it distinguishes between the diffusion of dynamic innovations and other kinds of innovations. Anchored on the case of diffusion of residential solar photovoltaic (PV) systems, this thesis is composed of a cover essay and six appended papers. The first two appended papers are systematic literature reviews, aiming at understanding the state of the art of the theoretical and contextual research domains. The third paper is based on a case study in southern Germany and explores the diffusion of a dynamic innovation at adopter level. The fourth paper is empirically focused on a local firm's business model, which is assumed to be a key to understanding the mechanism behind the diffusion of dynamic innovations. The fifth paper is based on lead market hypothesis and tries to explore the diffusion of innovations at the regional level. The sixth paper studies a semi-hypothetical case and offers an innovative method to forecast the diffusion of innovations in general.

The contribution of this PhD thesis lies in three research dimensions: context, method, and theory. Firstly, the thesis takes the existing theories (e.g., diffusion of innovations theory and lead market hypothesis) and methods (e.g., case study) and applies them in different contexts of the diffusion of residential solar PV systems: the individual, sub-national, and national level. Secondly, it proposes a new research method, namely the finite element method for forecasting the diffusion of innovations, based on an existing theory (e.g., wave-like diffusion of innovations in time and space) and context (e.g., solar PV systems). Last but not least, the cover essay of this thesis takes the findings of the appended papers and employs an extension of theory of diffusion of innovations. In doing so, it includes the role of the dynamic characteristic of innovations that do alter in time and space during the diffusion process.

Overall, the findings of this thesis indicate that the diffusion of dynamic innovations is different in nature, and continuous efforts of change agents are critical for enhancing the diffusion of such innovations. Change agents are especially important to help potential adopters to find out and develop the form of innovation that best fits their needs, limits, and preferences, which are heterogeneous in space and time.

Keywords: Dynamic innovations; diffusion; residential solar; photovoltaics; time; space.

Sammanfattning

I litteraturen om innovationers diffusion är det allmänt känt att användarna (adopters) av innovation och deras omgivning förändras över tid och rum. Hur är det med själva innovationerna? Genomgår inte vissa innovationer en kontinuerlig förändring under diffusionsprocessen? Om så är fallet, hur påverkar en sådan dynamik själva diffusionsprocessen? Tidigare forskning har utgått från att innovationer är oföränderliga under diffusionsprocessen, dvs. de har inga dynamiska egenskaper. Detta antagande innebär att innovationernas dynamiska egenskaper bortses från. Är det även så i praktiken?

En nyutvecklad innovation är sällan anpassad till var och en av användarnas begränsningar, preferenser, begränsningar och geografiska läge. Därför är innovationer "dynamiska" och förändras under själva diffusionsprocessen. Denna avhandling syftar till att undersöka spridningen av dynamiska innovationer, ett relativt underforskat ämne. På så vis skiljer denna forskning mellan dynamiska innovationer och andra typer av innovationer. I denna avhandling studeras innovationers dynamik under diffusionsprocessen genom en fallstudie av "residential solar photovoltaic (PV)" –system. Avhandlingen består av en kappa samt sex bifogade artiklar. De två första bifogade artiklarna är systematiska litteraturöversikter med syftet att ge insyn och förståelse till det vetenskapliga, teoretiska och kontextuella forskningsområdet. Den tredje artikeln är baserad på en fallstudie av PV spridning i södra Tyskland och utforskar dynamisk innovation på brukarnivå. Den fjärde artikeln är empiriskt inriktad på affärsmodellen hos ett lokalt företag - som antas vara en nyckel till att förstå mekanismen bakom spridningen av dynamiska innovationer. Den femte artikeln är baserade på den så kallade "lead market"-hypotesen och utforskar spridningen av innovationer på regional nivå. Till sist är den sjätte artikeln en semi-hypotetisk fallstudie som föreslår en innovativ metod för generell uppskattning utav innovationsspridning.

Avhandlingens bridrar till tre olika forskningsdimensioner: kontext, metod och teori. För det första, tillämpar avhandlingen av befintliga teorier (t.ex. teori om innovationsdiffusion och den så kallade "lead market hypothesis") och metoder (t.ex. fallstudier) för att spridningen utav ”residential solar PV” system på individ, regional och nationell nivå. För det andra utvecklas en ny undersökningsmetod, nämligen finita elementmetoden, för att förutsäga spridningen utav innovationer. Tills sist, gör avhandlingens kappa ett teoretiskt bidrag inom litteraturen för innovationers diffusion med hjälp av de bifogade artiklarna. Därmed tar avhandlingen hänsyn till de dynamiska egenskaperna innovationer kan ha och deras förändring i tid och rum under diffusionsprocessen.

Sammantaget visar avhandlingens resultat att dynamiska innovationers spridning är annorlunda. Därför är kontinuerliga insatser gällande förändring avgörande för att stöda spridningen av dessa innovationer. Olika aktörer visar sig vara viktiga i att för att hjälpa potentiella användare att ta reda på och utveckla den typ av innovation som bäst passar deras behov, begränsningar och preferenser.

Nyckelord: Dynamiska innovationer; diffusion; bostäder sol; solceller; tid; utrymme.

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Everything in life happens for a reason. When I started my journey from Germany to Spain (and to Sweden) in 2011 September, I did not know this opportunity might turn into a great platform to discover the knowledge about the society and, consequently, myself. I did not know that the degree of Doctor of Philosophy (PhD) would not help or change me, but my day-to-day interaction with people would do so. I have extremely enjoyed having the opportunity to learn from my peers, friends and colleagues from all over the world, particularly those I met in Spain, Sweden and Germany. These people have inspired me in every aspect, both academically and socially, and have definitely influenced who I am today and how this PhD Thesis has been developed.

Actually, I spent only one year, the academic year of 2013-2014, at KTH Royal Institute of Technology in ***Sweden****. However,* ***Cali*** *(my PhD supervisor at KTH) and I have been able to establish a close collaboration since 2011. Cali deserves very special thanks. He has always supported me, believed in me and motivated me in every way possible. His countless comments on my academic work and his continuous support during the whole process have guided me in the best way possible. Moreover, I thank* ***Johan*** *for his valuable feedback and help on my FEM model during my stay at KTH. During this one year, I was surrounded by amazing people at INDEK:* ***Monia, Fabian, Maxim, Jonatan, Pranpreya, Niklas, Yasmine M., Mats, Richard, Sudipa, Nidal, Michael, Annika, Matthew, Serdar*** *and* ***Vicky****. Thanks to these people, I was amazed by the friendly and productive atmosphere at KTH and I felt like home in Sweden!*

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Stockholm, 28.10.2015

Emrah Karakaya

List of appended papers

This thesis is based on six papers which are enclosed at the end.

Paper A

Karakaya, E., Hidalgo, A., & Nuur, C. **(2014)**. Diffusion of eco-innovations: A review. *Renewable and Sustainable Energy Reviews*, *33*, 392–399.

Paper B

Karakaya E., & Sriwannawit, P. **(2015)**. Barriers to the adoption of photovoltaic systems: The state of the art. *Renewable and Sustainable Energy Reviews*, *49*, 60-66.

Paper C

Karakaya, E., Hidalgo, A., & Nuur, C. **(2015)**. Motivators for adoption of photovoltaic systems at grid parity: A case study from Southern Germany. *Renewable and Sustainable Energy Reviews*, *43*, 1090–1098.

Paper D

Karakaya, E., Nuur, C., & Hidalgo, A. **(2016)**. Business model challenge: Lessons from a local solar company. *Renewable Energy*, *85*, 1026–1035.

Paper E

Karakaya, E., Nuur, C., Breitschopf, B., & Hidalgo, A. Lead markets at sub-national level. Under review in *Technological Forecasting and Social Change.*

Paper F

Karakaya, E. Finite element method for forecasting the diffusion of photovoltaic systems: Why and how? Conditionally accepted in *Applied Energy.*

Index

List of Figures

List of Tables

1. Introduction

Diffusion of innovations theory (Rogers, 1962) is an influential framework for understanding how new ideas, products, or services spread from sources to adopters within a social system. For decades, the theory has been used by many scholars from a variety of disciplines, such as economics, sociology, engineering, and management (Sriwannawit and Sandström, 2015). In this field, micro-level analysis on diffusion (Leonard-Barton and Rogers, 1979; Rogers and Bhowmik, 1971) meso-, and macro-level approaches (Beise, 2001; Griliches, 1957; Mansfield, 1961) have enriched our understanding on why some particular innovations do diffuse and while others do not. However, one of the shortcomings of the most research on diffusion is the assumption that innovations do not continuously evolve or get modified in the process of diffusion. This assumption means that the innovation is invariant as it diffuses, i.e., the innovation is not dynamic. Is this always the case of innovations in practice? What happens if an innovation has continuously and dynamically changing characters?

Individuals are heterogeneous in their preferences (e.g., in terms of esthetic aspects and lifestyle) and they are limited by a different set of factors (e.g., financial or climatic). There are also a variety of residence households (e.g., single-family vs. multi-family houses). In this context, sometimes a single form of an innovation is not necessarily compatible with each sort of preferences, limitations, and residential settings. If this is the case, more actors are involved for easing the diffusion process. As a result, such innovations are changed on the spot by an adopter or a change agent when diffusing from sources to new adopters. This change of innovation can be in different forms, such as in technical capacity, appearance, or functions. The change can be so continuous that the innovation gets modified in every adoption that takes place in diffusion process. Consequently, the same innovation might appear in different forms in space and time. In this thesis, these types of innovations are referred to as "dynamic innovations." In doing so, the emphasis is on a key aspect which was not the main focus of attention in previous diffusion of innovations literature. The term, "dynamic," refers to the variant character of an innovation that tends to change or alter continuously; this means that the same innovation exhibits a high variety or diversity in the dimensions of space and time.

The dynamic character of innovations has been partially discussed by the previous innovation literature. However, not much attention has been paid to the variant character of an innovation that continuously changes or alters during diffusion. For example, it is widely known that, as a part of dynamic industrial change, firms can introduce relative changes to the existing innovations, which result in incremental innovations, or thorough changes, which result in radical ones (Dewar and Dutton, 1986; Henderson and Clarl, 1990). Also, a dominant design of innovation can emerge, shaping the destinies of firms by acting as both a creative and destructive force (Utterback, 1996). In addition, when it comes to adoption of innovations, adopters can re-invent the innovation in the process of its adoption (Rogers, 2003). However, neither the re-invention of innovations by adopters, nor the different forms innovation in the market (such as incremental, radical innovations or a dominant design), necessarily refers to a continuous dynamic change of innovation that occurs in every adoption possible that takes place during diffusion of the same innovation.

An interesting example of dynamic innovations could be the residential solar photovoltaic (PV) system, which generates electricity from solar radiation for the households. Residential solar PV systems have a variant character, exhibiting a rich variety in space and time. Even in the same neighborhood, each adopter tends to have a different form of residential solar PV systems. The variety of residential solar PV systems is evident in several forms, such as nameplate capacity, mounting system, or physical appearance. The reason behind this diversity is threefold. Firstly, not every adopter has the same preferences or the same type of residence. Secondly, the nameplate capacity of solar PV systems in the market is continually evolving with time (i.e., week to week). Thirdly, solar PV system installers—e.g., local solar firms—continuously re-invent the innovation depending on the need and limitations of potential adopters.

This PhD thesis deals with both the theoretical and contextual research domains of innovation diffusion. In the theoretical domain, it focuses on what a dynamic innovation is and how it diffuses. The dynamic innovation concept provides a coherent approach to distinguish the innovations that have a continuous evolutionary change during the each step of diffusion from those that have static or incremental states. In doing so, it builds on the theoretical foundations provided by the diffusion of innovations theory (Rogers, 2003), the spatiotemporal model of diffusion (Hägerstrand, 1967), and the lead market model (Beise, 2001). In the contextual domain, it focuses on the diffusion of residential solar PV systems. This empirical case is important to study for two reasons. Firstly, it contributes inductively to our understanding of diffusion of innovations that have a dynamic character. Secondly, it extends the current debate on diffusion of environmental innovations, innovations that avoid or reduce environmental harms, such as residential solar PV systems.

1.1. Research aim and question

The diffusion of innovations is often considered as a complex phenomenon (see Garcia and Jager, 2011; Kiesling et al., 2011). This means that if an innovation is adopted by some individuals, it might (or not) give a rise to diffusion on meso and macro scales. What are these micro, meso and macro levels? In the literature, the definitions of micro, meso and macro levels are diverse (see e.g., Geels, 2010; Hannah and Lester, 2009; MacVaugh and Schiavone, 2010; Waarts and van Everdingen, 2005). For the purpose of this dissertation, these levels are defined as same as the level of observation on diffusion. The micro level is the individual level; the meso level is the regional level, and the macro level is the global level. Although, the term, "region," is often used for sub-national territories (see e.g. Cooke and Morgan, 1998), "region" in this thesis refers to any particular geographic or political area of the world. This means a region can be a country, a sub-area of a country, or a set of countries

As Rogers et al., (2005) argues micro and meso level behaviors influence each other. Micro-level is vital to be understood, as it leads to the emergence behavior at the meso level. The meso level is also important to be observed, as it influences micro behaviors as a feedback. Diffusion of dynamic innovations, particularly those that have environmental innovation and public good characteristics such as solar PV systems, constitutes even more complex patterns. One the one hand, policy makers or incumbent actors might intervene the process at national level, i.e., meso level (see e.g. Jacobsson and Lauber, 2006). On the other hand, the influence of local actors could drive the diffusion at individual or sub-national level, i.e., micro or meso level (see e.g. Fabrizio and Hawn, 2013; Graziano and Gillingham, 2014). Therefore, I believe, in order to understand the diffusion of dynamic innovations, it is better to consider the multi-levels of phenomenon. Interplaying between micro and meso level of diffusion, this thesis raises the following research question:

- How do dynamic innovations, which are continuously evolving in the diffusion process, diffuse at micro and meso level?

Thus, the aim of this thesis is to explore how dynamic innovations diffuse in space and time. In doing so, it tries to distinguish between diffusion of dynamic innovations and other kinds of innovations. Although the previous research on diffusion has studied such innovations e.g., residential solar PV systems, empirically, the importance of the dynamic evolutionary character of these innovations have been often ignored. However, the diffusion of an innovation that has a dynamic character during the diffusion process may be different than those of which does not have such characteristic. In the diffusion process, the time- and space-dependent variables are composed of not only the characteristics of adopters and socio-environmental settings, but also the characteristics of innovations.

1.2. Outline of the thesis

This thesis presents a cover essay and six appended papers, four of which have been already published in international journals (see Karakaya and Sriwannawit, 2015; Karakaya et al., 2016, 2015, 2014). With the appended papers, the thesis is based on a multi-methodological approach. (see Table 1).

Table 1. Overview of papers

	Level of observation	Method	Focus
Paper A	-	Literature Review	Environmental innovations
Paper B			Solar PV systems
Paper C	Micro level diffusion	Case Study	Solar PV systems
Paper D	Business model		Solar PV systems
Paper E	Meso level diffusion	Indicator-based	Both innovations in general and solar PV in particular
Paper F		Finite Element	

Paper A (*Diffusion of eco-innovations: A review*) and paper B (*Barriers to the adoption of photovoltaic systems: The state of the art*) are literature reviews. Paper C (*Motivators for adoption of photovoltaic systems at grid parity: A case study from Southern Germany*) and paper D (*Business model challenge: Lessons from a local solar company*) are based on case studies in Southern Germany. Paper C is underpinned by diffusion of innovation theory (Rogers, 2003), while paper D is primarily framed through a business model concept (Morris et al., 2005). Paper E (*Lead markets at sub-national level*) is based on an indicator-based approach. It tries to extend the lead market model of diffusion (Beise, 2001) from the national level to a sub-national level. Paper F (*Finite element method for forecasting the diffusion of photovoltaic systems: Why and how?*) proposes a new method for forecasting the diffusion of solar PV systems in time and space.

This cover essay (i.e., kappa) mainly builds on the findings of the appended papers and offers a meta-analysis of them. When writing this cover essay, I have tried to take the discussions to the next level, i.e., diffusion of dynamic innovations. In doing so, the cover essay positions the papers in a theoretical context and provides substantial extension of both diffusion of innovation theory (Hägerstrand, 1967; Rogers, 1962) and lead markets hypothesis (Beise, 2004, 2001).

The structure of the kappa is as follows. The introduction section is followed by six sections. The second section presents empirical and conceptual background related to residential solar PV systems. The third section discusses the theoretical underpinnings of the kappa and its appended papers, while the fourth section briefly explains methodological approaches used in this dissertation. The fifth section is dedicated to the summaries of the appended papers. The sixth section presents the discussions by synthesizing the findings of appended papers, trying to answer the research question of this dissertation and explaining the theoretical and methodological contributions along with the industrial and policy implications. Last but not least, the seventh section tries to summarize the conclusions of this dissertation and presents the limitations and future research areas.

2. Residential solar PV systems

This section has several purposes. Firstly, it presents the motivation behind studying renewable energy technologies in general and residential solar PV systems in particular. Secondly, it provides a brief description of PV technology and its state of diffusion. Thirdly, it attempts to clarify why residential solar PV systems can be conceptualized as (environmental) innovations.

2.1. Why?

Concerns about scarcity of natural resources, climate change, and geopolitics have prompted governments to support the diffusion of sustainable modes of energy production. As a recent special report from the Economist (2015, p. 3) argues, "*modern life is based on the ubiquitous use of fossil fuels, all of which have big disadvantages. Coal, the cheapest and most abundant, has been the dirtiest, contributing to rising emissions. Oil supplies have been vulnerable to geopolitical shocks and price collusion by producers. Natural gas has mostly come by pipeline—and often with serious political baggage, as in the case of Europe's dependence on Russia. Nuclear power is beset by political troubles, heightened by public alarm after the accident at Japan's Fukushima power station in 2011.*" For a long time, increasing the share of renewable energy share, mainly for replacing the fossil fuels and nuclear power, has been high on the policy agenda of several countries. For instance, the European Union (EU) has set a target of 20% share of renewable energy in the overall energy consumption by 2020 (EP, 2009). This is a part of the process of "democratizing" the energy market (da Graça Carvalho et al., 2011). The democratization of the energy market is often linked to the decentralized structures of electricity production through renewable energy innovations (see e.g. Wirth, 2014, p. 236). In such markets, households do not only have the right to choose between the renewable energy sources (e.g., solar, wind, and biomass) and non-renewable ones (fossil and nuclear fuels) but also to produce energy and distribute it.

There are several sources of renewable energy which are expected to pave the way for this transition towards sustainable modes of energy production. One of these is solar photovoltaic (PV) technology, which generates electricity from solar radiation. One of the ambitions is that the residential PV adopters can generate electricity, consume the part they need, and then supply the rest of the electricity to the grid (if they cannot store it). Although the electricity generated by PV systems account only for 0.7% of the global electricity production and 2.6% of the Europe's (EPIA, 2013; Ren21, 2014), the International Energy Agency (IEA) argues that the sun could be the world's largest source of electricity by 2050, ahead of fossil fuels, nuclear power, and other sources of renewable energy, such as wind and hydropower (IEA, 2014). Through the reduction of production costs and the increase of technology efficiency, solar PV systems could be argued to be becoming competitive when compared with conventional electricity sources in terms of the levelized cost of electricity generation. This cost competitiveness is often referred to the "grid parity," which is a time- and space-specific stage. When solar grid parity is achieved in one region, it means that the cost of generating PV electricity is cheaper than the retail price of electricity.

Recently, in some regions of the world, grid parity of solar PV systems has been achieved. According to the PV parity project, co-financed by the Intelligent Energy Europe programme of the European Commission, Italy, Spain, and Germany did achieve the grid parity in 2012, while Austria, Belgium, Czech Republic, France, Greece, Portugal, the Netherlands, and the United Kingdom had not yet (PvParity, 2013). A recent literature review by Munoz et al. (2014) shows that several scholars believe that achieving the grid parity is an important milestone for wider diffusion of solar PV systems. The hope is that grid parity might make the diffusion of PV systems independent of policy support. But the question is whether this is happening.

2.2. Empirical context

Generally, there are three different ways of generating energy from the sun: passive heat energy that we receive naturally, solar thermal energy which provides us with hot water (e.g. the case of solar thermal heating systems), and photovoltaic (PV) energy that we use to generate electricity to run appliances and lighting (EPIA, 2010). The solar PV system is the field of technology and research related to the devices which directly convert sunlight into electricity; and the solar cell is the elementary building block of the photovoltaic technology (EC, 2007). Solar cells can be made from different semiconductor materials, such as silicon, which is the most widely used material for this purpose. There is no limitation to silicon availability as a raw material as silicon is the second most abundant material in the world (EPIA, 2010). Compared with fossil-fuel-based electricity generation technologies, solar PV systems produce far less life-cycle air emissions. According to Fthenakis et al. (2008), if electricity from photovoltaics replaces electricity from the average grids in the US and Europe, it will lead to at least 89% reductions of greenhouse gas emissions, pollutants, heavy metals, and radioactive species. These pollution reductions are expected be even greater if the PV systems are decentralized systems, such as the ones on the roof-tops of households, instead of centralized ones.

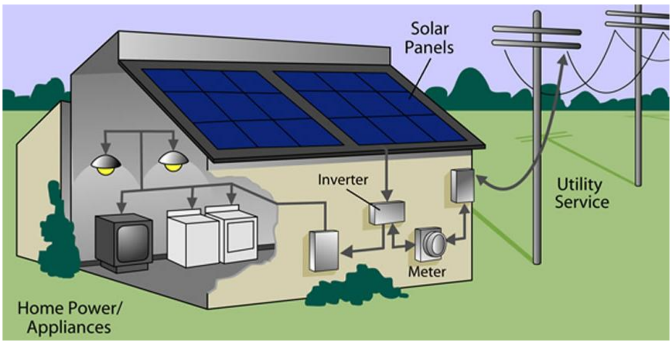
2.2.1. Technology

The history of PV systems goes back to the discovery of photovoltaic effect and the discovery of the fact that sun's energy creates a flow of electricity in selenium in the 19th Century (Petrova-Koch et al., 2009, p. 2). However, the turning point was in the early 1950s, when the accidental discovery of Pearson et al. (1954), the scientists from Bell Labs, took place (Kazmerski, 2006, p. 105). It changed the history of photovoltaic systems. The discovery was to use silicon instead of selenium. In a short period, the scientists invented more efficient PV cells than selenium cells at generating electricity. After this invention, the technology of PV has started to diffuse in different areas of use, such as satellites, cars and aircrafts (see Figure 1).

Sources, from left to right: 1) http://www.corp.att.com/attlabs/reputation/timeline/54solar.html 2) http://nssdc.gsfc.nasa.gov/nmc/masterCatalog.do?sc=1958-002B 3) Schoolgen (2012) 4) SEIA (2010)

Figure 1. Some historical steps for PV systems

Nowadays, the majority of the electricity generated by solar PV systems is located on residential and commercial areas. For example, a PV system on a residential roof-top consists of several parts, the solar PV panels (made of solar cells), mechanical and electronic connections, and inverters (and sometimes batteries) (see Figure 2). The PV systems are usually rated in peak kilowatts (kWp), which is the amount of electrical power that a system is supposed to deliver under maximum solar exposure (Parida et al., 2011, p. 1626).



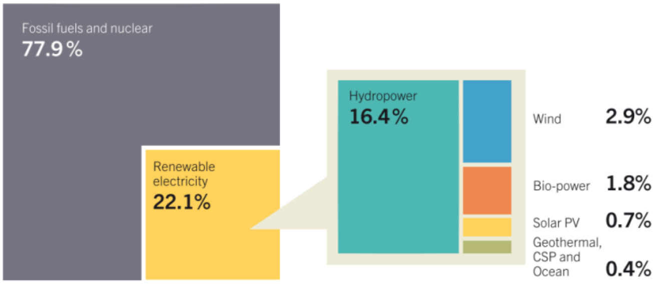
Source: http://www.sundialsolarnh.com/Residential-solar-services.htm

Figure 2. A residential solar PV system on a roof-top

The main manufacturing processes (as well as the technology) of photovoltaic can be currently categorized into mainly two groups: crystalline silicon technology (so-called wafer based) and thin film technology. There are also many different cell types developed recently which are starting to be commercialized or still at the research level (EPIA, 2010). The efficiency of all these PV technologies is diverse (NREL, 2014). The efficiency rates reached by various research and development institutions worldwide are continuously increasing. However, as some of them are laboratory prototype cells, a couple of years may be needed for them to be commercialized. For example, the laboratory prototypes of crystalline Si cells have already reached higher levels of efficiency, but the most of the crystalline Si cells in the market have lower efficiency than those in the laboratories. For many new PV technologies reaching high levels of efficiency rates, the main challenge is the high costs needed for implementation at the commercial level.

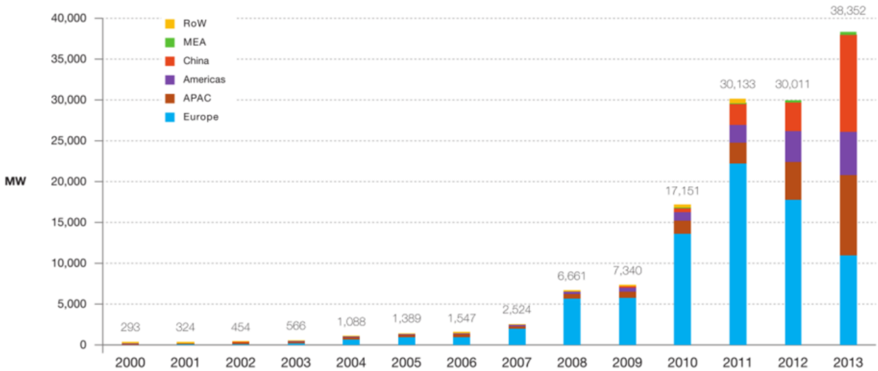
2.2.2.Diffusion

Solar PV systems count for less than 1% in the global share for electricity production (see Figure 3). A recent report from the European Photovoltaic Industry Association (EPIA, 2014) shows the diverse PV diffusion patterns among different regions of the world (see Figure 4). While some regions have a slowdown in their diffusion, others are on the way to achieving a rapid growth. Breaking the long-term domination of Germany, China becomes the top market with its annual installations in 2013, followed by Japan and the USA. The decline in annual installation in European countries was compensated with the growth in China and Asia-pacific countries in the world. Yet, in terms of cumulative installation capacities by 2013, Germany still tops the market with its 27% share on global installations, doubling that of China and Taiwan (13%), Italy (12%), and Japan (10%).



Source: Ren 21 (2014, p. 25). This estimation is based on the end of 2013 as compiled from several sources as explained in p.145 of Ren21 (2014).

Figure 3. Renewable energy share of global electricity production

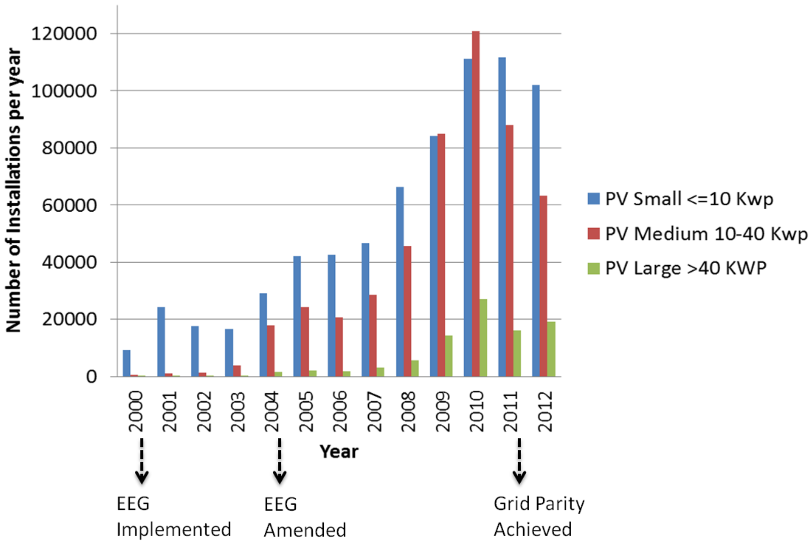


Source: EPIA (2014, p. 18). MEA: Middle East. APAC: Asia Pacific Countries. RoW: Rest of the world. The data for RoW is not available for 2011 and 2012.

Figure 4. Annual installations of PV systems

Germany is usually viewed as the frontrunner country on the diffusion of PV systems. In 2012, solar PV systems generated almost 35% of current consumption on sunny days (Wirth, 2013). Between 2004 and 2010, solar PV diffusion had the fastest growth in Germany, far in front of other renewable energy innovations. Figure 5 presents the evolution of diffusion of solar PV systems in three market segments: small (less than 10 KWp capacity), medium (between 10 and 40 KWp capacity) and large (more than 40 KWp). In this figure, the times of implementation and amendment of the

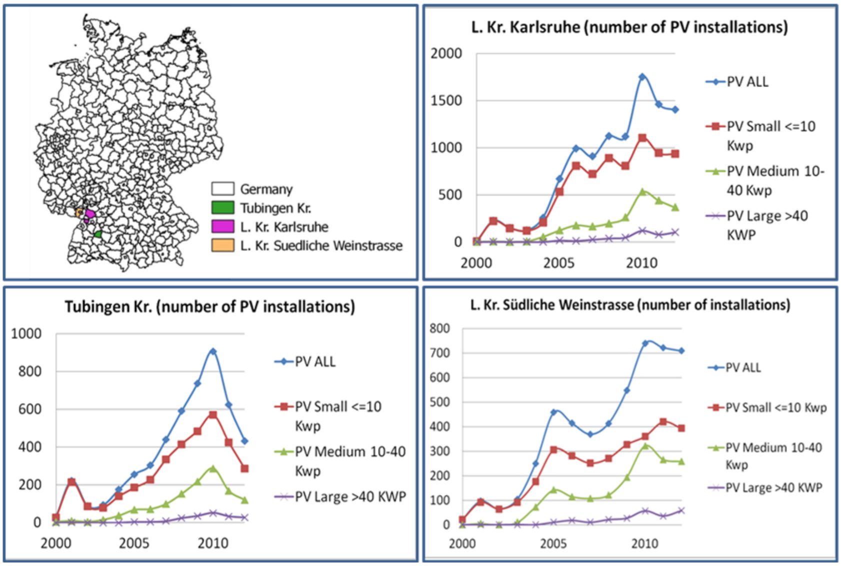
German Renewable Energy Act (EEG), along with estimated time of the grid parity, are plotted. In terms of number of installations, the small PV systems have the largest diffusion in Germany. By 2012 in Germany, PV systems are assumed to be at grid parity—i.e., the price of solar PV electricity can compete with the price of conventional electricity sources (Lettner and Auer, 2012; Pérez et al., 2013; Spertino et al., 2014). How can the cost of solar PV electricity be compared to the cost of conventional electricity sources? One way of doing this comparison is based on the calculation of the levelized cost of electricity (LCOE), €/kW. It is a calculation of the cost of electricity generation based on different variables, such as the initial capital, solar radiation, costs of continuous operation, service life time, and costs of maintenance. When the LCOE of solar PV electricity is below the price of purchasing electricity from the grid, it means that solar grid party has been achieved in the corresponding region.



The data is compiled from the Information Platform of four German Transmission Network Operators for the Renewable Energy Sources Act (EEG) and the Combined Heat and Power Act (KWK-G)

Figure 5. Numbers of yearly PV installations in Germany

Although the PV systems achieved the cost competiveness (grid party) in Germany, there has been a continuous decrease in number of PV installations since 2011, which directly influenced the local firms. Turnovers of many local PV firms have been decreasing, not only because of the declined number of installations, but also because of the decreased price of PV modules. However, the diffusion paths of solar PV installations are not the same all over the country. Depending on the location, different diffusion trajectories can be observed. For example, Figure 6 shows a district analysis from southern Germany. In this comparison, Südliche Weinstrasse (a population of 108,875) has a stable growth in the total number of installations during 2010-2012. However, Tübingen (a population of 212.800) had a relatively rapid decrease in this period. In addition, Karlsruhe (a population of 424.510) presented a rather slightly different pattern: sharp decrease in 2011 and stable growth in 2012.



The data is compiled from the Information Platform of four German Transmission Network Operators for the Renewable Energy Sources Act (EEG) and the Combined Heat and Power Act (KWK-G). The Germany map is plotted via the QGIS 2.6.0 Brighton Software.

Figure 6. Number of photovoltaic installations in three districts

2.3. Innovation or not?

For the purpose of this thesis, PV systems are conceptualized as environmental innovations. However, this raises the questions of why and how this could be possible. In policy discourse, the notion of innovation is used rather loosely. It appears that everything is about innovations. Influenced by policy discourse or not, the diffusion of a variety of innovations has been the subject of study for management and economics scholars for several decades. Innovation, defined as an idea, practice, or object that is perceived as new by an individual or other unit of adoption (Rogers, 2003), is the core of the diffusion process. Innovation is a very broad term and indeed can be anything as long as it is perceived new by adopters. The variety of innovations that are analyzed in the literature goes back to the early scholars of diffusion. For example, Griliches (1957) analyzed the diffusion of hybrid seed corn, which is a product of controlled crossing of specially selected parental strains among American farmers. Mansfield (1961) studied the diffusions of twelve types of innovations, such as a trackless mobile loader and a continuous mining machine among firms in particular industries. The examples of innovations in the literature are many. Solar PV system is just another kind of innovation for adopters. However, from a conceptual viewpoint, one can raise a question worth pondering: Why can electricity generation from the solar PV system be perceived as an innovation? There are two possible arguments for conceptualizing the electricity generation from PV system as an innovation. Firstly, none of the new PV adopters had adopted the PV systems before. Therefore, the solar PV installation is (or will be) perceived as new. Secondly, even in the case of re-adoption, solar PV system installation would still be perceived as new. This is because solar PV systems have been characterized by continuous incremental changes on their efficiency and appearance, and therefore the new installation will be perceived as an innovation by re-adopters as well. Moreover, if PV systems can be conceptualized as innovations, why do I name them as environmental ones? Beise and Rennings (2005) argues that environmental innovations are the innovations that avoid or reduce environmental harms. Is it really the case for the PV systems? This can be an important debate to discuss in detail which will probably go beyond the scope of this thesis. In a nutshell, I am aware of the limitations of the conceptualization PV systems as environmental innovations. For example, the manufacturing of solar PV systems can lead to some negative environmental impacts in terms of waste disposal (Kannan et al., 2006, p. 562) and greenhouse gas intensive production in some particular regions (Hsu et al., 2012, p. 132). In addition, the regional diffusion of solar PV systems may result in global rebound effects—i.e., the reduction of greenhouse gas emissions through PV systems in a particular region may lead an increase of emissions in another region (see Van den Bergh, 2013a, 2013b). In spite of all these, for the purpose of this dissertation, it is assumed that the adoption of PV systems reduce the usage of non-renewable energy sources, such as fossil fuels. This is due to the fact that, in many cases of PV adoption, the electricity generation from PV systems replace the electricity generation from fossil fuels and nuclear energy. As is widely known, the combustion of fossil fuels produces the greenhouse effect and air pollutants. This means that each adoption of PV systems is likely to reduce or avoid the production of greenhouse effect and air pollutants. This is also in line with the research on life cycle analysis that compares the environmental impact of solar PV systems and fossil fuels (e.g., Fthenakis et al., 2008).

Moreover, solar PV systems are often also considered as renewable energy innovations, which are typical examples of environmental innovations (Huber, 2008, p. 361). Renewable energy innovation is any renewable energy related idea, object, or practice that is perceived as new by the adoption unit. The term, "renewable energy innovation," is often used by scholars studying the renewable energy technologies, such as solar PV systems, wind power, biomass, and solar thermal (e.g. de Araújo and de Freitas, 2008; Huijben and Verbong, 2013; Mallett, 2007; Wüstenhagen et al., 2007). Renewable energy innovations and their diffusion bring some particular aspects to the debate. Wüstenhagen et al. (2007) analyze these aspects in three dimensions. Firstly, for the adoption of renewable energy innovations, more than one decision-maker approval might need to be taken. For example, this is a typical case of multi-family residential buildings willing to adopt solar PV systems. Secondly, the adoption of renewable energy innovations has a visual impact on both the adopters and non-adopters. This is mainly because the energy production usually happens where the energy users live. However, for conventional electricity sources, such as nuclear or coal, the production units are easily visible to energy users. Thirdly, renewable energy innovations have high short-term costs.

3. Diffusion of innovations

The term, "diffusion," lies on the core of this cover essay, and correspondingly in all appended papers. In the history of science, diffusion as a term was primarily used in the chemistry and physics in order to define the process of movement of molecules from high-concentrated regions to other regions. Later on, the term was introduced to social science by Tarde (1903). In social science, diffusion is the process by which an innovation is disseminated amongst potential adopters (Teece, 1980, p. 464). Diffusion of innovation theory, written from a sociological perspective, has been popularized since the seminal work of Rogers (1962), who is accepted as one of the most well-known scholars of innovation studies (see Fagerberg et al., 2012).

The following sub-sections present the theoretical basis and brief discussions on the literature gaps that are related to kappa and its appended papers. These include both theoretical and contextual dimensions of research: diffusion of innovations in theory and diffusion of solar PV systems in context. The first sub-section focuses on the role of innovation in diffusion (i.e., public vs. private; high cost vs. low cost, and static vs. dynamic). The second sub-section briefly explains the micro-level dynamics of diffusion, while the third sub-section discusses the diffusion at the meso level.

3.1. Role of innovation

Innovation is the core element of diffusion of innovation process. The assumption is that innovation can diffuse among potential adopters. The characteristics of innovations are important factors for modulating the diffusion process. These characteristics of innovations can be distinguished in three dimensions (1) public vs. private, (2) cost factors, and (3) dynamic characteristics. While the first two dimensions are mainly based on Wejnert's (2002) work, the third dimension is the contribution of this thesis.

Public vs. private

The diffusion of innovations might result in either private or public consequences, or sometimes both. If there are some public consequences at hand, the diffusion process usually involves several actors and collective actions, such as policy makers, organizations, and social movements (Wejnert, 2002). For example, environmental innovations have both public and private consequences, as they avoid or reduce environmental harms for the whole society. The diffusion of environmental innovations also involves policy makers, as it was seen in the case of the Europe 2020 strategy of European Union (EU). As a public consequence, it is widely assumed that the diffusion of environmental innovations will ensure future employment, contribute to economic growth in Europe, and respond to today's major societal challenges, especially environmental (ETAP, 2010). In general, the diffusion of innovations that have public consequences is a more complex and lengthier process in comparison with those that have only private consequences.

Cost factors

The cost of adoption of an innovation could be both monetary and nonmonetary forms, and it is directly or indirectly associated with the innovation (Wejnert, 2002). In general, for high-cost innovations, the economic aspects are often the most important factors for understanding the diffusion of such innovations (Rogers, 2003). When the cost of adoption of an innovation is perceived as high, the potential adopter needs to understand clearly the outcomes, benefits, risks, and costs, both in short-term and long-term, associated with the adoption. That is why high-cost innovations require more time to be diffused and involve more actors for the diffusion process in comparison with low-cost (non-cost) innovations.

Dynamic characteristics

In some cases, innovations do change or get modified in the process of diffusion. The change can be so continuous that the innovation gets modified in every adoption that takes place in space and time. In this thesis, these are referred to as dynamic innovations. A dynamic innovation can evolve during the diffusion phase when the adoption is highly restricted by adopter's settings. Some possible examples could be cornrows hairstyles, as adopted by individuals; solar PV systems, as adopted by households; and internet websites, as adopted by firms. However, some other innovations can be standardized in one or a limited number of forms, appearing in the market on an incremental basis, e.g., automobiles, Facebook, or smart phones. In this case, the innovation does not represent a fully heterogeneous form in space and time, and therefore cannot be easily conceptualized as a dynamic innovation; instead, it is an incremental one. In general, dynamic innovations require an active involvement of change agents. Change agents might help to potential adopters discover and develop the form of innovation that fits best to their needs, limits and preferences.

3.2. Micro level

The micro level of diffusion happens at the adopter level. Adopters are the individuals or other units of adoption that make the decision to adopt the innovation (Rogers, 2003). Any individual can be a potential adopter; however, not all potential adopters necessarily decide to embrace the innovation at any certain point of time. The diffusion rate of innovations, which is the ratio of current number of adoptions to the total number of potential adoptions, is mainly based on the attributes of an innovation as perceived by potential adopters. Rogers (2003) deduces these attributes to be the *relative advantage* (the degree to which an innovation is perceived to be better than the other), *compatibility* (the degree to which an innovation is perceived as being consistent with the existing values), *complexity* (the degree to which an innovation is perceived as being relatively difficult to understand and use), *trialability* (the degree with which an innovation may be experimented on a limited basis), and *observability* (the degree to which the results of an innovation are visible to others).

Research on renewable energy innovations also asserts that adopters are often influenced by the local actors. Wüstenhagen et al. (2007) describe this influence as the role of technology cooperation on the diffusion, at which several actors (technicians, industry representatives, local companies, and so on) take an active role in eliciting the adoption. The actors, in general, correspond to what Rogers (2003) conceptualizes as the efforts of *change agents*. A change agent is an individual (or institution) that influences the decisions of potential adopters in a desirable direction. In the case of renewable energy innovation, the studies on the PV systems in Germany (Dewald, 2008) and wood-fueled heating systems in Austria (Madlener, 2007) have revealed that there are a vast variety of change agents, depending on the space-specific context and particular innovation.

The adoption of renewable energy can also be boosted by the adoption of previous adopters, i.e., *peer effects*. In general, potential adopters are often influenced by what they see and hear from their peers. The peer effect has received a lot of attention from scholars analyzing the academic and health practices (e.g. Trogdon et al., 2008; Zimmerman, 2003). In the case of the diffusion of PV systems, several scholars (e.g. Bollinger and Gillingham, 2012; Graziano and Gillingham, 2014; Müller and Rode, 2013) have also asserted that the peers who have already adopted the PV systems in the same neighborhood increase the diffusion rate among potential adopters. This resonates quiet well with the recent work of Pentland (2014) on social physics. He emphasizes that innovations and good ideas spread faster if the peers have regular physical, e.g. face-to-face, interactions. In a well-connected global world, although the potential PV adopters might have tight virtual connections with their peers from other regions, most of the physical interactions take place in the local neighborhoods. As Graziano and Gillingham (2014) also argue, such a spatial dimension is especially critical for innovations that have both private and public good characteristics, like solar PV systems.

Some empirical studies have emerged and have focused on understanding the adopter-specific factors that influence the diffusion rate of solar PV systems. These factors could be endogenous, originating internally from the adopters, or exogenous, originating externally (e.g. from the climatic and physical conditions), or sometimes a mix of both types. Several scholars conceptualize such factors through a variety of constructs: the desire to be independent from the electricity supplier, familiarity with the technology, religion, education, housing investment of per capita, income level, climatic conditions, limited roof space, and environmental problem awareness (Balcombe et al., 2014; Jäger, 2006; McEachern and Hanson, 2008; Peter et al., 2002; Zhang et al., 2012, 2011). If the innovation has dynamic characteristics, such as solar PV systems, different forms of innovation can alter in diffusion process and, therefore, the innovation can have the opportunity to best fit such endogenous and exogenous factors that are heterogeneous in space and time.

3.3. Meso level

Notwithstanding the dynamic complexity of diffusion (see e.g. Brockmann and Helbing, 2013; Delre et al., 2007), one can still observe the regional differences of diffusion patterns at the meso level. For example, some sub-national regions may be at the frontier at adoption of the innovations, while the others act as lags. In the vast literature on diffusion of innovations, there are myriad examples that show some regions have been the frontrunner (or have potential to be the lead): Montana and Wyoming for home food freezers in the US (Ormrod, 1990), Baden-Württemberg and Bayern for Solar PV systems in Germany (Dewald and Truffer, 2012), New York and Massachusetts for policy innovations in the US (Walker, 1969), and some regions (northern Finland, Paris of France, Lombardy of Italy and Andalucía of Spain) for electrified vehicles in Europe (Zubaryeva et al., 2012).

At the meso level, we can often observe the wave-like diffusion curves of innovations in time and space. This can be associated with the dynamics that a contagion phenomenon can undertake. By this token, based on a case study of the city of Wiesbaden in Germany, Müller & Rode (2013) show that the adopters' decision for adopting PV systems are positively influenced by previously installed PV systems that are located nearby. This phenomenon, as mentioned above, is also known as the peer effect. The potential adopters are highly influenced by the previous adopters in the local neighborhood, resulting in a chain of effects (as if a contagion phenomenon occurs) and, therefore, an s-curve type of diffusion.

Recent literature on sustainable transitions, which analyze the systematic shifts for the adoption of environmental innovations in a variety of areas including renewable energy, has paid attention to the importance of sub-national regions and spatial dimension. For example, Coenen et al (2012) criticize the majority of previous literature for being unable to reflect on the space-specific contexts. In the same line, Truffer and Coenen (2012) argue that there is a lack of regional studies on sustainable transitions. In order to fill this gap, they extend an invitation for research on cities and regions. Addressing this need, some recent studies shed light the understanding of space on sustainable transition, with a special focus on the actors, networks, and institutions (e.g. Binz et al., 2014; Smith et al., 2014). However, little systematic attention has been paid to the diffusion side of sustainable transitions, i.e. diffusion dynamics at the sub-national level.

Beise's (2004, 2001) *lead market model* (i.e., lead market hypothesis*)* is one of the important concepts, shedding lights on the role of demand-side factors in the diffusion of environmental innovations (see Quitzow et al., 2014). Anchored in the demand advantage of Porter's (1990) diamond model, the lead market concept deduces the international diffusion of innovations to the five interrelated innovation-specific attributes of regions: *cost advantage* (factors related to price decreases), *demand advantage* (conditions related to anticipation of the benefit of an innovation), *transfer advantage* (conditions that increase the perceived benefit of innovation by foreigners), *export advantage* (factors that support the inclusion of foreign demand preferences), and *market structure advantage* (conditions that increase the level of competition) (Beise, 2001, p. 85). Consequently, Beise (2004, 2001) argues that if particular regions that have higher advantages in these five attributes adopt an innovation, the diffusion can spread to other regions rapidly.

However, the conceptual and empirical studies, which use the lead market model, have two major limitations: one in contextual dimension and the other in theoretical dimension. In the contextual dimension, this model has been used in many studies, analyzing the global diffusion of innovations, traditionally at the country-level (e.g. Beise and Rennings, 2005; Cleff et al., 2009; Horbach et al., 2014; Jacob et al., 2005; Tiwari and Herstatt, 2012; Walz and Köhler, 2014). However, as Beise (2001, pp. 125–126) already outlines, lead markets can be sub-national regions as well. This can be seen, for example, in the case diffusion of Facebook, the largest global social network to date. It was pre-dominantly adopted by the Northeast region of the US, particularly by the Ivy League universities, before it spread further in the US and then worldwide. However, all previous studies on lead market model have been applied to the diffusion of innovations only at the country level. In the theoretical dimension, the lead market model presumes that a globally diffused innovation is in a single dominant form (Beise, 2001). This assumption is an important theoretical limitation because dynamic innovations do not necessarily diffuse in a single form.

Modeling approaches

Diffusion models have been used to capture life-cycle dynamics of new products, and they traditionally have been applied to forecast the demand for a new product at the meso level (Mahajan et al., 2000). The wealth of research on modeling diffusion of innovations has been impressive, confirming its continuing importance as a research topic (see e.g. Kiesling et al., 2011; Meade and Islam, 2006, 1998). However after the enhanced penetration of communication and other technological innovations, research in diffusion modeling will have to expand its horizons in order to remain timely and abreast of market trends (Peres et al., 2010).

The available models can be categorized into two main groups: "differential equation models" and "agent-based models" (similar to Rahmandad and Sterman, 2008). The term, "differential equation models," refers to traditional models of innovation diffusion, which provides an empirical generalization that is usually based on an aggregation at the cumulative market level. "Agent-based models" refers to the models that consist of a set of agents which encapsulate the behaviours of the various individuals that make up the system by emulating these behaviours (Parunak and Savit, 1998). In differential equation models, the path of the cumulative adoption of an innovation between introduction and saturation is usually modelled by an S-curve, based on Rogers' theory. The pioneer s-shaped diffusion models are those of Fourt and Woodlock (1960), Mansfield (1961) and Bass (1969) (as cited in Meade and Islam, 2006). One of the most used diffusion models in the literature and by the companies has been the Bass model. Bass (1969) presented the first purchase growth of a new durable product in the market.

This model suggests that individuals are influenced by a desire to innovate and by a need to imitate others in the population. After the Bass model, there have been many other models developed. Some of them are based on different mathematical equations while some proposed modifications on Bass model.

Agent-based modelling, within the growing computational power, has been increasingly applied to social and economic problems previously modeled with nonlinear differential equations (Rahmandad and Sterman, 2008). This method is rooted in complexity theory. It indicates that phenomena at the meso level can be understood as emerging from interactions between individuals at the micro level, while meso phenomena may affect the behavioral context at the micro level (Garcia and Jager, 2011). In the innovation diffusion field, agent-based models describes the market as a collection of individual elements (so-called agents) interacting with each other through connections (Peres et al., 2010). These models have been increasingly adopted in diffusion research in recent years in order to overcome the limitations of traditional aggregate models. Kiesling et al. (2011) explain that agent-based models' ability to model complex phenomena in a socio-economic system (e.g. the diffusion of innovations) is one of the most important reasons why agent-based models have gained momentum in recent years. However in the literature, there was a limited use of diffusion models in environmental innovations, especially in renewable energy technology analysis (Rao and Kishore, 2010).

The study of Mesak and Coleman (1992) is one of the first contributions on modeling diffusion of solar PV systems. Extending the model of Bass (1969), they studied the link between government subsidies and the PV systems' diffusion in Kuwait. Other early studies of modeling diffusion of solar PV systems were conducted through a variety of approaches: learning curves (Luque, 2001; Masini and Frankl, 2002), logistic growth function (Watanabe and Asgari, 2004), learning by doing and searching (Kobos et al., 2006), the extension of bass model (Guidolin and Mortarino, 2010), and statistical fixed effects model (Popp et al., 2011). Recently, probably a result of increasing computational power, the number of studies addressing the modeling diffusion of PV systems has been rapidly increasing. Although many scholars has recently used a downscaled unit of analysis at the regional level (Gooding et al., 2013; Higgins et al., 2014; Kwan, 2012), how spatial differences can affect the diffusion paths of solar PV systems in space and time has not been much addressed yet.

4. Research design

"Energy studies must become more socially oriented, interdisciplinary and heterogeneous. Problem-focused research activities that centre on both physical and social processes, include diverse actors and mix qualitative and quantitative methods, have a better chance of achieving analytic excellence and social impact (Sovacool, 2014, p. 530)*"*

This thesis has a multi-methodological approach. The first two papers (A and B) are literature reviews in nature. The papers C and D, at micro- and business-model levels respectively, are conducted through a case study approach. In addition, the papers E and F are at the meso level, based on indicator-based analysis and a finite element method. The papers have been developed in various timelines during the PhD project. For example, the literature reviews were conducted in different periods: paper A during 2011-2013 and paper in 2014. Figure 7 presents the timelines of the appended papers and the kappa. These timelines are calculated according to the time between beginning of data collection and finalizing the manuscript.

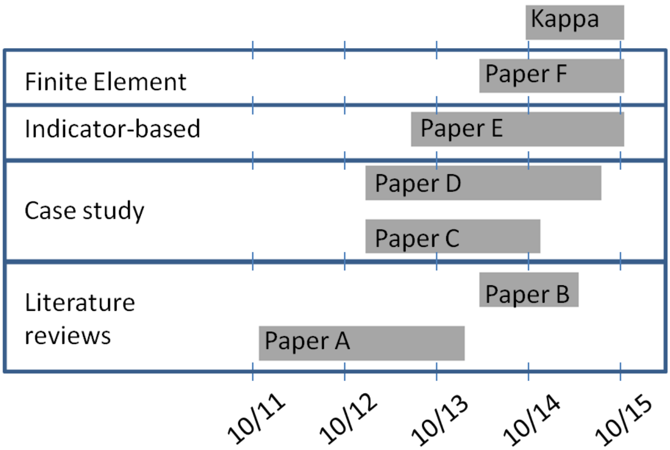


Figure 7. Timeline of kappa and appended papers

In this thesis, each paper has a slightly different combination of spatiotemporal and technological scope. For example, papers C and D are based on cases related to solar PV systems with less than 40kWp capacity in Tübingen in Germany in 2012, while the paper E focuses on the case of solar PV systems with less than 10kWp capacity in whole Germany from 2000 to 2012. In early 2000s, most residential adoptions had less than about 10 kWp capacity. However, in early 2010s, due to increasing technology efficiency, most residential adoptions had less than about 40 kWp capacity. Overall, the six appended papers have been based on a different combination of six data types. Table 2 presents both how these data were collected and which data were used in developing of which papers.

Table 2. Overview of data used in papers

Data	Data collection	Data size	Papers that uses the data
1. Research papers	Extracted from: Google Scholar (A) and Web of Science (B)	1024 papers (A) and 103 papers (B)	A and B
2. Interviews	3-month field study in Rottenburg in Neckar. Data collected in the firm, at the houses of adopters and a regional workshop	18 semi-structured (from 10 to 60 min)	C and D
3. Observations		600 hours	C, D, E and F
4. Internal Firm Data	The firm has given access to internal agreements, technical and feasibility reports of each PV installation, the documentation of each project and the sales database	All the available data from 2004 to 2013	C and D
5. Statistical indicators	Mainly collected from the several statistical offices in Germany	10 indicator for each of 16 administrative states	E
6. Geographic information	From GADM database (www.gadm.org), version 2.0, December 2011	GIS maps of postal and administrative regions in Germany (8,53 MB)	E and F

4.1. Literature review approach

The systematic literature review is a scientific methodology that is able to limit the bias of systemic assembly, critical appraisal, and the synthesis of all relevant studies on a specific topic (Cook et al., 1995, p. 167). According to Cook et al. (1997), systematic literature reviews distinguish from traditional narrative reviews by adopting a replicable and detailed methodology (as cited in Tranfield et al., 2003, p. 209). Recently, systematic literature reviews have become a fundamental scientific activity—for example, as a common part of PhD dissertations or, even sometimes the whole dissertation itself (Daigneault et al., 2012).

In this dissertation, two systematic literature reviews have been conducted (see Figure 8). The first review paper (A) focuses on the emerging field of diffusion of environmental innovations. It maps the scientific body of research, identifies the core contributors, and discusses the main research streams. It is based on a review of all kind of publications (from 1990 to 2012) on the Google Scholar Database. The second review paper (B) focuses on the empirical context of the diffusion of PV systems. It systematically reviews the articles that were published during 2011-2013 in the Social Sciences Citation Index of the Web of Science Core Collection. While the first review paper (A) is an important guideline to build the theoretical framework of this thesis, both review papers (A and B) serve as information sources for generating the theoretical and empirical implications of the papers C, D, E and F, in an inductive approach.

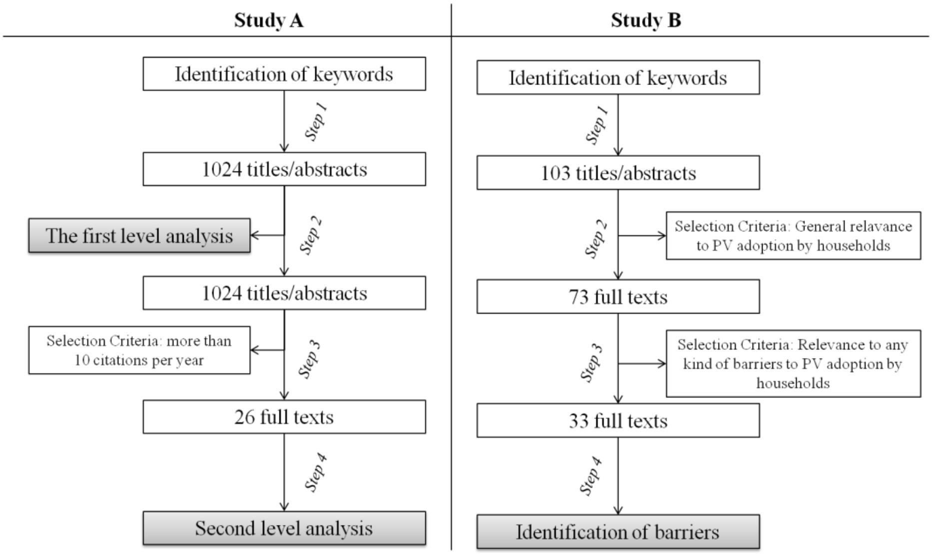


Figure 8. The comparison of two literature review studies

4.2. Case Study

The case study method is traditionally used for various purposes, such as providing description, testing theory, or generating theory (Eisenhardt, 1989). Case studies should not only address theory but also provide real world examples in a new way (Siggelkow, 2007). In this dissertation, the case study method is used in order to provide an in-depth description of the diffusion of a dynamic innovation, a rather under-researched phenomenon. When there is lack of previous research, a case study approach is appropriate for exploring a contemporary phenomenon, gaining a holistic view of complex instances through observation, and searching for patterns (Yin, 2011). The strength of case study lies in its approach to develop empirically collected and context-dependent knowledge with a "multiple wealth of details" (Flyvbjerg, 2006; Lincoln and Guba, 2009; Stake, 2000).

4.2.1. Empirical context

The case study used for papers C and D is based on the findings of a study conducted in Rottenburg am Neckar in southern Germany. It focuses on a local solar firm, Hartmann Energitechnik GmBH (HET). The town and the firm were chosen for two main reasons. Firstly, the town is located in the frontrunner region of PV systems' market formation (see Dewald and Truffer, 2012) and diffusion[1]. Secondly, the firm is one of the pioneer local solar companies in Germany. It has been a part of solar initiative movement (Drücke, 2004) and, consequently featured in the national media (e.g. SB, 2007; SWW, 2004). The firm was founded in 1995 by a local entrepreneur, Thomas Hartmann, a native of the region. He has been also the co-founder of two solar initiatives: Solar-Partner e.V (a network of companies, freelance solar consultants. and partner companies) and Sonnenhaus-Institut e.V (an association of architects, engineers, and managers of the solar industry, focusing on solar-heated and solar-electrified buildings).

Rottenburg am Neckar is located in a well-known region in Germany called "Swabia." It is distinguished by its cultural, historical, and linguistic characteristics. A special dialect of German, Swabian (*Schwabish*), is spoken in the region. Although the region struggled with poverty and scarcity until the beginning of 20th century, it has had significant economic and industrial development later on. Today, Swabians are famous for hating debt, avoiding extravagance, and getting the best deal (*The Economist*, 2014). They are also known as hard-workers; as one old saying expresses it, *"Schaffe schaffe, Häusle baue,"* which can be translated to mean, "*You should work hard.*" Rottenburg am Neckar is today surrounded by several villages, and this geographical area is dominantly full of single/double family houses rather than multi-family apartments. There are many farmers in the surroundings, living as single families with a relatively large amount of land per household.

4.2.2. Data collection and analysis

The data, which was collected during the case study from December 2012 to March 2013, includes 18 semi-structured interviews, approximately 600 hours observation, and the internal data of the company. The interviews, the

[1] Rottenburg am Neckar's normalized cumulative diffusion number, calculated by dividing the number of installations in a spatial area by its population, is *0.026*. This is higher than average values both in southern Germany (*0.015* as calculated through the zip code areas 7 to 9) and the rest of the Germany (*0.005* as calculated through zip code zones 1 to 6).

duration of which varied between 10 min to 1 hour, were conducted with Thomas Hartmann, the employees in the firm, the directors of 4 other partner local solar firms, and the adopters of PV systems. Such diversity in interviewees gave a holistic view in order to understand the diffusion of PV systems at grid parity both from adopter's perspective and firm's perspective. The interviews were conducted at various locations: the firm, the houses of adopters, and a regional workshop. Following a semi-structured interview approach, the interviewer had the freedom to add new questions, based on the flow of the discussions during interviews. Except one interview, the language of the interviews was German. All interviews were electronically recorded. The observations took place both in the firm and in the town. The observations in the firm were conducted through an average of 9 hours/weekday presence for 3 months. As a participant observer (Atkinson and Hammersley, 1994), all of the formal and informal gatherings of the company were attended. In addition, several ongoing PV installations projects were monitored on the site, and a 2-day regional workshop (of 150 participants) was actively attended. The internal data was composed of not only various documents, such as internal agreements, technical and feasibility reports of each PV installation, and the documentation of each project, but also the sales database. Data was analyzed throughout and after the fieldwork. With an insider-outsider team research approach (Bartunek and Louis, 1996) and data triangulation with multiple source of evidence (Yin, 2003), subjectivity was aimed to be avoided. To validate the results empirically, the findings were presented for the firm, both in an internal meeting and, on a later phase, in a written form.

4.3. Indicator-based approach

Indicator-based analysis was used in Paper E, regional analysis at the sub-national level. It is in three parts: the identification of relevant variables for PV context, an assessment of lead market attributes at the sub-national level, and a diffusion curve analysis. Following the methodological approaches in relevant literature (e.g. Beise and Cleff, 2004; Beise and Rennings, 2005; Horbach et al., 2014), in the first part, the results of the case study (see chapter 4.1) is triangulated with a literature review. The data for second and third parts were gathered from several sources:

- The information platform of the four German Transmission Network Operators for the EEG and KWK-G
- Federal and Regional Statistical Offices of Germany (SABL, 2013; SLBW, 2013)
- Other reports and studies (Berthold et al., 2009; Diekmann et al., 2012; Drücke, 2004; Kost et al., 2013)

The second part assesses the lead market attributes at the sub-national level. In order to tackle this, several indicators, which were identified in the previous part, were then retrieved and categorized according to the five attributes of the lead market model. In the last part, spatial diffusion curves were plotted in order to observe the regional differences on diffusion.

4.4. Finite element method

The finite element method (FEM) is one means to model the diffusion of innovations (see e.g. Shinohara and Okuda, 2010; Shinohara, 2012). It is a numerical tool for approximating the solutions of large scale problems that are based on partial differential equations. The advantage of using FEM is the ability to reduce the spatiotemporal continuum problem, which consists of an infinite number of unknowns, to one with a finite number of unknowns (Lewis et al., 2004). Although FEM was originated from the need for solving complex elasticity and structural analysis problems in engineering sciences in 1960s (Huebner et al., 2001), the model has also been borrowed by a number of studies on social phenomena (e.g. Ho et al., 2013; Jiang et al., 2011; Shinohara and Okuda, 2010). FEM is usually implemented in respective steps: one step carries out domain discretization, i.e. meshing, and the other deals with discretization of the equation in respect to both spatial and temporal dimensions. Finally, the model is solved with a numerical software tool, implementing the preprocessing, the main processing, and post processing stages.

5. Summary of the appended papers

The six appended papers constitute a four synchronized steps of the research conducted in this dissertation. Firstly, anchored in two literature reviews (papers A and B), the dissertation tries to shed lights on the accumulated knowledge of diffusion of PV systems and environmental innovations in general. Secondly, at the micro level (paper C), it explores the diffusion dynamics of a local case in southern Germany. Thirdly, at the business-model level (paper D), it illustrates a business-model challenge of a leading local solar company in the same region. Fourthly, at the regional level (papers E and F), it explores the meso-level dynamics of diffusion and how it can be mathematically modeled.

5.1. Papers A and B

On the one hand, paper A analyzes the emerging literature on diffusion of environmental innovations. This paper reveals that the lead-market model (Beise, 2004, 2001), sustainability transitions (Markard et al., 2012), and ecological modernization (Jänicke, 2008) are some of the most relevant research streams that might shed light on the diffusion of environmental innovations, including renewable energy innovations. However, there is a missing link between the Rogers' (2003) theory of innovation diffusion and relevant systematic approaches. On the other hand, based on a systematic review of 103 relevant publications, paper B identifies a variety of barriers to adoption of PV systems in four interrelated dimensions: socio-technical, management, economic, and policy. A varying sets of barriers are faced both in low and high-income economies all around the world, such as (among others) Bangladesh, Kenya, Ghana, China, Japan, Austria, and the United States.

5.2. Paper C

Analyzing the local case in Rottenburg am Neckar, this paper contextually aims to overcome the limitation related to the extant research on the adopters' motives for PV systems at grid parity. The findings demonstrate that achieving grid parity does not necessarily motivate potential adopters for PV systems. In line with Rogers (2003), high compatibility, high trialability, high observability, high relative advantage and low complexity are critical perceptions necessary for wide adoption. In the case study, the solar firm has been observed as an important motivator for the adoption of PV systems, primarily influencing the perceptions of the potential adopters. This is in line with the previous research on diffusion (Dewald and Truffer, 2012; Fabrizio and Hawn, 2013). In addition, the increasing retail prices of electricity, as influenced by policy measures, have motivated potential adopters to be less dependent on the electricity supply and to become self-sufficient in terms of electricity generation. Such desire is often reinforced with environmental awareness, peer effects, and financial stability. These factors confirm the previous research on similar phenomenon before grid parity (Balcombe et al., 2014, 2013; Jäger, 2006). Thus, this means that, albeit the high expectations (e.g. Breyer and Gerlach, 2013; Lund, 2011), achieving the grid parity would not be a very important milestone for the diffusion of renewable energy innovations.

5.3. Paper D

This study describes the business model of a local solar firm, Hartmann Energitechnik GmbH in Rottenburg am Neckar, and the challenge it faces. The challenge occurs not only at the time of grid parity, but also at the time of diminishing feed-in-tariff and declining adoption rates. All these circumstances, along with the decreasing turnover per PV system installation, have resulted in a rapid decrease in the firm's revenue. Although the firm has some possible options to tackle this challenge, such as expanding its market to other regions or coming up with incremental/disruptive innovations, it is reluctant to do either of them. This is because its existing business model is based on "being local," and the fact that existing PV adopters cannot adopt any incremental or radical innovation of PV systems easily due to the feed-in tariff. This challenge illustratively contributes to two streams in literature. The first one is relates to how existing business models can hinder new business models (e.g. Sosna et al., 2010), while the latter is related to how the businesses in energy sector are bound to political policy (Wüstenhagen and Menichetti, 2012).

5.4. Paper E

This paper applies the lead-market model (Beise, 2004, 2001) in a sub-national context. As a novel context-only extension of the lead-market concept, it identifies the presence of lead markets and their attributes at the sub-national level. Firstly, the theoretical underpinnings of the spatial dimension of the lead markets model are discussed, and then the model is applied to the case of spatial diffusion of residential PV systems in Germany. Based on spatial data and an extensive case study, how an innovation is deployed in sub-national regions of a country before being adopted nationwide is explained. Also the system of lead-market attributes (demand, price, export, transfer, and market structure advantages) is applied to the case and how a sub-national lead market could take off in a particular region of a country is discussed. The case of PV systems in Germany, therefore, is an illustrative example of how national-wide regulations might result in sub-national lead markets. As the EEG was able to drive the diffusion of photovoltaic diffusion in a particular sub-national region, i.e., Baden Württemberg and Bayern, the diffusion in other regions of Germany have might caught up incrementally.

5.5. Paper F

Anchored in FEM, Paper F aims to have three main implications for the literature. Firstly, through a literature review, it presents the scope of using FEM in social-science-related fields. Secondly, it discusses why and how FEM could be used to model the effects of spatial heterogeneity in the diffusion of solar PV systems. Thirdly, it applies FEM to a semi-hypothetical case study. This semi-hypothetical case is based on the diffusion of PV systems in Rottenburg am Neckar. Through the mathematical equation of Haynes et al. (1977), the applied FEM model is capable of generating the spatiotemporal patterns of diffusion. The results of the application show that the finite element method constitutes a powerful approach to understanding the diffusion of an innovation as a spatiotemporal process. It also responds to the difficulty of modeling the influence of spatial heterogeneity and generates detailed information, e.g., the spatial propagation of innovation flux. Such insights had not been possible to obtain from many other applications of the other modeling methods (e.g. Bass et al., 1994; Bass, 1969; Guidolin and Mortarino, 2010; Sharif and Islam, 1980). Therefore, the model could be an alternative to the agent-based models that have emerged in the last few decades (e.g. Guseo and Guidolin, 2014; Schwarz and Ernst, 2009).

6. Discussions

This section is composed of five sub-sections. The first sub-section offers a meta-analysis [2] that contrasts and combines implications from the six appended studies. The overarching discussions are organized according to three topics: micro level, firms, and meso level. These discussions do not summarize the findings of appended papers (see section 5 for such short summaries). Rather, they provide a meta-analysis that is not necessarily available in the appended papers. Then, the second and third sub-sections discuss the theoretical and methodological implications of this thesis. Last but not least, the fourth and fifth sub-sections present the implications for industry and policy.

6.1. Synthesizing the results of appended papers

Micro level

Papers B and C of this thesis offer a multi-dimensional answer for how residential solar PV systems diffuse at the micro level. Primarily, the adopters are usually motivated by financial and environmental reasons. This means that, by adopting a PV system, the adopter believes to gain financial benefit or contribute to the environment, and sometimes both. However, as the PV systems require a fundamental change at the adoption place (e.g., installing PV panels at the rooftop and inverter in the house), financial and environmental motives are not enough to drive the diffusion. This means that achieving grid parity cannot easily increase the diffusion of solar PV systems. Therefore, the change agents and peers—e.g., previous adopters, entrepreneurs and policy makers—do play an important role on motivating the households to adopt solar PV systems. Why are the efforts of change agents so critical in diffusion of solar PV systems? Because solar PV systems are high-cost and dynamic and, at the same time, they bring a mix of public consequences (e.g., they become a part of electricity supply) and private consequences (e.g., a fundamental architectural change at residences). For

[2] The term meta-analysis is usually used for statistical studies or literature reviews (Card, 2011). In this dissertation, the term is used for overarching analysis of the appended papers.

instance, as a dynamic innovation, the diffusion of PV systems is highly restricted and influenced by the adopters' settings. Nowadays, many internationally adopted innovations have been built upon the international diffusion of their standardized complementary innovations. For example, the international diffusion of high quality bike tires has built upon the wide international diffusion of standardized bicycles. If an individual does not have one of those bicycles, there is no way that can lead to adoption of a high quality tire. However, it is not the case for residential solar PV systems. This is mainly due to the fact that there is no standardized way of building housing around the world. For example, in some regions, households do have proper spaces for the installation of solar PV systems, while in some others, they do not. The diversity of residential, economical and climatic settings of adopters raises an important contrast between the firms' business models located in different parts of the world. For example, in low-income economies, after-sale services can be an important part of firms' businesses- mainly due to poor maintenance standards. However, in high-income economies, developing building integrated PV solutions can be a more suitable offering, as the potential adopters might be more willing to pay more for aesthetic reasons. This means that, if a compatible form of PV system is not developed for the potential adopter (or there is no proper service), the adoption is less likely to happen.

Solar PV systems have permanent private consequences and high indirect costs (especially in case of de-adoption). In other words, they are neither easy to adopt nor easy to de-adopt. What does it mean? Today, many innovations that are widely adopted are easy to adopt and easy to de-adopt at the micro level[3]. There are a myriad of examples that point to this: smart phones, electrified bicycles, virtual smart-phone applications, Facebook, computer software programs, and fashion-driven textile clothes. One can adopt them at any time and quickly de-adopt them at any other time. The decision process sometimes does not exceed a couple of minutes. They do not also have any long-term remaining and visible consequences on the adoption units. When de-adoption occurs, the main consequences of the

[3] By using de-adoption term, I refer to discontinuance which is the decision to reject an innovation after having previously adopted (Rogers, 2003, p. 182)

adoption quickly disappear. However, solar PV systems present particular differences from such kinds of innovations that influence the perception of potential adopters and, consequently, the diffusion process. One cannot easily adopt solar PV systems, not in five minutes and neither in one day. *In the high-income economy context*, solar PV systems need a relatively high financial investment by the adopter unit, e.g., twenty-thousand Euros (€) for a small single-family house in Germany in 2013, and they have long-term effects on the adoption units. By adopting the PV systems and benefiting from the feed-in tariff, the adopter makes a tacit agreement that binds him/her/them for the next 10 years. Once the adoption takes place, the PV adopter cannot easily de-adopt it, at least in the short term. This is due to the fact that the financial benefits of adopting PV systems appear in the long term, and adopters naturally prefer to wait for years to receive these benefits. *In the context of low-income economies*, adopting solar PV systems usually means "electrification." The potential adopters are often those who had been used to live without electrification. Adopting a PV system does change their lifestyle. For example, they can use mobile phones and charge them with the electricity generated by the PV systems or read a book under a lamp, the electricity of which is generated by the PV system. *In both contexts*, adopting a PV system becomes easily visible by others, making it a symbol of lifestyle and, sometimes, social status. Adoption has long-terms benefits for adopters in both low-income and high-income economies. Therefore, in a nutshell, solar PV systems cannot easily be adopted. Also, before adoption takes place, the form of the solar PV system should be changed in a way that it fits the needs, limits, and preferences of the potential adopter.

Firms

Papers B, C, D and E present a variety of perspectives for the role of firms at micro and meso level. By doing so, they also exemplifies the role of change agents in the diffusion of dynamic innovations. At the micro-level analysis of diffusion, firms act as change agents, which influence the perceived attributes of the solar PV systems. The representatives of the solar firms create effective communication with potential adopters and inform them about the technology, operation, and funding of the systems. They also find the best solution that fits the needs of the particular potential adopter (decreasing complexity and increasing compatibility). At the meso level, the solar firms can be conceptualized as the sources of diffusion, from where the solar PV systems diffuse into regional domain. This means that, the more the solar firms are located in one region, the more adoptions takes place in this region.

Generally, several supplier and adopter side factors might affect each other as well. For example, the production choice of the firms affects what customers buy in the market, or vice-versa: what customers buy in the market affects the production choice of the firms. In the case of Rottenburg am Neckar, the relation between the activities of the solar firm and the diffusion of PV systems seem to have influenced each other. The solar firm influences the potential adopters in favor of adoption of solar PV systems, resulting in a direct effect on the local diffusion. However, the wide adoption of solar PV systems (driven by many other local solar companies all over the country) leads to price reductions on solar PV panels and their installations (due to economies of scale). Consequently, the reduced prices result in decline on the turnovers of solar local companies, giving rise to business-model challenges. Although this has a context-limited basis (i.e., Germany), review paper B argues that local firms or other bodies of intermediaries, are important drivers of the diffusion in other countries as well. Therefore, such challenges (and versatile interplays) might occur in other contexts, including both low- and high-income level economies.

Meso and macro level

Paper E offers an interesting perspective for the mechanism behind the meso-level diffusion. Comparing the motives for diffusion of PV systems at the micro (paper C) and the meso level (paper E), one can observe some similar dynamics. Some individuals—with certain characteristics—might adopt the PV systems at an earlier phase than others and can motivate their peers in the neighborhood for the adoption of PV systems, i.e., the peer effect (Bollinger and Gillingham, 2012). By the same token, some regions—if they have the lead-market attributes—might have some leading effects on other regions, according to the lead-market hypothesis (Beise, 2001). When these different observation levels could be combined, one can analyze the cascading effects among the levels. Adoption takes place at adopters' level (i.e., micro level), but the diffusion occurs at the regional level (i.e., meso level). If the early adopters of an innovation do affect their peers and the pioneer regions do affect other regions (in favor of the adoption of an innovation), diffusion can outreach to national and global levels.

When it comes to macro level diffusion of solar PV systems, we should consider that climate change is a global issue. Reducing the emissions in some particular countries does not necessarily lead to stopping the climate change. For example, in the energy sector, a wide diffusion of renewable energy technologies in particular countries might surprisingly give a rise to reduction on the prices of fossil fuels (because of lack of demand in the countries that do not need any more fossil fuels), which can result in more use of those fuels in other countries, accelerating climate change. Therefore, the diffusion of renewable innovations should have a global outreach. This has also been addressed in the literature on international diffusion of environmental innovations (see e.g., Van den Bergh, 2013b). That said, if an immediate action is needed to be taken against the climate change, one can be interested to be able to forecast the diffusion patterns. In this token, the leading roles of regions (the regions that has the five lead market attributes as proposed in paper E) on the global diffusion of innovations could be modeled and forecasted with mathematical methods such as the finite element method (as proposed in paper F).

6.2. Theoretical contributions

Dynamic innovations

For several decades, the literature on innovations has studied the variables that influence diffusion in three major groups: environmental settings (such as geographical and sociopolitical context), the characteristics of innovations, and the characteristic of adopters (Wejnert, 2002). In this research domain, it has been widely known that the characteristics of adopters and the environmental settings are highly time and space dependent; meaning that both have a continuous evolutionary change in time and space. This thesis has demonstrated that the characteristics of some innovations might also have a continuously dynamic character, which may influence the diffusion process. In doing so, this thesis has challenged one of the mainstream assumptions of the most previous research on diffusion: innovations do not continually evolve or get modified in the process of diffusion. Although the incremental changes has been pointed out (e.g., Christensen, 1997), the continuous change has often been overlooked. This thesis shows that some innovations have a continuous, variant, and dynamic character in both space and time. For the diffusion of dynamic innovations, an active involvement of change agents is more critical in comparison to the diffusion of other kinds of innovations. Dynamic innovations cannot get easily adopted if change agents do not help potential adopters discover and develop a particular form of innovation for each potential adopter on a case-by-case basis. By doing so, change agents might decrease the perceived complexity and increase the perceived compatibility of a dynamic innovation.

Lead and lag sub-national regions

In line with the findings of other scholars (e.g. Fabrizio and Hawn, 2013), paper E confirms that country-level policies do not influence the diffusion of innovations in the same manner in all sub-national regions. Extending this argument, paper E makes an important contextual contribution to the literature. It argues that, if a national policy can drive the diffusion of an innovation in a particular sub-national region that has the lead-market attributes, the diffusion in other regions will follow subsequently. Therefore, paper E, which is partially anchored in the findings of paper C, represents a novel context-only extension of the lead-market concept (Beise, 2004, 2001) by applying it at the sub-national level, i.e., the meso level. Indeed, Beise pointed out the importance of sub-national dimension in his early work by indicating that "*Hitherto, I have referred to lead markets as countries without formal reasoning. The question arises whether lead markets can be other regional extensions… The evaluation of the regional dimension of lead markets depends on the availability of data of adoption preferences*"(Beise, 2001, p. 125). By this token, the findings of paper E is an important contribution to the literature, given the fact that all previous studies on lead market concept had been applied to the diffusion of innovations only at the national level.

In the theoretical dimension, it has often been thought that, if there is a variety of alternative designs (forms) of an innovation at initial phase, it results in competition among designs and, consequently, one internationally adopted dominant design can emerge amongst the alternatives in time (see Beise, 2001). However, this is not always the case. Sometimes, a single form of an innovation is not necessarily compatible with the preferences and limitations of adopters. If this happens, the innovation appears in different forms when it diffuses in space and time. This means that, instead of an emergence of an internationally adopted dominant form of innovation, a variety of alternative forms of innovation continually appear during the diffusion.

6.3. Methodological contributions

Playing with math: How to count the diffusion rate?

In the majority of the research on innovation (Bass, 1969; Griliches, 1957; Hägerstrand, 1967; Rogers, 2003), the diffusion rate is calculated through on a simple rule: if a potential adopter has adopted the innovation, it counted for 1. However, diffusion research on renewable energy innovations, e.g., residential solar PV systems, traditionally has a different approach when evaluating diffusion. For calculating the diffusion rate, the scholars usually have focused on the capacity of electricity generated through installations, instead of the number of installations (see e.g. Dewald and Truffer, 2012; Guidolin and Mortarino, 2010). However, this might lead to a misunderstanding on whether the diffusion is increasing or decreasing. For example from 2010 to 2011 in Germany, there was an increase in the total capacity of PV installations, while a corresponding decrease of the number of installations. In papers C, D, and E of this dissertation, we intentionally used the number of installations for diffusion evaluation. Therefore, we hope that future studies will carefully consider the way they calculate the diffusion rate of solar PV systems. In many cases, the continuing increase of capacity of PV systems might create a misleading bubble on the calculation of diffusion rates. For example, in order to calculate the diffusion rate of electrical cars, no one calculate the sum of the power capacity of all adopted cars. Instead, the scholars calculate the number of adoptions. Why not do the same for solar PV systems? The adoption number of PV installations does tell about diffusion rate, while the capacity of installations does tell about something else—technological efficiency.

Finite element method

Theories on the social patterns of organizations and societies have been rooted several decades ago (e.g. Durkheim, 1933; Marx, 1954; Weber, 1922). However, neither the pioneers nor the followers had an access to the big data, the newly ubiquitous digital data that is available now about all aspects of human experiences (Pentland, 2014). Today, for example, we can precisely know the location of many individuals through global positioning system (GPS) during 24 hours per day. Similarly, we have an access the detailed information of diffusion of a variety of innovations through public and private databases. Consequently, leveraging the big data with high computational power, social sciences (including economics and management) have tremendously been advancing (e.g. Brockmann and Helbing, 2013; Mani et al., 2013; Pentland, 2013, 2012). In the same token, paper F, using today´s high computational power, presents an application of the finite element method, which has traditionally been used in engineering disciplines. If there is access to the big data, the model might serve as a powerful method for solving the partial differential equations describing the social phenomena. For instance, in the case of solar PV systems in Germany, there is a public database on the information of PV adopters, revealing the information on precise adoption time, the precise location of adoption, and the capacity of installations. This, indeed, motivated the development of paper F.

The strong similarities between how salt diffuses in water and how innovations or diseases diffuse in societies attracted many scholars to model the diffusion of innovations through a variety of approaches inspired by natural sciences. However, social processes are complex, and it is hard to measure the micro characteristics of societies that might hinder or drive the diffusion of innovations. In case of environmental technologies, not many innovations have been able to diffuse to a larger extent. Recently, many scholars have attempted to model and forecast the diffusion of environmental innovations through agent-based models (see, for example, the findings of the literature review paper A).

It is difficult to forecast the behavior of individual adopters or firms. Although two potential adopters in the same neighborhood may seem to be similar, one may adopt the innovation while the other not. In the same manner, two firms in the same sector may seem to have similar business models. However, one can have an incline in the revenue, while the other can have a decline. That said, if the observation is conducted at a meso level, e.g., at sub-national regional level, one can have some analytical basis to model and forecast systemic behaviors such as the diffusion of innovations. The regional trends become observable; therefore, better predictions, based on historical data, can be possible. By this token, the results of paper F show that the FEM could be a powerful method by which to study the diffusion of an innovation at meso level.

6.4. Industrial implications

Marketing strategies

The well-known Bass model (1969) has been used by firms to develop marketing strategies for decades. Similarly, one can use the finite element method (see paper F). Finite element analysis, by using the historical data on the micro level, is just another alternative method to tackle the modeling issues at meso level. The method can successfully model the diffusion of salt in water in time and space because we can know precisely the micro characteristics of the water used in the respective experiment. In the same token, based on the big data collected at the micro level, the method can be used as an important tool to forecast the diffusion of innovations at meso level.

By using the spatiotemporal historical diffusion data through a finite element method, firms can forecast the declines and inclines in specific regions, developing strategies to harvest the maximum out of such diffusion trends. This is specifically important for the cases, at which the spatial proximity matters. For example, in the case of Hartmann Energietechnik GmbH, the firm offers installation services for the potential PV adopters.

This means that the firm needs to transport the PV panels to the households when the installation takes places. The farther the potential adopter is from the firm, the more costly it is to transport the PV system. Thus, if a firm is able to forecast the spatial trends of diffusion, the firm can optimize its strategy in a way that it can harvest the increase of diffusion rate in some far away regions but, at the same time, keep the transportation cost as low as possible. One possible way of doing this could be setting up new branches of the firm at high-growing regions which might be located far away.

Grid parity: A disillusion?

The literature on environmental and renewable energy innovations has often assumed that high cost has been one of the main barriers for the wide adoption of such innovations (e.g. Jacobsson and Johnson, 2000; Lund, 2011; Painuly, 2001). There has been a great hope that achieving the grid parity for renewable energy innovations, or cost competiveness of environmental innovations in general, would boost diffusion. A recent study by Munoz et al. (2014), based on a discourse analysis of the literature, also shows that the majority of scholars claim that achieving the grid parity is either one or the key milestone(s) of the diffusion of solar PV systems. However, a few scholars, e.g., Yang (2010) (as cited in Munoz et al., 2014), expected that grid parity would not necessarily guarantee the wide adoption of solar PV systems.

To my knowledge, there have not been many studies conducting an in-depth analysis of diffusion of solar PV systems at grid parity to date. Paper C of this dissertation, therefore, represents probably one of the first in-depth attempts that falls into this interesting gap in the literature. Paper C illustrates that achieving grid parity has not necessarily boosted the diffusion of renewable energy innovations, in particular that of the residential solar PV systems. This is also in line with the primary argument of paper B, which focuses on the barriers to the adoption of PV systems. Paper B shows that cost and price related barriers have been only a little part of the big picture. Most of the barriers that hinder the wide adoption of solar PV systems have been related to the socio-technical, political, and managerial dimensions. Therefore, this thesis argues that grid party alone cannot explain the boost of the diffusion. This can be a bad news for those who expected much from the grid parity. Grid parity could be an important factor, but cannot be the only critical factor alone for the wide adoption of solar PV.

Local firms: drivers or victims?

In regard to the firms, Penrose (2009, p. 4) suggests that, "*a comprehensive theory should take account of not only the sequence of changes created by a firm's own activities but also the effect of changes that are external to the firm and lie beyond its control.*" By this token, Paper D illustrates both the firm's activities and the effect of external changes. These external changes have been the reduction of turnover per PV project, the decline in diffusion (dynamics of which is evident in paper E), and the decrease in feed-in tariff. All these external factors consequently resulted in a rapid decline in the revenue of the solar firm and stimulated a challenge to the business model. However, as the other study (paper A) and other scholars (Dewald and Truffer, 2012; Fabrizio and Hawn, 2013) argue, local solar firms are the important drivers of the diffusion, acting as intermediaries among the technology, policy makers, and the adopters. This means that, if the local solar fails to survive, so does the diffusion. Nevertheless, I argue that a local actor, which has driven the diffusion, can also become a victim of the high diffusion rate.

6.5. Policy implications

How can policy makers promote the diffusion of environmentally friendly innovations? This question has been addressed in the literature for a long time. When it comes to the sub-national dynamics, this dissertation argues that developing sub-national policies (e.g., policies like those suggested by Fabrizio and Hawn, 2013; Zhang et al., 2011) is not the only effective way to drive the diffusion of environmental innovations. This dissertation argues that policy makers might also choose to develop a national measure that fits the lead sub-national region and, consequently, drives diffusion at the national level in a progressive manner. This means that if a national policy is able to drive the diffusion of an environmental innovation in a particular sub-national region that has lead-market attributes (advantages on demand, transfer, export, market structure and cost), the diffusion in other regions might follow. Therefore, by responding to the lead market's demand at the first hand, policy makers can foster and drive national adoption innovations. Therefore, this thesis argues that policymakers should not always be worried about the lagging regions in the early phases of diffusion. If the diffusion of an innovation in a region with lead market attributes can be boosted, the lag regions are likely to catch up.

This dissertation also argues that change agents are highly influential on the diffusion of dynamic innovations. However, in the case of the diffusion of residential solar PV systems, local companies, which act as important change agents to motivate potential adopters, have a business model challenge due to new conditions in the market. Given that the cost competiveness of renewable energy innovations—i.e., grid parity—does not fully foster wide diffusion, policymakers might need to consider new policy measures to support local companies. As paper D and other scholars (Dewald and Truffer, 2012; Fabrizio and Hawn, 2013) argue, policy measures are unlikely to have the expected impact without local solar companies, and thus survival of such companies are critical for the wide adoption of PV systems. Therefore, this thesis argues that, if the local firms are on the edge of a cliff, it sometimes means the diffusion of PV systems is on the edge of a cliff as well. The local solar firms help potential adopters both to understand the benefits of adopting solar PV systems and to find out and develop the form of solar PV systems that best fits their needs, limits, and preferences. Given that diffusion of solar PV systems has a limited outreach, even in the most developed market (for instance, Germany), the findings of this thesis may recommend policymakers to support the local drivers of diffusion. Otherwise, potential adopters' negative perceptions on the PV technology (e.g., related to the complexity, trialabilty, compatibility, and relative advantage) might hinder diffusion and cannot be easily overcome.

7. Conclusions

This PhD thesis has tried to contribute on the theoretical, contextual and methodological research domains of innovation diffusion. In the theoretical dimension, it has dealt with what a dynamic innovation is and how it is diffused. In doing so, it has distinguished the innovations that have a continuous evolutionary change during the each step of diffusion from those that have a static state or incremental change. This means that some innovations can have a variant character, tending to continuously change or alter, by exhibiting a variety or diversity in space and time dimensions. As also seen in the case of residential PV systems, dynamic innovations cannot get easily adopted if change agents, e.g., local firms, do not facilitate the process on a case-by-case basis.

In the contextual domain, it has focused on the diffusion of residential solar PV systems. Firstly, at the level of adopters, it explored the diffusion dynamics of a particular local case in southern Germany. Secondly, at the business model level, it illustrated how a business model challenge of a leading local solar company can arise and how this can influence the diffusion. Thirdly, at the regional level, it explored how leading regions might affect the lagging ones. Through these three levels, the thesis has provided in depth-analysis of a case of environmental technology which has achieved, to some extent, the cost competitiveness. Overall, the thesis has argued against the notion that achieving cost competitiveness would boost the diffusion of environmental innovations such as renewable energy technologies

In the methodological dimension, this thesis has taken an existing theory (e.g., Hägerstrand, 1967; Rogers, 2003) and context (e.g., solar PV systems) and, based on them, has proposed a relatively new method. This has been done by presenting and applying the Finite Element Method— which had traditionally been used in the field of continuum mechanics in engineering disciplines for several decades—for a social science phenomenon, i.e., diffusion of innovations.

7.1. Limitations and future research

Given the many dimensions of the diffusion of PV systems, there are some limitations to this study which could motivate to open new avenues for future research. Papers C and D are illustrative case studies in nature and have some limitations. For instance, they are only based on a single-case study. However, as argued by Flyvbjerg (2006), they contribute to the collective process of knowledge accumulation in a particular field that lies among several fields, e.g., energy research and social science. In addition, the diffusion of PV systems in Germany has been strongly influenced by its particular conditions, including the German feed-in tariff. Therefore, the results of papers C and D might not easily be transferable to the cases in other regions. However, similar processes might occur in other regions as well. Yet, like other energy-related single-case studies in particular regions (e.g. Fjaestad, 2013; Sriwannawit and Laestadius, 2013; Zhao et al., 2014), I believe that the case studies in paper C and D of this dissertation can provide empirical insights that can be used as a basis for future research. In addition, in this thesis, the notion of dynamic innovation has been studied through the case of residential solar PV systems at micro and meso level in Germany. Therefore, future theoretical and contextual studies on diffusion of dynamic innovations might choose to include different empirical cases in their research.

There have also been some more methodological limitations. In paper E, finding the indicators and aggregating them was a challenge. The data for some indicators were not available to collect. In paper F, not all the data used for the model was empirically collected. This could be easily overcome by using the historical s-curve data in future studies. Moreover, the literature reviews (paper A and paper B) may lack some important keywords to be used for generating the databases. For example, the terms "acceptance" and "deployment" are missing in the sets of keywords in both studies. Nevertheless, one can argue that these terms do not necessarily correspond to the diffusion process. That being said, including these terms might be useful to expand the scope of future studies in similar contexts.

Moreover, several topics beyond the scope of this thesis appear to be promising for future research. Firstly, the influence of the recent German policy support for solar batteries (implemented in 2013) on the adoption of PV systems should be studied further. Solar batteries make it possible for households to store the electricity they generated. This means that they will not necessarily need to supply the electricity to the grid. Instead, they can store it during the day (when the sun is shining) and use it during the night. Secondly, the future studies could also investigate the barriers to the adoption of a variety of PV systems, including building integrated systems, particularly in times of grid parity. To do this, several factors can be important to be considered: socio-technical, managerial, policy, and economic factors (as suggested by paper B). Thirdly, further research can also further develop the indicators used for lead-market attributes of PV at the sub-national level. Moreover, scaling down the unit of observation can provide new insights. Fourthly, the finite element method of the paper F is a promising starting point for more detailed and advanced investigations in the future, including the modeling the diffusion of environmental innovations through analyzing the big data. Fifthly, in a movement towards energy transition to more decentralized energy solutions, adopters are supposed to, as first step, discontinue using conventional electricity sources (in high-income economies) or discontinue living without electrification (in low-income economies) (see paper B and C). However in energy research, surprisingly, less attention has been paid to the discontinuance. This topic could be a promising future research area. Sixthly, the case study in Rottenburg am Neckar also provided additional perspectives about other technologies that could have competed with solar PV which go beyond the scope of this dissertation. One example is the solar thermal systems. The diffusion competition between solar PV systems and other alternatives could be an interesting future research topic. For example, the number of yearly solar thermal installations was around 15,000 in Germany, whereas it was 18,000 for PV in 2012. The case study showed that adopters usually decide between solar PV systems and solar thermal systems. In some cases, they decide to adopt both—for example, adopting PV for half of the roof and solar thermal for the other half. However in some cases, adopters choose either of them. According to the number of yearly installations, the time period that PV had the highest growth corresponds to the time period that solar thermal had the sharpest decline. From 2008 to 2010, the number of yearly installations of PV has increased 120%, whereas the number of yearly installations of solar thermal decreased 45% as the sharpest decline in its history. This contradiction supports the argument that PV and solar thermal might compete with each other, at least to get a place in the roof as the capacity of a roof is often limited. As Thomas Hartmann already asked in one of the interviews: To whom belongs the roof? PV systems or solar thermal systems? Seventhly, studying the role of cost competiveness for environmental innovations can be a promising future research area. As happened in the case of PV systems in Germany, reaching cost competiveness alone cannot explain the boost of solar PV. Eighthly, interlinks among the micro, meso, and macro level of diffusion could be studied further. For example, the future research can focus on how the macro level diffusion can influence the micro and meso level of diffusion, and the vice-versa.

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