

Decentralization Dynamics of Energy Systems: From Prosumer Preferences to System-Level Perspectives

DISSERTATION
of the University of St. Gallen,
School of Management,
Economics, Law, Social Sciences
and International Affairs
to obtain the title of
Doctor of Philosophy in Management

submitted by

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from

Basel (Basel-Stadt)

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Dissertation no. 4780

Difo-Druck GmbH, Untersiema 2019

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St. Gallen, May 22, 2018

The President:

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“Remember, always, that everything you know, and everything everyone knows, is only a model. Get your model out there where it can be viewed. Invite others to challenge your assumptions and add their own.”

Donella H. Meadows, *Thinking in Systems: A Primer* (2008, p. 172)

Acknowledgement

This thesis is the result of my research conducted at the Institute for Economy and the Environment at the University of St. Gallen and the Institute of Sustainable Development at Zurich University of Applied Sciences. I highly appreciate that I had the chance to write this dissertation while being employed at two inspiring institutes and thank Prof. Dr. Bettina Furrer, Dr. Silvia Ulli-Ber and Prof. Dr. Rolf Wüstenhagen for providing me the institutional framework to conduct this dissertation work.

Foremost and most importantly, I would like to thank my two supervisors Dr. Silvia Ulli-Ber and Prof. Dr. Rolf Wüstenhagen, who supported me throughout the process of this dissertation with advice and encouragement. Working with them was an invaluable learning experience and will not only inspire my future research but also sustainably changed my mental model of the world. I also thank my co-referee Prof. Dr. Oliver Gassmann for his constructive questions and feedback during the colloquium and his encouragement.

During the dissertation period, I had the pleasure to collaborate with Dr. Juliana Zapata, Michael Wurzinger, Mirjam West and Prof. Dr. Moritz Loock on different projects and publications. Working with them was very fruitful and enriched my daily work life. I thank my collaborators at BKW, EBS Schwyz, Romande Energie, Siemens and all participants of the TREES workshops for the valuable discussions and relevant insights into the energy system. Furthermore, I profited from the broad expertise on the energy market of my father Thomas Kubli. At my two home institutes but also beyond, I had the pleasure to interact with many great researchers. I would like to thank namely Dr. Yuliya Blondiau, Dr. Hans Curtius, Dr. Samdruk Dharshing, Dr. Andreas Gerber, Dr. Stefanie Hille, Dr. Corinne Moser, Dr. Matthias Müller, Dr. des. Adrian Rinscheid and Dr. Sarah Salm for the inspiring discussions and their backing.

I would like to express my special thanks to my parents, my brother and best friends for their steadfast support and love. Finally, I would like to thank Christoph, my safe haven in the stormy times of this dissertation but also first to celebrate every reached milestone with.

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Abstract

Our generation has the task to ensure a sustainable energy provision for all. The key challenge is integrating new renewables into energy systems. Current trends show exponentially growing installations of solar photovoltaics (PV). While the electricity supply has traditionally been centralized, solar PV is well suited for decentralized installation. Self-consumption of locally generated electricity is becoming possible, allowing for a wide range of new decentralized energy solutions. The line between consumers and producers starts to blur, challenging utility companies to reshape their business models and forcing policy makers to reconsider policy settings.

With this dissertation, I contribute to a holistic understanding and management of the energy transition, by focusing particularly on the decentralization dynamics of energy systems. With three foci, each addressed in one paper, I investigate three particular challenges of the paradigm change in the energy system, linking prosumer preferences and system-level perspectives.

In the *first paper*, we investigate the drivers of the decentralization dynamics. We analyze the diffusion of self-consumption concepts, focusing on network effects and complementarities arising from an increasing number of prosumers and microgrids. Simulations of the conceptual model highlight that recovering distribution grid costs is a decisive network effect of decentralization dynamics.

In the *second paper*, I simulate the impacts of different grid tariff designs and PV metering schemes on consumers' decision to become solar prosumers and to install storage. I also quantify the distribution effect between consumers with and without self-consumption. The role of politics and policy is crucial in balancing distributive justice of power grid costs and incentives arising from grid tariff design.

In the *third paper*, we investigate prosumers' willingness to provide flexibility in three technology application areas. Decentralized generation is thus far an un-exploited potential for flexibility. Utility companies, together with flexible prosumers, can co-create flexibility by pooling and valorizing flexibility on markets, potentially leading to benefits for both. The results of our choice experiment indicate the required premium to compensate flexible prosumers and locate target technology areas for business models for decentralized flexibility.

Zusammenfassung

Unsere Generation hat die Aufgabe, eine nachhaltige Energieversorgung sicher zu stellen. Die zentrale Herausforderung dabei ist es neue erneuerbare Energien in das Energiesystem zu integrieren. Aktuelle Entwicklung zeigen ein exponentielles Wachstum von Photovoltaik (PV). PV ist für dezentrale Installationen besonders geeignet, im Gegensatz zu der traditionell zentral organisierten Stromversorgung. Die verschmelzende Linie zwischen Konsumenten und Produzenten fordert Energieversorgungsunternehmen und politische Entscheidungsträger, einerseits neue Geschäftsmodelle zu finden sowie andererseits Gesetzgebung und Förderpolitik zu überdenken.

Mit dieser Dissertation trage ich zu einem ganzheitlichen Verständnis und Management der Energiewende bei, indem ich mich spezifisch auf die Dezentralisierungsdynamiken von Energiesystemen konzentriere. Ich untersuche drei spezifische Herausforderungen des Paradigmenwechsels im Energiesystem.

Im *ersten Beitrag* untersuchen wir die Treiber der Dezentralisierungsdynamiken. Wir analysieren die Diffusion von Eigenverbrauchskonzepten mit einem Fokus auf Netzwerkeffekte und Komplementaritäten, die aus der steigenden Anzahl von Prosumen und Mikronetze entstehen. Simulationen des konzeptionellen Modells zeigen, dass die Kostendeckung von Stromverteilnetzen ein entscheidender Netzwerkeffekt von Dezentralisierungsdynamiken ist.

Im *zweiten Beitrag* simuliere ich die Auswirkungen verschiedener Netznutzungstarife und PV-Vergütungsschemas auf die Kundenentscheidungen ein Prosumen zu werden. Zudem quantifiziere ich den Verteileffekt zwischen Konsumenten mit und ohne Eigenverbrauch. Die Rolle von Politik, Gesetzgebung und Fördermassnahmen sind entscheidend, um die Kosten der Stromverteilnetze gerecht zu verteilen und kosteneffiziente Anreize zu setzen.

Im *dritten Beitrag* untersuchen wir in die Bereitschaft von Prosumen Flexibilität bereitzustellen. Dezentrale Produktion ist ein bisher ungenutztes Potenzial für Flexibilität. Die Resultate von unserem Wahlexperiment eruieren die erwartete Prämie, um flexible Prosumers zu vergüten, und lokalisieren geeignete Technologiebereiche für Geschäftsmodelle mit dezentraler Flexibilität.

Introductory Chapter

1. Background and motivation

Integrating new renewable energies is the key challenge for a successful energy transition. Globally, states coordinate efforts to facilitate energy transitions (Hauff et al., 2014). Fossil fuels must be reduced drastically to keep climate warming within tolerable limits, and nuclear power is about to be phased out in numerous countries; at the same time, energy demand is increasing and developing countries need to increase the electrification rate of their populations (IEA, 2017; United Nations, 2015; World Energy Council, 2017). Renewable energies are the designated solution to manage these enormous tasks (World Energy Council, 2017). One promising technology is solar photovoltaics (PV). Due to impressive learning curves (Fraunhofer ISE, 2015; IEA, 2017; IRENA, 2018b), but also to governmental support schemes (IRENA, 2018a), solar PV is being deployed at increasing rates (Figure 1). Globally, the installed capacity of solar PV grew exponentially in 2016, reaching a level of 291 GW (IRENA, 2017 p. 56).

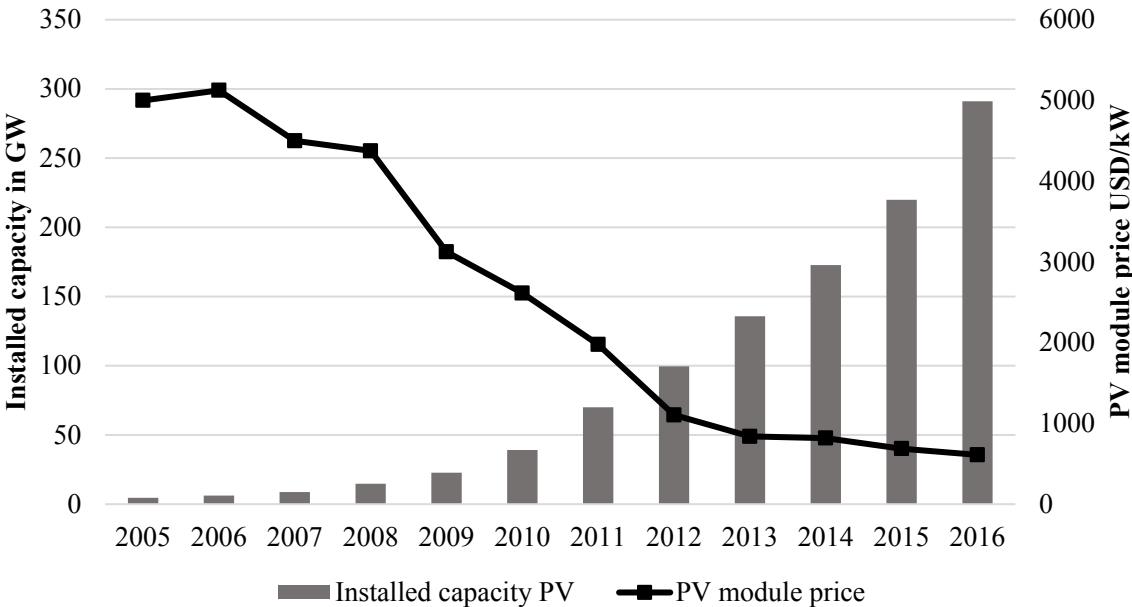


Figure 1: Global installed capacity (IRENA, 2017) and technology learning curve of solar PV (Fraunhofer ISE, 2015; IRENA, 2018b)

Global investments in renewable energies totaled up to 263 billion US dollars until 2016, of which 135 billion US dollars went to solar PV (IRENA, 2018a p. 15). A large number of solar PV plants have been installed in the residential sector as rooftop solar PV plants. In the US for instance, residential PV made up 56%¹ of the installed capacity of PV (EIA, 2017). While capacity-wise, a single residential solar PV plant is not as impressive as a large-scale solar PV plant, as an aggregated mass, residential solar PV still reaches impressive capacity.

Potentially even more revolutionary, decentralized installed solar PV will fundamentally change the logic of the energy industry. Solar PV, sometimes in combination with other technologies, opens up space for completely new ways of providing electricity to consumers. While previously, incumbent utilities generated electricity centrally and transmitted and distributed it to consumers, local generation is bringing various changes. The *self-consumption* of locally generated electricity² is becoming possible, so owners of a rooftop solar PV plant can partly cover their electricity needs with their own production. Hence, local generation allows consumers to become *prosumers* (*pro*ducers and *con*sumers at the same time). But self-consumption concepts on a larger scale are also feasible, for example prosumer communities or microgrids³. As an immediate consequence, decentralized generation is competing against the traditional offers of utility companies. The business models behind decentralized energy solutions are causing the paradigm of the centralized electricity system to totter. The paradigm is about to change – where the line between producers and consumers starts to blur (Bergman & Eyre, 2011; ITRE, 2010; Marris, 2008; Schleicher-Tappeser, 2012; Verbong & Geels, 2007). A paradigm change is a powerful leverage point in a system; it enlarges the existing system with a new structure and sets off new dynamics (Meadows, 1997, 1999).

Not only are solutions for self-consumption becoming increasingly popular, further reaching business models can also enter the market. With the intelligent connection of local generation, storage and electricity consumers, solutions such as demand side

¹ EIA (2017) define residential PV as installations smaller than 1 MW.

² Local generation is frequently also called decentralized production, distributed generation, embedded generation or small-scale generation (Pepermans et al., 2005).

³ For definitions, see section 3.2.

management, battery swarms and virtual power plants can be created (Burger & Luke, 2017). These concepts are spurred by the increased need for flexibility to balance supply and demand. *Flexibility* is very broadly defined as “the capacity to adapt” (Golden & Powell, 2000, p. 1), or in the specific context of the electricity market, as “a power adjustment sustained at a given moment for a given duration from a specific location within the network” (Eid et al., 2016, p. 3). With the increasing capacity of solar PV and wind energy, both technologies producing with fluctuations, there is both an increased need for flexibility and a thus far unexploited potential (Denholm & Hand, 2011; Gordijn & Akkermans, 2007; Marris, 2008; Veldman et al., 2013).

With decentralized electricity production, new actors enter the energy market, attracted by new investment and participation options (Helms et al., 2015). New renewable energies are no longer only the business of managers of large utility companies; private people become active as investors and engaged consumers. Worldwide, 72% of investment in new renewable energies has been made by private investors, of which 16% was undertaken by households (IRENA, 2018a)¹. But not only do house owners enter the energy sector by investing in solar PV, technology developers also provide consumers with turnkey solutions for local energy. ICT companies also enter the market with digital solutions to connect and control small-scale plants and consumers.

Local generation and self-consumption are elements of the fundamental transition of the energy system. This dissertation will address three particularly important challenges of these decentralization dynamics:

- **Understanding the drivers of the decentralization dynamics of energy systems:** The actions and interactions of actors, technologies and policies shape the energy transition. Strategies of utility companies define the offers in the market, but regulatory frameworks set the playing field and can induce new incentives. Network effects arise through a larger installed base of decentralized energy solutions and new technologies can uncover complementarities with other technologies. Finally, it is the consumers and investors who decide the success of new

¹ In Germany in 2012, 47% of investments were made by private investors, while institutional investors accounted for 42%, and only 12% of the capacity of new renewable energies was owned by utility companies (Helms et al., 2015).

business models by adopting decentralized energy solutions – or not. Hence, it is essential to understand the complex interplay of the various drivers, determining the direction and speed of decentralization.

- **Role of politics and policy:** Decentralizing energy systems poses many questions for politics and policy design. Through the paradigm shift, a new equilibrium state is about to emerge. Politics is in charge of steering the energy system towards a societally desirable state. Important measures include policies such as subsidies and tariff design, which must be well designed to achieve the desired impact.
- **Consumer preferences:** Consumers decide on products, invest in technologies and adopt concepts and by doing this, drive the diffusion of decentralized energy solutions. In decentralization dynamics, it is particularly important to get a detailed understanding of consumer preferences for self-consumption concepts as well as for consumers' willingness to engage in decentralized flexibility concepts.

This dissertation is particularly relevant for two kinds of stakeholders. *Utility managers* face the challenge of reacting to the new developments in energy systems. Utility companies must adapt their business models, to assert their place in the new system and transition towards it. Wrong decisions may lead to fatal misinvestments that last for decades. *Policy makers* must consider newly emerging concepts and newly entering actors to adjust regulatory frameworks and policies. Providing a level playing field for all actors is important, but politics must also govern the system, guiding it towards solutions that are societally desirable. An accurate understanding of the processes that govern the energy transition is essential for energy companies and policy makers to successfully co-create a new sustainable energy system.

With this thesis, I contribute to an enhanced understanding and management of the *energy transition* by placing a particular focus on the decentralization dynamics in the electricity system. The goal of this dissertation is to locate levers for a successful integration of new renewable energies on the demand side. For this objective and ex-

ante analysis, I develop methods capable of addressing the particular challenges of energy systems in transition.

2. Focus and objectives

This dissertation consists of three research papers. I selected three particular foci of decentralization dynamics within the context of electricity systems, and each paper addresses one focus. The three papers are interconnected in their topics, each one building on the insights of the previous paper. To give a broad overview, I present the three papers along their foci and interconnections in Figure 2; and provide a list of the three publications in Table 1. In the following, I call the publication Kubli and Ulli-Ber (2016) the *first paper*, the publication Kubli (2018) the *second paper* and Kubli, Loock & Wüstenhagen (2018) the *third paper*.

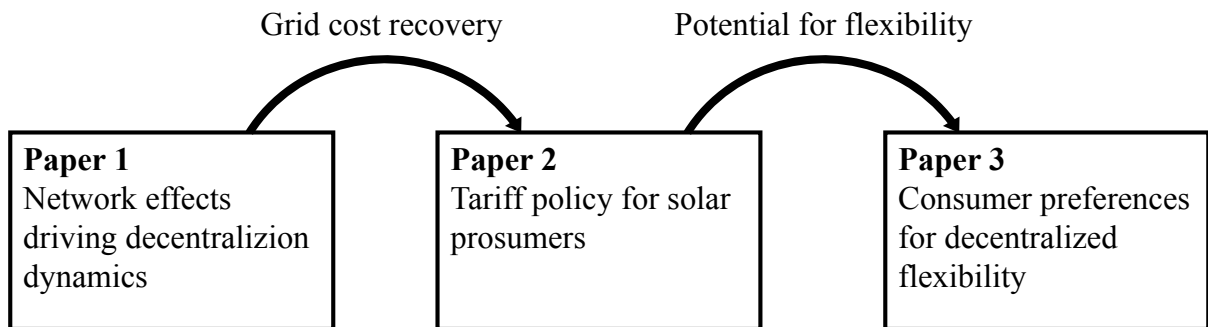


Figure 2: Foci and connections between the three papers of the dissertation

In the *first paper*, we investigate the drivers of the decentralization dynamics of energy systems. We conceptualize emerging self-consumption concepts, the underlying drivers of their diffusion and likely occurring decentralization patterns. To develop a holistic view of the governing structures of the transition, we build on the existing knowledge on drivers and barriers to energy transitions and the diffusion of self-consumption. We apply the lens of network theory to synthesize the knowledge pieces into the overarching context of decentralization dynamics. Direct network effects occur between the installed base of a technology and its utility as perceived by consumers (Katz & Shapiro, 1985). The reinforcing character of network effects influences the speed of diffusion (Abrahamson & Rosenkopf, 1997; Gupta et al., 1999; Sterman, 2000), but it

also causes lock-in (Davis et al., 2007; Sterman, 2000; Unruh, 2000). Indirect network effects, also called complementarities or co-benefits, emerge from complementary goods (Katz & Shapiro, 1985) and have been found to play an important role in socio-technical transitions (Markard & Hoffmann, 2016). The study follows the research question: “Where are network effects in energy systems, and how do they influence the scope and timing of decentralization dynamics?” The underlying hypothesis of the paper is that network effects play a crucial role in the rise of self-consumption and determine which self-consumption concepts consumers adopt most frequently. We focus on the emerging deployment patterns of solar prosumers, autarkic solar prosumers, microgrids and autarkic microgrids. The results of the paper highlight the cost recovery of power grid costs, among others, an important network effect in the decentralization dynamics of energy systems. Adjusting distribution grid tariffs due to increased self-consumption raises calls to revise the grid tariff design.

In the *second paper*, I investigate the dynamic interactions between increasing numbers of solar prosumers and the distribution grid tariff. The diffusion of solar prosumers challenges utility companies to recover the costs of the distribution grids, since they consider self-consumed electricity as lost income. In particular, when it comes to recovering the large fixed costs of distribution grids, this gives rise to political discussions on policy design and whether regulations must be adapted that consider the new developments. A capacity-based tariff is frequently mentioned as a potential solution to maintain distributive justice for all consumers (Costello & Hemphill, 2014; Eid et al., 2014). Previous literature on the topic addresses separate aspects of the cost recovery feedback loop only in isolation. One focal topic is the impact of increased self-consumption on the financial situation of power grid operators (Costello & Hemphill, 2014; Darghouth et al., 2016b; Felder & Athawale, 2014). Another focus lies on how adjusting grid tariffs influences the electricity bill savings of prosumers (Darghouth et al., 2011, 2014; Darghouth et al., 2016a; Eid et al., 2014). However, changing the rules of the system by defining a new grid tariff design, sets new incentives for existing and emerging self-consumption concepts and therefore shapes the transition.

I study the two interlinked aspects of the cost recovery feedback loops in an integrated manner. I build on the above-mentioned literature and technical research on

self-consumption and peak demand reduction as well as on the literature on distributive justice. Firstly, I aim to quantify the resulting distribution effect between consumers with and without self-consumption under alternative grid tariff designs. Secondly, I intend to capture the incentives of alternative grid tariff designs for investing in solar PV. I simulate the diffusion of solar prosumers with and without storage and consider the three groups of consumers. Besides the impacts of grid tariffs, the study reveals an increasing potential for flexibility emerging from the diffusion of solar prosumers. An important insight is that grid tariffs can set incentives for using this flexibility in a system-conducive manner, but they do not fully exploit the potential.

In the *third paper*, we investigate prosumers' willingness to co-create flexibility. There is a growing potential for flexibility from decentralized generation (Gordijn & Akkermans, 2007; Kubli, 2018; Santos et al., 2014; Veldman et al., 2013). At the same time, balancing supply and demand is a key challenge in energy markets and becomes even more pressing with fluctuating generation. Consequently, there is a high interest in accessing new sources of flexibility (Lund et al., 2015). With the new potential for flexibility from decentralized production and storage, new concepts are being developed to exploit this potential (Burger & Luke, 2017; Lund et al., 2015). The new concepts pool the flexibility from numerous small providers and valorize it on flexibility markets (He et al., 2011; Helms et al., 2016; Lund et al., 2015). Both energy-intensive consumers and owners of generation and storage units can provide flexibility and can become flexible prosumers¹. Hence, the aggregator must co-create flexibility with the flexible prosumers. While existing literature addresses the consumer perspective in demand response programs (Gamma, 2016), for example, when consumers adjust laundry times (Moser, 2017), the role of flexible prosumers has not thus far been addressed in empirical research.

The objective of the third paper is to measure prosumers' willingness to co-create flexibility. The sample addresses the three technology application domains of solar prosumers, electric vehicle drivers and heat pump owners. We test various electricity contracts with increasing levels of flexibility provision. Providing flexibility leads to

¹ See definitions in chapter 3.2.

trade-offs for flexible prosumers through the constrained availability of their own infrastructure, indicating the costs of discomfort as an important moderating factor.

Table 1: Overview of the papers of the dissertation

No.	Title	Authors	Objective	Theoretical foundation	Method	Publication status
1	Decentralization dynamics of energy systems: A generic simulation of network effects	Merla Kubli ^{a,b} , Silvia Ulli-Beer ^a	Analyze network effects that drive the diffusion of self-consumption concepts	Network theory, socio-technical transitions	Conceptual System Dynamics simulation model	Published in <i>Energy Research and Social Science</i>
2	Squaring the sunny circle? On balancing distributive justice of power grid costs and incentives for solar prosumers	Merla Kubli ^{a,b}	Simulate the interplay between the diffusion of solar prosumers and grid cost recovery, evaluate incentives and the distribution effect	Tariff design for solar PV, behavioral consumer decision making, distributive justice	Calibrated System Dynamics model, Policy analysis	Published in <i>Energy Policy</i>
3	The flexible prosumer: Measuring the willingness to co-create distributed flexibility	Merla Kubli ^{b,a} , Moritz Looock ^b , Rolf Wüstenhagen ^b	Survey prosumers' willingness to provide flexibility	Consumer acceptance, co-creation, service-dominant logic	Conjoint analysis (Choice-based conjoint)	Published in <i>Energy Policy</i>

^a Institute of Sustainable Development, Zurich University of Applied Sciences, Switzerland^b Institute for Economy and the Environment, University of St.Gallen, Switzerland

3. Conceptual model

The conceptual model presented in Figure 3 embeds the three research foci of this dissertation. The conceptual model builds on the framework for renewable energy investments by Wüstenhagen and Menichetti (2012), on the definition of (direct) network effects (Katz & Shapiro, 1985) and on path dependence (Arthur, 1994; Pierson, 2000). The conceptual model links *systemic context factors* with *individual context factors* as determinants of the consumers' decision for renewable energies.

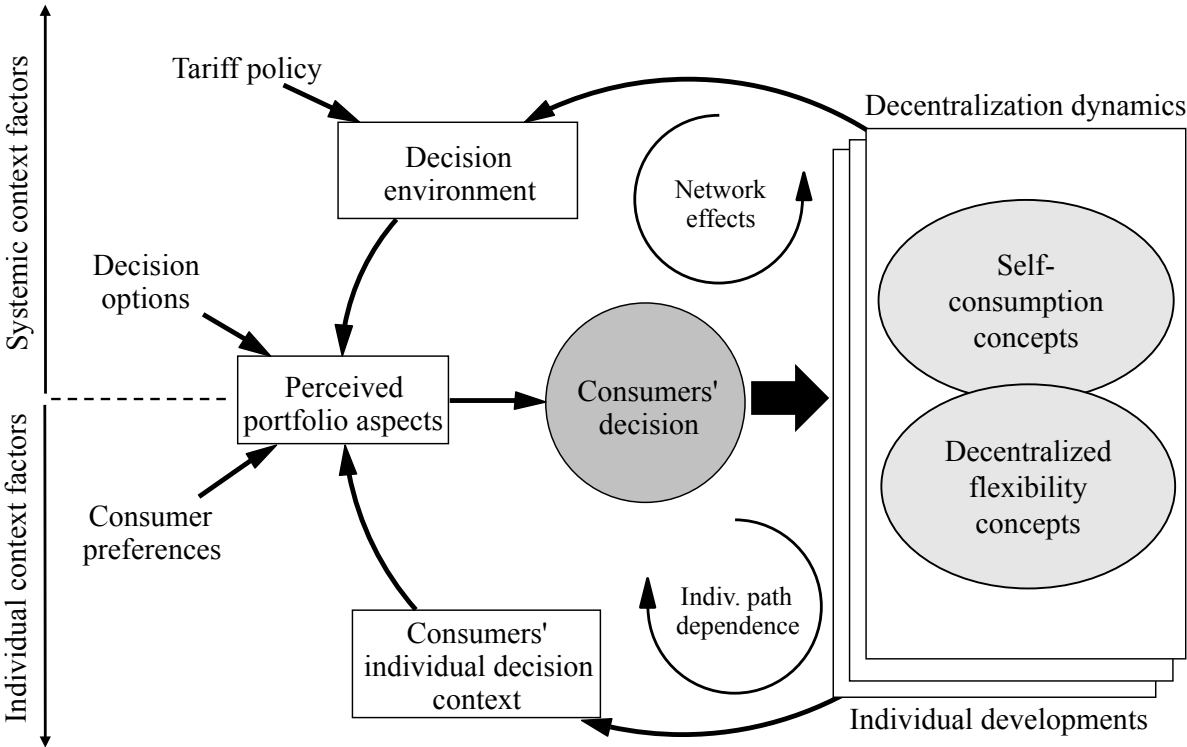


Figure 3: Conceptual model overarching the three papers of the dissertation

The conceptual model highlights the *decentralization dynamics of energy systems* as the dependent, to-be-explained variable, forming the main theme of this dissertation. The diffusion of self-consumption concepts and decentralized flexibility concepts characterize the decentralization dynamics. Accumulated over the mass, *consumers' decisions* shape the decentralization dynamics.

Based on the *perceived portfolio aspects*, consumers decide which decision is best for them. I build on the framework by Wüstenhagen and Menichetti (2012) for renewable energy investments and extend it to decisions that concern renewable energy products¹. While Wüstenhagen and Menichetti (2012) go into detail with regard to how return and risk influence the portfolio aspects “filtered” through cognitive aspects, here I aggregate this process into one variable, acknowledging the relevance of cognitive factors by calling them perceived portfolio aspects. Four determinants form the perceived portfolio aspects, including *decision environment*, *decision options*, *consumer preferences* and *consumers’ individual decision context*. While these determinants describe the factors individually, in the perceived portfolio aspects, consumers evaluate the decision options, analyzing how they fit to their (portfolio) situation, considering the decision environment and their specific preferences.

The *consumers’ individual decision context* relates to the “prior investment” variable in Wüstenhagen and Menichetti (2012), but it also considers the socio-economic context of the consumer. In the conceptual model, I set the prior decisions directly in context by representing the *individual path dependence* of decisions. Path dependence describes the influence of previous actions on future decisions (Arthur, 1994; Pierson, 2000). In contrast to path dependence on a systemic level (David, 1985; Sterman, 2000; Unruh, 2000), the path dependence on an individual level is a rarely discussed topic in the literature. Notable exceptions include Barnes et al. (2004), who elaborate on the behavioral lock-in of individuals, and Roedenbeck (2011), who presents a complex model of individual path dependence based on the motoric, sensory and cognitive systems. In this conceptual model, individual path dependence describes the influence of prior investments on future decisions about individual energy supply situation.

There is a stream of literature highlighting the importance of *consumer preferences* and the role of cognitive aspects (Wüstenhagen & Menichetti, 2012). The type of investor plays an important role (Karneyeva & Wüstenhagen, 2017; Kaufmann et al.,

¹ This is relevant for this dissertation, since I do not only consider investment decisions only, but also decisions for electricity products that include flexibility co-creation.

2013; Salm, 2018; Wüstenhagen & Menichetti, 2012), but preferences for specific product attributes also do (Burkhalter et al., 2009; Kaenzig et al., 2013; Roe et al., 2001; Tabi et al., 2014), as do risk-return evaluations (Karneyeva & Wüstenhagen, 2017; Lüthi & Wüstenhagen, 2012). In the conceptual model, consumer-specific preferences are there to evaluate the decision options based on the individual decision context as well as on the decision environment.

The *decision options* describe the constellation of options a consumer has as potential investments or product offers. The decision options represent the consumer value of an investment or product offer.

The *decision environment* refers to the development of the system context factors that influence decision making for renewable energies, such as market factors, technology costs, knowledge diffusion, peer effects and social norms (Abrahamson & Rosenkopf, 1997; Bollinger & Gillingham, 2012; Curtius et al., 2017; Pillai et al., 2014; Salm et al., 2016). In particular, I am interested in the direct influences of the decentralization dynamics on the decision environment. Through the accumulated consumer decisions, *network effects* arise and close this feedback loop.

Energy policy can tackle several of the described variables in the conceptual model, affecting the system as well as the individual context factors (Kaufmann-Hayoz et al., 2001; Wüstenhagen & Menichetti, 2012). For this dissertation, the *tariff policy* is particularly relevant. Therefore, the conceptual model highlights the tariff policy influencing the decision environment by altering market factors.

3.1. Embedding the three papers in the conceptual model

The three papers address different foci within the conceptual model presented above. In the following, I describe how the research foci relate to the conceptual model.

In the *first paper*, we set the foundations for the coming studies by building up a formalized model structure that captures the individual path dependence for consumers

applying a self-consumption concept and the network effects arising from decentralization dynamics. Consequently, we address the two feedback loops represented in the conceptual model.

In the *second paper*, I investigate the impact of different grid tariff designs and PV metering schemes. Consequently, in terms of the conceptual model, I extend the simulation model with a focus on the impacts of the variable tariff policy. The tariff policy is a strong lever for the network effect feedback loop. A further focus lies on the consumer decision-making process for self-consumption concepts, which is modelled more realistically. In particular, I incorporate a more fine-grained consideration of investor types and their preferences and individual contexts.

In the *third paper*, we empirically investigate consumers' willingness to co-create flexibility. The focus therefore lies on consumer preferences for providing decentralized flexibility. A contribution of the third paper is the elaborated design reflecting the decision options for consumers when it comes to co-creating decentralized flexibility.

3.2. Emerging decentralized energy concepts

The emerging consumption concepts around self-consumption of locally generated electricity and decentralized flexibility are particularly relevant for this dissertation. In Figure 4, I display the defined self-consumption concepts along two dimensions – degree of self-sufficiency and scope. Self-sufficiency describes how much of the electricity needs can be covered with decentralized production. In extreme cases, consumers become fully autarkic, where they are independent of the electric utility company. The scope addresses the basis on which the locally generated electricity is balanced with demand. In the following, I explain and define the concepts used.



		Degree of self-sufficiency 		
		Low	Varying	Maximum
Scope 	SFH / CC	Prosumers	[Flexible] Storage prosumers	Autarkic prosumers
	MFH	Prosumer community	[Flexible] Prosumer community with storage	Autarkic prosumer community
	District	Microgrid	[Flexible] Microgrid with storage	Autarkic microgrid

Figure 4: Categorization of self-consumption concepts along the dimensions of self-sufficiency and scope (SFH: Single-family house, MFH: Multi-family houses, CC: Commercial consumer).

Grid consumers: Grid consumers consume their electricity entirely from the main electricity grid. Grid consumers pay the local utility company for the electricity, the transmission and distribution costs and, in some cases, taxes. In this dissertation, I also use the synonym “conventional (grid) consumer”.

Self-consumption concepts: Decentralized generation and storage units allow for various constellations of self-consumption. I use the term “self-consumption concept” throughout the dissertation as the umbrella term for all concepts focusing on self-consumption. In contrast to the term “business model”, the self-consumption concept connotes the consumer perspective, focusing on customer value.

Prosumers: Prosumers *produce* and *consume* electricity right at their location (Kesting & Bliet, 2013). The most common technology used for prosumer systems are PV plants installed on rooftops. Prosumers achieve different degrees of self-sufficiency, depending on the installed system. The degree of self-sufficiency of prosumers can be increased by installing storage units (“storage prosumers”) and/or by shifting load or generation (“flexible prosumers”). Autarkic prosumers cover their entire energy demand by independently producing energy.

Prosumer community: Prosumer communities share the locally generated electricity within a multi-family house covering several households. In the same way as prosumers, prosumer communities can also be operated in a grid-connected as well as a grid-isolated manner, depending on the installed infrastructure.

Microgrid: In microgrids, households consume geographically proximate electricity within a district, in the area of a transformer. A small-scale grid connects the generation plants to the consumers (Chowdhury et al., 2009; Platt et al., 2012). The defining feature of a grid-connected microgrid is its single connection point to the main grid, except for the fully autarkic microgrid. There are various formations of technologies and systems. Combined heat and power (CHP) plants are frequently installed for the provision of heat and electricity in microgrids (Soshinskaya et al., 2014).

Flexible prosumers: Throughout this dissertation, I describe as flexible prosumers those consumers who provide flexibility services with their own electricity generation, storage or consumption facilities. A potential application case is a storage prosumer who not only uses the battery for optimizing her self-consumption but also provides flexibility to the main electricity system (Lund et al., 2015). By pooling the flexibility of numerous flexible prosumers, the so-called aggregator can valorize the flexibility in the balancing power markets (He et al., 2011) or use it as balance energy or ripple control on the grid side (Veldman et al., 2013). Through providing flexibility, flexible prosumers likely do not reach the same self-sufficiency, as they would if they focused on maximizing self-sufficiency (Santos et al., 2014).

Different load patterns result from the different decentralized energy concepts, in terms of the degree of self-sufficiency, the residual load (the remaining consumption from the grid) and surplus production that is fed into the grid or into a decentralized storage unit. Figure 5 displays a conceptual representation of the load patterns for prosumers, storage prosumers, autarkic prosumers and flexible prosumers.

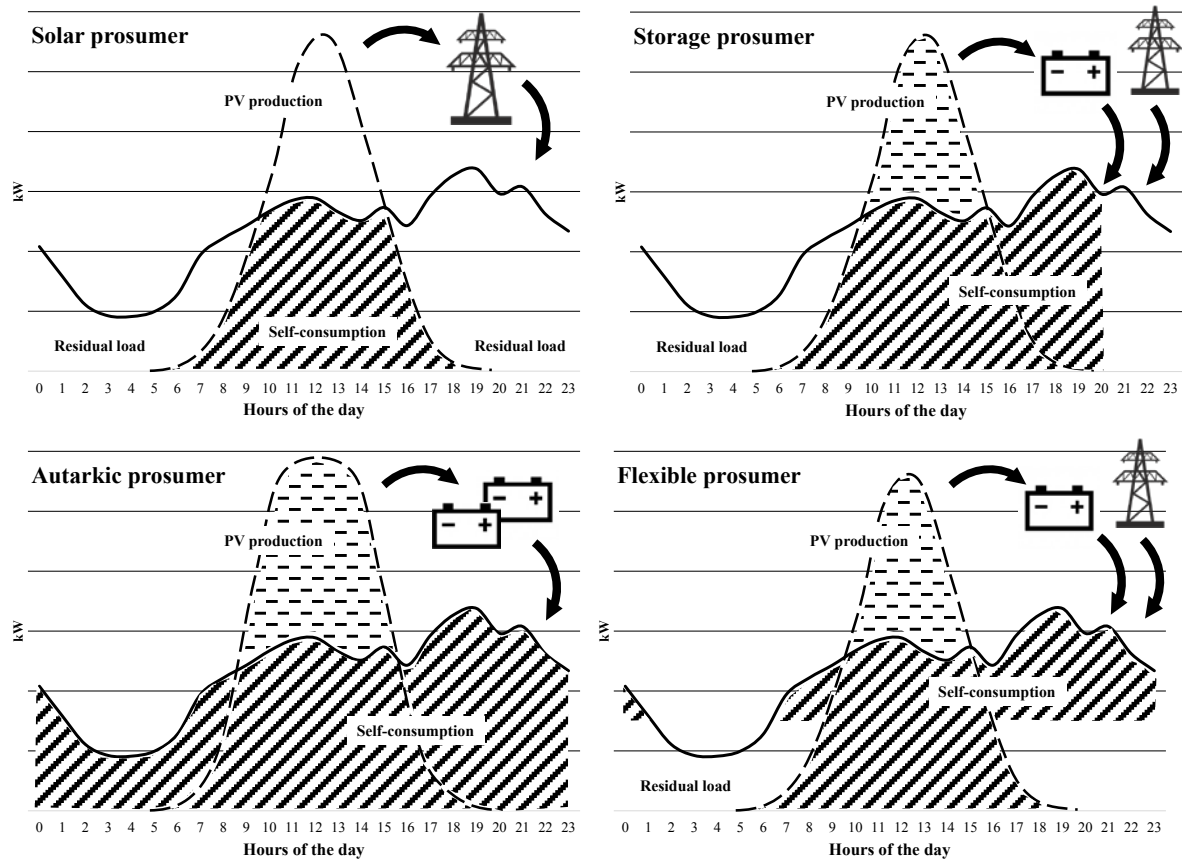


Figure 5: Demand patterns of prosumers, storage prosumers, autarkic prosumers and flexible prosumers (conceptual representation¹)

4. Methodology

To address the three selected foci, I apply different methodological approaches. The methods are complementary and provide a broad picture on important aspects on decentralizing energy systems.

For the *first paper*, we choose a conceptual simulation approach to capture some of the decentralization dynamics of energy systems. Simulation is considered a valuable addition to often rather qualitative transition studies (Holtz et al., 2015; Ulli-Ber, 2013;

¹ The demand curve is based on a standard load profile for household consumers, kindly provided by Romande Energie SA.

Ulli-Beer et al., 2017) as well as to technical optimization models (Manfren et al., 2011). We develop a conceptual simulation framework describing how network effects drive the diffusion of self-consumption concepts. To build the simulation framework, we choose the modelling language and method of System Dynamics (Forrester, 1961; Sterman, 2000). System Dynamics is particularly suitable for studying transition processes, since it allows integrating different domains of a system. System Dynamics is also well suited to the translation of network effects, the theoretical lens applied for this paper, into the modelling language. While various calibrated System Dynamics models are well known (e.g. World3, Forrester’s Market Growth Model, iSDG¹), and causal loop diagrams are a common tool, at least in the System Dynamics community, the middle way of conceptual simulation models appears less frequently. A conceptual simulation model comes with the advantages of simulation, so that complex interactions do not have to be executed mentally, but the models do not get as complex as fully calibrated simulation models. We apply a model-based theory development approach (Davis et al., 2007; Pool, 1992; Rohlf, 1974; Schwaninger & Grösser, 2008) by integrating knowledge pieces from literature into the conceptual simulation model to obtain new insights on the decentralization dynamics from their interactions. To test the strength and the impact of the different network effects, I aim for disciplined imagination (Weick, 1989). We conduct what we call a “complex thought experiment” by bringing a quantitative dimension to the disciplined imagination through what-if analyses (Zagonel et al., 2004). In concrete terms, we simulate extreme conditions that arise from cutting the feedback loops of the direct network effects and test extreme inputs for the indirect network effects.

In the *second paper*, I further develop the model of the first paper to a fully calibrated simulation model suitable for policy testing. While the feedback structure is still based on the structure capturing the network effects governing the decentralization dynamics, I focus on the self-consumption concepts of solar prosumers and solar prosumers with storage. To appropriately represent the situation of the five simulated scenarios,

¹ Formerly known under the name Threshold 21 (T21).

the model is refined in nearly all of its sections. Most importantly, I put the focus on realistically modelling the investment decision for solar PV and batteries. I use conceptual insights from the field of behavioral decision making (Johnson, 1984; Tversky & Kahneman, 1974), as well as empirical results from studies investigating energy consumers (e.g. Ebers & Wüstenhagen, 2015). I also include investor-specific characteristics of the self-consumption concepts for single-family houses, multi-family houses, and commercial consumers and I refine the calculation of the PV bill savings and income, based on the path dependencies of the consumer groups. To calibrate the model, I model the policy change from the feed-in tariff policy to the investment grant for PV in Switzerland (Swiss Federal Office of Energy, 2015). Finally, I develop structures for the grid tariff designs and metering schemes for the PV of interest. To analyze the distributive justice of the cost recovery of power distribution grids, I introduce two measures: the distribution effect and the cost-causality of consumers. Finally, the analysis follows a policy analysis, where I test the impact of different grid tariff designs and PV metering schemes.

The *third paper* focuses on the prosumers' preferences of providing decentralized flexibility. Here we apply an empirical approach to test the willingness to co-create flexibility under different circumstances. With a choice experiment following the choice-based conjoint analysis method (Lancaster, 1966; Louviere et al., 2000; Sawtooth, 2017), we elicit the prosumers' preferences for electricity contracts that include different levels of flexibility provision. In the case of flexibility contracts, the market is not developed enough to empirically evaluate the revealed consumer preferences. Conjoint analysis is a suitable method to test stated preferences for products that are not (yet) available on the market, or in this case a fundamentally new product (Hensher et al., 2005). Since the perfect flexible prosumer with various decentralized generation and storage facilities does not yet exist, we investigate prosumers' willingness to provide flexibility in three technology application areas: heat pumps, electric vehicles and solar PV with batteries. Our sample consists of 902 owners and people interested in these technologies, as we consider these the most likely early adopters of flexibility contracts. The presented electricity contract has four attributes: the monthly electricity costs, the

use of flexibility, the electricity mix and the contract duration. While the standard attributes of the electricity contract are the same for all, we design the flexibility attribute specifically for the technology application area. The analysis focuses on the importances of the electricity contract attributes and the part-worth utilities of the specific levels. We also provide a qualitative comparison across the three technology areas and elicit the premiums required by prosumers to provide varying degrees of flexibility.

5. Conclusion

The three papers of this dissertation lead to insights valuable for different theoretical fields and methodological approaches as well as contributions to practical aspects of the management of the energy transition. Below, I also discuss the limitations of this dissertation and the emerging avenues for further research.

5.1. Theoretical contributions

This dissertation contributes to the understanding of the *energy transition* as a specific case of a socio-technical transition (Geels, 2002; Markard et al., 2012) focusing on different transition phenomena and illuminating different levels of aggregation.

Network effects strongly influence the paradigm change of decentralization occurring in the energy system by diffusing self-consumption concepts. Network effects emerge between solar PV and battery storage as well as through complementary production technologies such as combined-heat and power plants. These network effects and co-benefits lead to new (self-)consumption concepts and accelerate the diffusion of the technologies. The reinforcing processes influence not only the speed of the transition (the rate of change) but also the direction of change, showing the extent to which consumers adopt certain consumption concepts (*first paper*). We find a shift between the analyzed self-consumption concepts; in a first phase, the solar prosumer concept is most popular, but at a later stage of the transition, advanced self-consumption concepts such

as prosumers with storage and microgrids become more attractive (*first and second paper*). A particularly relevant network effect forms around the tariff setting for the distribution grid, which influences the attractiveness of self-consumption concepts (*first paper*).

The network effect of the cost recovery of distribution grids starts a discussion on *policy design*. I contribute to this discussion by simulating the impacts of potential policy options regarding the design of grid tariffs, as well as the metering scheme of decentralized solar PV. With my findings, I highlight the idea that regulatory options should always be seen in the light of multiple aspects. There is no perfect tariff design for distribution grids or PV metering schemes that will satisfy them all to the maximum. Furthermore, regulatory designs are the lever by which to improve distributive justice for all actors, but set at the same time, they are also important incentives in the investment decision. Policy changes for self-consumption concepts lead to trade-offs that should be subject of a (political) value discussion on how to weight them. With the developed simulation model, I provide a first foundation for an impact assessment and bring into focus the previously less discussed grid-tariff induced incentives for investments into new renewable energies (*second paper*). Grid tariffs and metering schemes can also set incentives for how consumers shape their consumption profiles, which can be an important source of flexibility.

Taking into account the *consumers' preferences* as well as the technology application areas with the lowest cost of discomfort for consumers is the key to successfully using decentralized flexibility (*third paper*). In particular, companies aiming to access decentralized flexibility should design business models addressing potential flexible prosumers in the domains of energy use of electric mobility and solar PV owners. With these insights, the third paper contributes to the literature on consumer/investor preferences and consumer acceptance in the field of energy (Wolsink, 2012; Wüstenhagen & Menichetti, 2012; Wüstenhagen et al., 2007).

The *co-creation* of value through direct and indirect interaction between provid-

ers and consumers (Vargo, 2008), is a popular area of (re-)search activities in areas beyond the energy transition. Co-creation can be understood as a sub-field of the service-dominant logic, which suggests a change from firm-inside focus to a customer focus (Prahalad & Ramaswamy, 2004; Vargo, 2008; Vargo & Lusch, 2004). Researchers investigate the active roles that consumers play as co-creators of new product development (Cui & Wu, 2016; Hoyer et al., 2010; O’Hern & Rindfleisch, 2010), innovation (Baldwin & von Hippel, 2011), service production and delivery (Bitner et al., 1997; Kelley et al., 1990) or embedded lead-users (Schweisfurth & Raasch, 2015). The application cases of the studies investigating consumers’ willingness to co-create include industries such as health care service encounters (Gallan et al., 2013), virtual co-creation platforms for product design (Füller, 2010), public transportation services (Gebauer et al., 2010) or the organization of large-scale events (Pera et al., 2016). A common ground of these studies is that they focus on high-involvement industries where there is already direct contact between the consumer and the provider. The electricity industry, in contrast, is characterized by low consumer involvement, which, for instance, can be seen in low switching rates for electricity products (Herbes & Friege, 2017). The third paper is among the first to measure the *consumers’ willingness to co-create in a low-involvement industry*. The results of the *third paper* can therefore be of interest beyond the energy field, since the tested situation resembles the field of various utility providers (such as water supply, waste collection, heat and transportation providers) and that of other low-involvement industries.

5.2. Methodological contributions

The research approach chosen in the *first and second paper* of this dissertation links to the calls for innovative simulation approaches capturing socio-technical transitions in a quantitative manner (Holtz et al., 2015; Manfren et al., 2011). The *modelling of socio-technical transitions* with System Dynamics was already outlined by Ulli-Beer (2013) as a promising approach. Here I contribute by simulating the socio-technical determinants of the decentralization dynamics of energy systems.

One particular focus is to model the investment decisions of consumers who shape the decentralization. The focus on the consumers' investment decision implies an endogenous modelling of the decision process (*first and second paper*). I demonstrate how empirical insights into investment preferences of electricity consumers can be successfully integrated in a dynamic simulation model (*second paper*). *Empirical-based modelling of the investment decision* is the key to representing the decision process more realistically, and it therefore contributes to a holistic understanding of the transition process.

Concerning the grid tariff design, the discussion of distributive justice is central. To capture and *measure distributive justice* in a quantitative manner, I develop two measures: the distribution effect and cost causality (*second paper*). While the distribution effect measures the increase in grid tariffs caused by self-consumption on a systemic level, the cost causality measures how consumers contribute to recover their caused costs on a consumer-group-specific level.

To assess the prosumers' willingness to co-create, we develop a choice experiment design capable of *measuring the willingness to co-create* (*third paper*). To translate co-creating flexibility in a consumer-relevant decision, we embed the impact for consumers of providing flexibility with respect to an electricity product. To quantify the premium required by prosumers, we adopt the concept of willingness-to-accept and willingness-to-pay for the particular situation of co-creating flexibility. By doing so, we also provide data for modelling approaches that "take the humans in the loop" (Eichler et al., 2017; Kubli, 2018; Sowe et al., 2016). The developed measure has the potential to be adopted into related fields where consumers' willingness to co-create is essential.

5.3. Practical contributions

The three papers of this dissertation address practical phenomena within the energy transition and provide findings that are not only relevant for academic research on

the transition processes, but that also generate insights that can be of concrete practical value to policy makers and energy professionals.

The *first paper* demonstrates that the decentralization of energy systems begins with the diffusion of prosumer concepts with only one technology. In a second phase, more advanced self-consumption concepts will overtake that benefit through the combination of multiple technologies, contributing to a higher degree of self-sufficiency (later confirmed, with the second paper by the two concepts of solar prosumers and storage prosumers). This is important information for energy managers. The two-stage development implies that self-consumption will increase more strongly and that utility managers should plan capacity investment and business innovation accordingly. Through the two-stage development, there is the potential for business model designs that offer a retrofit of existing systems and make use of co-benefits between technologies. Network effects and co-benefits are relevant drivers for this two-phase development to happen. In particular, the learning effect is crucial and can be stimulated with pilot projects and active communication about successful implementations. Adjusting the grid tariff to higher levels will set off new incentives for investment to increase self-sufficiency. The simulation framework also proved to be a helpful tool for practitioners to expand their learning, using it as a boundary object in participative workshops (Ullrich et al., 2017).

The *second paper* highlights the dynamic interaction between the diffusion of solar prosumers, the recovery of grid costs, the setting of tariffs and incentives for consumers to invest in self-consumption. This interaction has not received much attention in the political discussion so far. However, incentives arising from tariffs are highly crucial when discussing alternative grid tariff designs, as they have a strong impact on the diffusion of renewable energies. The paper contributes to the political discussion by countering the belief that the diffusion of solar prosumers causes a large distributive effect between consumers with and without self-consumption. The scenarios of alternative grid tariffs reveal that a capacity-based tariff, which is often mentioned as the solution, also leads to a distributive effect. The paper provides some new avenues for thought

for future tariff design in strongly decentralized energy systems. The results have been communicated, together with other research findings, in a white paper addressing policy makers and energy professionals (Ulli-Beer et al., 2016).

The *third paper* provides a first glimpse into prosumers' willingness to provide flexibility. If utility companies aim to make use of decentralized flexibility they need to co-create it together with their consumers, addressing those consumers' preferences. This implicitly requires a shift from a product-oriented business logic towards a more service- and consumer-oriented logic. The elicited empirical data is highly relevant for companies designing business models for decentral flexibility, such as virtual power plants, battery swarms or the pooling of heat pumps. The paper provides relevant insights on which technology application areas are the lowest hanging fruit for exploiting decentralized flexibility. The required flexibility premium that is derived is a key indicator for companies intending to enter the flexibility market, on that was previously not available in this form. Finally, along with the concept of "costs of discomfort", the paper provides an explanatory framework for where to locate further promising areas for decentralized flexibility.

5.4. Limitations and avenues for further research

First and foremost, it is very important to say that this dissertation does not aim to address all aspects relevant to the decentralization of energy systems. The energy transition brings a huge number of opportunities and needs for research. This dissertation is a selection of questions that appear to be relevant for the energy transition but which, by fare, are not exhaustive of the numerous challenges to come. While this dissertation provides valuable insights into some highly relevant questions about the decentralization dynamics of energy systems, it is also subject to limitations. I discuss study-specific limitations relating to the particular research in each paper and focus here on the overarching limitations in this dissertation. The limitations of this dissertation point towards new fields for further research.

In the three papers of this dissertation, I study the dynamics of a particular transition, the decentralization dynamics within the energy transition, focusing on particular cases in Switzerland. The *Swiss context* resembles the situation of many developed countries, in terms of the electricity supply infrastructure, although with a small share of new renewable energies. However, it certainly does not represent the situation in all countries. One limitation of this dissertation, which I would consider a strength at the same time, is that it developed and grew together with the Swiss energy transition. The foci were selected based on what appeared to be pressing issues, issues that were also relevant for energy system managers and for utility managers in particular. Likely (and hopefully), the knowledge created in this dissertation will be overtaken and outdated by the developments of the energy system. At very best, this knowledge will become part of the memory of the system in one way or another, by influencing decisions made in the energy system. However, the contexts of other countries can be very different and would lead to different (model) structures of the driving factors of the energy transition. Consequently, future research should select the research foci and research approaches addressing the challenges arising from each particular context. Two streams of further research arise that build on the existing work. Firstly, the simulation models and choice experiment model could be applied in the *context of other countries*, and the differences and similarities could be compared. Secondly, and in the larger picture, the structures of the shift of consumers to some form of prosumers happens in *other industries* as well (e.g., telecom industry, social media) and is crucial for innovation and transition processes. Eliciting the generically relevant dynamics and translating to these settings could contribute to a more holistic understanding of these transitions.

A general limitation for the first and second paper is the limited *data availability*. On the one hand, data on a transition that is in the midst of occurring is naturally scarce. On the other hand, some data is hard to access or is not available in the required quality. One answer to this limitation is to conduct research like that in the third paper, where primary data is elicited. Still, it is important to actually make relevant data accessible. Updating the studies in a decade with *longer data rows and a model structure* based on the developments over that period (*first and second paper*), as well as with *revealed*

consumer preferences (third paper) is an interesting research avenue. The updated analysis would enhance the understanding of the historic developments and would allow a more accurate calibration of the model, leading to simulations that would be more robust. Studies focusing on revealed consumer preferences provide more detailed and realistic insights on the actual consumer behavior and preferences in the very concrete decision context. However, pure ex-post studies do not have the same practical relevance as an ex-ante study. Therefore, the new challenges ahead should define the purpose and focus of these studies.

In the simulation studies as well as in the choice experiment, I build on a *pre-defined set of decentralized energy solutions* (this becomes obvious in the conceptual model presented in Figure 3). While this is very helpful for a research design leading to concise insights, realistically, the best concepts will be adapted over time, based on the available technology, the costs and the state of the system as well as on changing consumer preferences. Further research can address this limitation by endogenously simulating the decision options of consumers by integrating the *dynamics of business model innovation*. Further developments are needed, for instance, to better understand the dynamics of *decentralized flexibility business models*. In particular, it will be important to capture the dynamics between the revenue generated from valorizing flexibility, the compensation provided to flexible prosumers and the participation rate in the business model. The existing simulation model and empirical data on the prosumers' willingness to provide flexibility provide an excellent basis upon which to tackle this promising avenue of research.

To simulate the dynamics of decentralized flexibility business models on the basis of the choice experiment data, the elicited part-worth utilities must be integrated into the decision structure of the System Dynamics model. *Fusing choice experiments with System Dynamics* has been, surprisingly, very rarely addressed in the literature thus far (for two notable exceptions, see Kopainsky et al. (2012) and Schmidt and Gary (2002)). I perceive this as a very promising avenue for further research, relevant beyond business models for decentralized flexibility. On the one hand, System Dynamics models often

address socio-technical transitions, where consumer decisions are critical. Representing the choice of consumers in a more realistic manner by capturing the preferences for trade-offs allows for an improved simulation of the diffusion of a product, service or business model. On the other hand, choice experiments focus on consumer preference for a selection of attributes at a certain instant of time. To understand the potential market share, choice experiments are often combined with market simulators that make a linear forecast of market shares. System Dynamics can add to the market simulation by integrating important feedback loops between the product diffusion and the product attributes.

A final note. After all, the knowledge acquired in this dissertation provides only a theoretical-empirical basis. To create real value, the insights gained must be adopted by policy makers, utility companies and investors. I hope this foundation inspires further developments in science as well as practical implementations. We need to implement and test the ideas and insights for tariff designs, business models and consumer preferences. Learning from the real world is crucial for double-loop learning (Argyris & Schön, 1974), enabling feedback from reality to strategy adjustments and strategic renewal (Simons, 1994). Together with its accompanying research and learning from practical implementations, we will bring the energy transition forward. Learning through implementing will allow us to adjust our mental models and will keep the cycle of researching, creating, learning and shaping ongoing.

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Paper I

Decentralisation dynamics in energy systems: A generic simulation of network effects

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Abstract

Distributed generation is becoming increasingly important in energy systems, causing a transition towards decentralisation. These decentralisation dynamics are difficult to predict in their scope and timing and therefore present a major challenge for utility companies. This paper aims to make a contribution to the field of energy transitions with a model-based theory-building approach. A conceptual framework of the major (circular) causalities of regional energy systems is presented. It improves the knowledge on transition patterns of distributed generation concepts and the interplaying network effects. Network effects between technologies, the installed base and the investment decision criteria are important elements in the transition dynamics. A System Dynamics simulation model is built, capturing the consumption concepts related to distributed generation, as well as arising network effects, to analyse the likely transition patterns of regional energy systems. Our simulation results highlight the significance of network effects steering the investment decision for distributed generation concepts, pilot projects to accelerate the transition of regional energy systems and the general role of microgrids in the decentralisation dynamics.

Keywords: energy systems, transition, network effects, distributed generation, death spiral, simulation, System Dynamics.

1. Introduction

Energy systems are facing a period of transition. New renewable energies open up opportunities for new consumption concepts. So far, electricity consumption has been one-directional. Consumers obtained electricity from the main grid and paid the utility company for this service. This is now changing with the emerging of prosumer and microgrid concepts (Kesting & Bliiek, 2013; Marris, 2008; Soshinskaya et al., 2014). Therefore, current energy systems show strong decentralisation tendencies (Alanne & Saari, 2006; ITRE, 2010; Verbong & Geels, 2007). The increasing attractiveness of new renewable energies and their continuing integration into the energy system as local and small scale production plants are driving these decentralisation dynamics. Crucial for the diffusion of prosumer and microgrid concepts is the utility perception of consumers of these distributed generation concepts, feedback processes and network effects within the energy system. Despite the significance for the energy transition and the growing number of regional initiatives, decentralisation dynamics and network effects have enjoyed little attention in the research so far. Technology-specific assessments and qualitative discussions of the barriers and drivers of prosumer systems and microgrids dominate the literature. However, further factors – such as environmental motivations, increased security and independency, regulatory barriers and familiarity effects – are particularly relevant in energy planning (Stern, 2014) and largely influence the decision-making process of small-scale investors to invest in prosumer systems or to form a microgrid (Schelly, 2014; Soshinskaya et al., 2014). Insights from the social sciences, as such, are chronically underrepresented in energy research (Sovacool, 2014). A detailed understanding of likely decentralisation dynamics in a region is essential for production planning, business model development, grid maintenance for utilities, producers of technological components and the political governance of a region. To avoid the high costs of late adaptation, early strategy development and stakeholder engagement are crucial. This requires an improved understanding of the underlying processes that drive the decentralisation dynamics.

We hypothesise that the deployment patterns of prosumer systems and microgrids strongly depend on early co-ordinated initiatives in general – and network effects in particular. Katz and Shapiro (1985) define *network effects* as the dependency of the product utility on the network size as well as the positive effect of coalitions with other

products. We presume that network effects between technologies and the installed base of the particular consumption concepts can promote distributed generation systems to a breakthrough, which otherwise would not happen on a comparable scale. Hence, a better understanding of the evolving network effects is critical for choosing early on the right investment strategy and partners. For instance Hagiú (2014) stresses the importance of network effects for commercialisation strategies for multi-sided platforms.

A systemic analysis that integrates technological, economic and social behaviour aspects is essential in achieving a holistic understanding of the interplay of the different distributed generation systems and consumption concepts, technological solutions and actor-specific decision criteria. We apply System Dynamics (Forrester, 1961; Sterman, 2000), a causal modelling approach that focuses on feedback mechanisms in a system. The likely deployment patterns of distributed generation systems are simulated under extreme-condition scenarios to weigh the strength of the distinct network effects. Results are gained on the impact of network effects in terms of the dominance of different distributed generation concepts. The novelty of this paper is the application of the network theory in the field of energy transitions combined with a simulation-based theory-building approach.

The paper is structured as follows: The introduction is followed by the second section embedding our research in the existing literature and discussing the definitions of the consumption concepts related to distributed generation. In the third section, we present the conceptual framework and the developed System Dynamics model explaining the captured network effects. In the fourth section, we present the simulation results and the analysis of the impact of the network effects on the transition of regional energy systems. We close with a section on our conclusion and further research.

2. Background

Energy transitions are a widely discussed topic in scientific literature. Araújo (2014, p. 112) defines *energy transition* as “a shift in the nature or pattern of how energy is utilized within a system”. There are various forms of energy transitions. Naill (1992) describes transitions in the energy sector in terms of the choice for the primary energy

source to produce the energy, mentioning the changes from wood to coal, gas and nuclear. Today, new renewable energies are about to transform the energy system (ITRE, 2010; Schleicher-Tappeser, 2012). New renewables favour distributed generation, which is defined as an “electric power source connected directly to the distribution network or on the customer site of the meter” (Ackermann et al., 2001, p. 201). The transition towards distributed generation is observed on the entire European continent (ITRE, 2010) and brings with it multiple implications and challenges for actors in energy systems. In this paper, we analyse the trend towards distributed generation by shedding a more detailed view on the network effects that play a role in determining the diffusion of the consumption concepts related to distributed generation.

2.1. Distributed generation concepts

Different consumption concepts related to distributed generation emerge through these decentralisation dynamics and become increasingly attractive for consumers. With the installation of a distributed generation concept consumers also become investors. Wüstenhagen and Menichetti (2012) and Helms et al. (2015) find that – in contrast to centralised generation – private investors, such as home-owners, farmers and cooperatives make the largest share in investment into renewables. In this paper we solely focus on consumer concepts related to physical capacity installation. As a reference and starting point, we use the standard consumption concept here called the *grid consumer*.

Grid consumers refer to consumers purchasing the required electricity from the main electricity grid. The price for grid consumption paid to the local utility company is divided into three parts: the actual costs for the energy consumed, transmission costs and taxes. Usually, transmission costs make about half of the total electricity price.

For the categorisation of consumption concepts related to distributed generation, we define two dimensions – the concept, based on the scale of self-consumption optimisation, and the autarky level, the level of economic independence from the main grid.

Figure 1 displays the categorisation of the distributed generation concepts discussed below.

		Autarky level	
		Grid connected	Fully autarkic/isolated
Scale of optimisation	Single house	Prosumers	Autarkic prosumers
	District (multiple houses)	Microgrid	Autarkic microgrid

Figure 1: Categorisation of distributed generation concepts

Prosumers are entities in the electricity system that consume and produce electricity (Kesting & Bliet, 2013). The optimisation of electricity consumption and production is made on the scale of one house. The most common technology used for prosumer systems are photovoltaic (PV) plants installed on rooftops, but also small-scale wind and hydro power plants may be considered. Prosumers can be either autarkic or non-autarkic. **Autarkic prosumers** cover their entire energy demand by independently producing energy. No energy is taken from the main grid or fed into the grid. This status is usually reached by the installation of a storage technology, such as a battery, in addition to the electricity production unit. These households can be considered as completely decoupled from the grid. **Non-autarkic prosumers** produce part of their energy needs themselves but still consume electricity from the main grid in times when their production plant does not provide the required amount of energy. In periods with excess energy, the surplus of electricity is fed into the grid. Hence, the main grid is used as a buffer for fluctuations in the distributed generation capacity or phases without production from the fluctuating renewables. These residual loads of prosumer systems are a major challenge for grid operators aiming to stabilise the grid frequency and to ensure security of supply.

Microgrids are geographically proximate producer units that are installed close to multiple consumer units and are connected through a small scale grid (Chowdhury et al., 2009; Platt et al., 2012). The defining feature of a microgrid is its single connection point to the main grid. In this local grid, production and consumption are adjusted to each other in an optimal manner. Usually, in microgrids both, renewable and fossil, energy sources are used (Soshinskaya et al., 2014). Combined heat and power (CHP) plants are frequently installed for the provision of heat and electricity. The efficiency of microgrids can be greatly increased by the application of ICT technology, which is used

for load shifting and the regulation of production (Chowdhury et al., 2009; Soshinskaya et al., 2014). Due to different locations, varying local technological potential and different load patterns, microgrids do not have a standardised structure; there are multiple formations of technologies and systems. Microgrids can be deployed on the initiative of local utility companies or by bottom-up initiatives from producer and consumer units. A **non-autarkic microgrid** has still one connection point to the main grid, which is used to cover the remaining demand and balance excess energy. The operation of an **autarkic microgrid** is fully independent of central utilities and the main grid.

2.2. Simulation models addressing distributed generation concepts

Prosumer systems and microgrids are frequently analysed from a technological point of view (Basu et al., 2011; Chowdhury et al., 2009). Furthermore, several simulation studies are conducted in the area of distributed generation systems. Hiremath et al. (2007) and Manfren et al. (2011) provide useful overviews of the simulation models applied at various levels of decentralised energy systems and their planning. An interesting simulation study is presented by Orehounig et al. (2014). It discusses the case of the village of Zernez (Switzerland). Here, different technology constellations for fossil-free energy provision to the village are analysed on the basis of the energy hub concept. Further simulation models address technical aspects of prosumer systems or microgrid systems (Hollmann & Voss, 2005). Hiremath et al. (2007) observe that most of these simulation models use an optimisation technique to find the ideal constellation of technologies for the specific area. This type of simulation model is usually very precise in the technical assessment of the generation concept and focuses on the optimisation of the technological constellation of the distribution concepts, such as the optimal size of a battery system connected to a PV system or the optimal mix of technologies for the energy provision in a district. The diffusion of these concepts and technologies in the energy system and their impact on the transition are not addressed in these simulation models. In some cases, qualitative discussions of the benefits and challenges of distributed generation systems in terms of diffusion are provided (Basu et al., 2011;

Chowdhury et al., 2009; Soshinskaya et al., 2014). This study makes a contribution to fill this research gap.

2.3. Simulation models in transition research and the energy sector

Manfren et al. (2011) call for innovative simulation models addressing the diffusion aspects for distributed generation systems, taking into account the complex interlinkages between technology, actors, the economy and institutions. Simulation models dealing with these diffusion and transition aspects of the energy system are very rare. One crucial aspect for this gap in the research is certainly the challenge of simulating the societal changes, which are part of every large transition. Some transition processes are very well understood in an isolated framework, such as increasing returns to scale (Holtz et al., 2015). The difficulty arises, as Holtz et al. (2015) clearly state, through the simultaneous consideration of such processes and their interactions. The bridging function of models to bring together knowledge from various domains could add significant value to transition research – a potential that has just begun to be explored by researchers (Holtz et al., 2015). However, transition models face multiple challenges in conceptualisation and validation due to the complexity of the issue, high uncertainty and the lack of empirical foundations for model calibration.

2.4. Network effects and energy systems

One essential aspect of transition processes are the so-called network effects that are well known in industrial economics. Network effects are defined as the dependency of the product utility on the network size as well as the positive effect of complementary goods (Katz & Shapiro, 1985). Reinforcing processes between the network size and the utility of the product can push its diffusion or cause standards to establish its priority over others. A classic example is the telecom sector. The telephone is essential and of high utility for the consumers only through a large network (Rohlf, 1974). In the energy sector, investments are made for a very long time horizon, causing lock-in effects for future decisions (Unruh, 2000). Coalitions between companies with different products

– complementary goods – can significantly influence the perceived value of a product. In energy systems, a typical symbiosis is the combination of fluctuating producing technologies and storage technologies. The occurrence of one technology increases the utility of the other technology. Furthermore, consumer decisions can be affected by social network effects and the availability of a complementary good that improves the utility of certain concepts. These processes develop over very long time frames and require a long-term perspective to be properly analysed. In energy field research, it seems that network effects are rarely considered, although it is absolutely crucial. Simulations of network effects have been made in a couple of studies, usually looking at one particular network effect (Abrahamson & Rosenkopf, 1997). The relevance of network effects was also demonstrated with simulation in earlier versions of our work (Kubli & Ulli-Beer, 2015).

This study looks at the interplaying effect of different network effects in the decentralisation dynamics of distributed generation concepts by means of a simulation framework. The decentralisation dynamics of energy systems provide a unique opportunity to analyse the transition processes, as there is clearly one current dominating concept: the standard consumption model of the *grid consumer* (see page 3). But various options for the application of distributed generation exist and are in the process of emerging. To our knowledge, a formal quantitative analysis of the likely diffusion patterns of distributed generation concepts or and the analysis of the impact of network effects in a simulation study have not yet been provided in the literature.

3. Method and model

A System Dynamics model is built to address the issue of likely transition patterns of consumption concepts related to distributed generation in energy regions. A simulation framework is chosen to support this complex thought experiment, which cannot just be conducted mentally. With our simulation approach, we tackle the need for innovative simulation models addressing the transition aspects for decentralised energy systems. The model takes into account the complex interlinkages between technology, actors, the economy and institutions, as highlighted by Manfren et al. (2011), and links

to the emerging field of societal transition modelling (Holtz et al., 2015). System Dynamics is considered the most suitable modelling and simulation technique to address the issue of decentralisation dynamics in regional energy systems, since multiple feedback processes, delays and the state of the systems are critical in understanding the transition patterns of regional energy systems. System Dynamics (Forrester, 1961; Sterman, 2000) is a simulation and mapping method based on causal modelling. The method finds applications as a planning, analysis and policy design method in various areas of the wide field of energy research (Dyner, 2000; Ford, 1997). Some of these System Dynamics simulation models address aspects of distributed generation systems, such as the diffusion of PV plants (Movilla et al., 2013; Scheidegger & Gallati, 2013) or the diffusion of CHP plants (Ben Maalla & Kunsch, 2008). The method is also used for strategy development for utility companies in the framework of energy market liberalisation (Dyner & Larsen, 2001). In addition, System Dynamics is applied as a method for simulation-based theory-building (Davis et al., 2007; Pool, 1992; Rudolph et al., 2009; Schwaninger & Grösser, 2008). Modelling, formalisation and operationalisation are used to enhance theory development on assumptions about causal circularities that explain system behaviour phenomena that can be expected at an aggregated system level (Lane, 2000; Ulli-Ber, 2013, chapter 3). Simulation is used to test Popperian statements on these system structure behaviour assumptions. Data and fragmented knowledge from different sources and perspectives are informing the iterative process of theory building and testing.

System Dynamics applies a stock and flow notation to represent a system's structure on an aggregated level. The most central elements of System Dynamics are feedback loops – chains of causal interlinkages that form a back-coupled cycle. The concept of feedback loops also exists in other methods and theories, such as the multi-level perspective or network theory. However, the simulation of multiple complex feedback loops is solely conducted with System Dynamics. The intuitive and suitable language of System Dynamics facilitates the translation of the theoretical concepts of network effects into a simulation model.

The model presented here is generic in its structure and applies a consumer perspective. The consumer perspective is highly relevant, as consumers have wide options for their choice of their energy consumption and energy provision solutions (Stern,

2014). We aim to model typical patterns that can arise from the interplay of network effects in the decentralisation dynamics of regional energy systems. Technology learning curves have been omitted by purpose to facilitate the analysis of the impact of the network effects. Initial values are chosen to give the model a plausible starting point comparable to the current state of many regional energy systems in Europe. We define *region* as one larger municipality or a cluster of smaller municipalities. The regional level of analysis is crucial, as the installation of distributed generation occurs locally, and the major effects of this transition play out in distribution grids, and the major effects of this transition play out in the distribution grids.

3.1. Deployment pathways of distributed generation concepts

The core structure of the model represents the consumption concepts related to distributed generation, which are captured in the model with five stocks, each designating one concept. The stocks measure the number of households applying the different concepts: grid consumers, prosumers, autarkic prosumers, microgridders and autarkic microgridders. The term *microgridders* refers to consumers and prosumers involved in a microgrid. The definitions of these concepts were discussed in section 2. Households decide on their preferred consumption concept, given their situation and preferences. Different deployment pathways exist for the distinct consumption concepts. Grid consumers can decide whether they want to become prosumers, autarkic prosumers through direct installation of the system or microgrid consumers with a direct installation or whether they prefer to remain at the status quo. Basu et al. (2011) explain that the deployment of microgrids is most frequently done through the prior installation of distributed generation, such as prosumer concepts, which are subsequently combined to a microgrid. This pathway is captured in this model with the flow term *change to microgrid*. Households using the concepts of prosumer or microgrid may change their system with an additional investment in an autarkic setting. Figure 2 displays the pathways between different consumption concepts and how they are modelled in the System Dynamics model. To maintain the simplicity of the model and to facilitate the analysis of the impact of the network effects, we do not model potential backward flows of consumers, which choose to leave their distributed generation concept and would return to the grid

consumer concept. This implies the assumption that potential reinvestments do not influence the choice of concept.

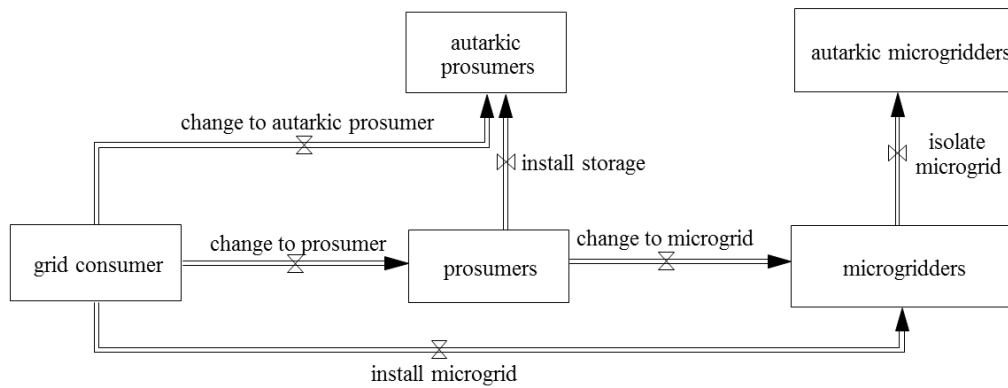


Figure 2: Structure of the stocks for consumption concepts in the model

3.2. Network effects in decentralisation dynamics

The deployment pathways of the distinct distributed generation concepts are influenced by a set of determinants. On the other side, the ongoing diffusion of distributed generation concepts affects other variables in the system, which in turn influence the determinants of the diffusion of distributed generation concepts. The causal chain between effect and cause and back to the effect is what is called a feedback loop. Arising network effects in the decentralisation dynamics of the energy system are represented either by specific determinants or by feedback loops. In this section, we discuss the represented network effects in relation to the concepts used in network theory and how they are treated in System Dynamics. Figure 3 gives an overview of the central feedback loops represented in the model. A round arrow with a letter marks a feedback loop. The “R” in the round arrow indicates a reinforcing feedback loop. “B” stands for a balancing feedback loop. The term *feedback loop* is only rarely used in network theory; here, the term *bandwagon pressure* is more frequent. Bandwagon pressure refers to a self-reinforcing process, increasing the number of adopters, which creates pressure on non-adopters and pushes, pushing them to adopt the innovation as well (Abrahamson 1997). Network effects start to form in the pervasive diffusion of an innovation, that is, when the market share of the good reaches 5 percent to 50 percent (Ulli-Beer, 2013; chapter 2, page 29).

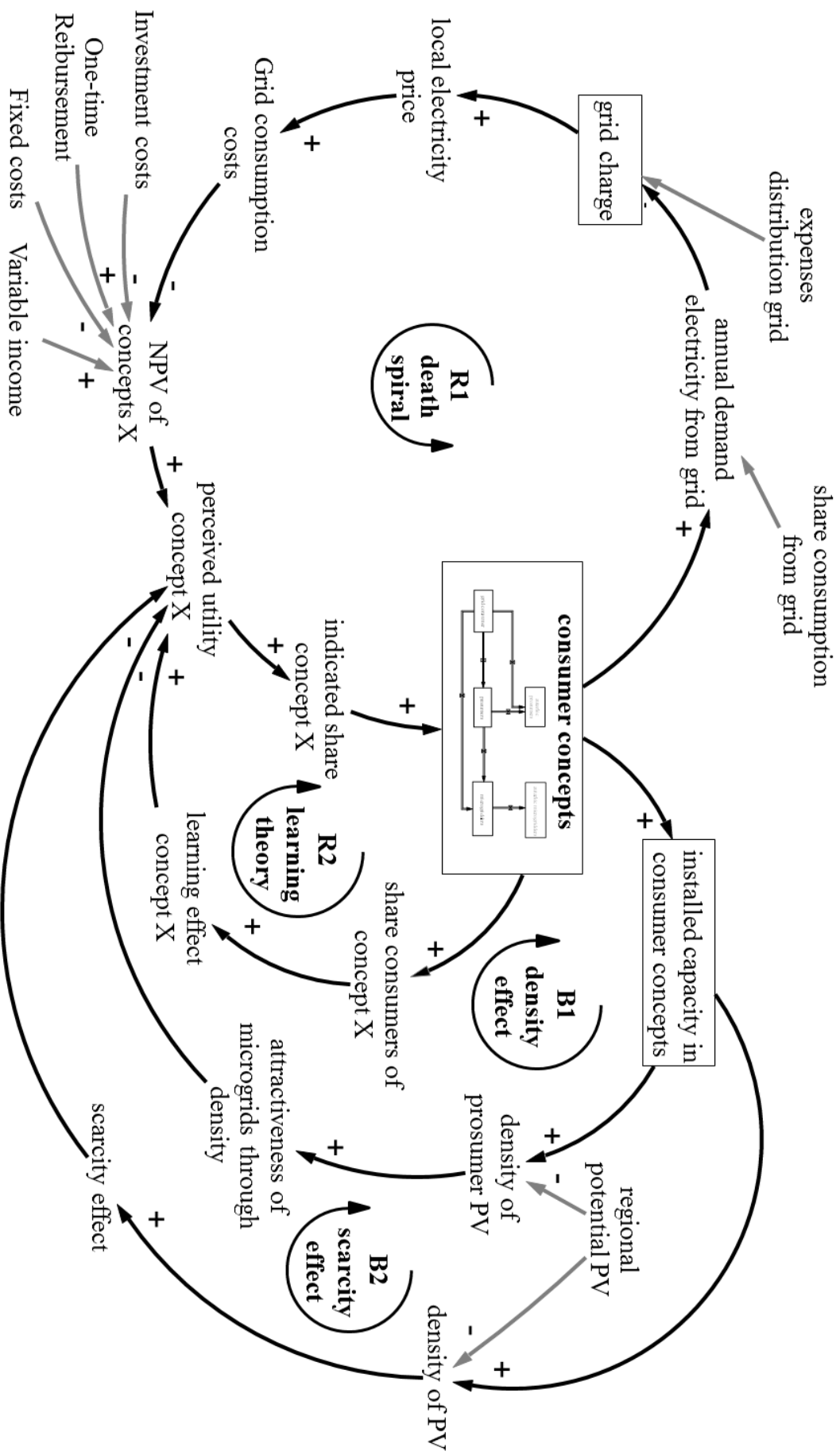


Figure 3: Overview of the feedback loops represented in the model

The feedback loop R1 *death spiral* addresses the effect on the grid charge of reduced demand from the main grid due to increased self-consumption, which feeds back to the investment decision for distributed generation concepts. In particular, the number of prosumers is crucial in terms of the tension on the coverage of the transmission grid costs. Prosumers consume less energy from the grid, contributing less to the coverage of the grid cost, but they still heavily rely on the main grid as a buffer. Consequently, the grid charge per electricity unit has to be increased to cover all costs, all else being equal. This closes a feedback loop of a reinforcing character. The grid charge is a significant leverage point in determining the attractiveness of distributed generation systems. Grid parity – when generation costs of distributed generation systems are equal to the electricity price paid by the consumers – is considered as the crucial point for the diffusion of prosumer systems (Schleicher-Tappeser, 2012). Consequently, grid parity is a sensitive issue as it relates to the attractiveness of all other distributed generation systems. In network theory, scholars frequently speak about the positive externalities of increasing the installed base. Gupta et al. (1999) define *direct network effects* as the increase in use of the utility through a larger network. In the case of distributed generation, that type of network effect plays out over the feedback loop of the *death spiral* (R1) (Costello & Hemphill, 2014). The direct functioning of distributed generation concepts is not altered by an increasing number of prosumers, since the technology remains the same. However, the increase in the grid charge raises the net present value (NPV) of these concepts, and with this, the perceived utility, which ultimately changes the investment decision. In Abrahamson (1997) this process is categorised under the bandwagon theories as the increasing return theory.

The *learning theory* feedback loop R2 is built based on the insights gained in network theory. The awareness and the information level of households on the distributed generation systems increase with a larger installed base. The adjustment of perceived utility due to higher awareness and improved information is in network theory called the learning theory (Abrahamson & Rosenkopf, 1997). In marketing literature this effect is usually called the peer effect (e.g., Bollinger & Gillingham, 2012). In System Dynamics, the concept of the word-of-mouth effect (Sterman, 2000) or familiarity effect (Struben & Sterman, 2008) is more common. In contrast to the learning theory, the main argument for the word-of-mouth effect is the exposure to advertising, which

refers more referring to awareness rather than the actual information level. In this model, it is assumed that a higher information level leads to a more positive evaluation of the concepts. This theory is supported by Basu et al. (2011) for the case of microgrids by Basu et al. (2011), who mention a lack of experience and information as barriers for the deployment of microgrids. In Bollinger and Gillingham (2012) find in an empirical study, conducted in California, a positive correlation between the number of solar PV installations and the probability of additional installations of solar PV systems. For this model, we assume that the learning effect functions in the same manner for all consumption concepts.

In network theory literature, a set of fad theories are discussed. Fad theories become important in innovation diffusion when the profitability of an innovation is ambiguous and when there is unclear or no information flow. Therefore, the social processes involved and information about the adopters become more important and affect the diffusion. Abrahamson and Rosenkopf (1997) distinguish between four types of fad theories. They suggest that the motivation for adoption is driven by assumptions that others have through the assumption of better knowledge of others; an evaluation bias due to a higher share of adopters; the threat of lost legitimacy through emerging social standards; and finally the competitive bandwagon pressure that arises through the pressure to maintain a competitive advantage. These types of network effects are not represented in this System Dynamics simulation model. The fad theories would all have a very similar formulation to the learning theory feedback loop, due to the high aggregation level of the model, which would result in redundancies.

The *density effect* feedback loop B1 addresses the aspect of geographical proximity as a crucial factor for microgrid deployment. If microgrids are formed through the connection of existing prosumer systems, to build a reasonable microgrid physical closeness is required. This interlinkage is also a network effect. On the one hand, the installed base is the driver for this development, but in contrast to the definition of the direct network effect, here the installed base of prosumers affects the perceived utility of microgrids – meaning that the complementary installed base is decisive for microgrid deployment. Hence, it is related to the concept of complementary goods, although it does not fit its classical definition. Prosumers that move into a microgrid become part of a larger system designed in a more complex manner with several extensions; they do more

than just increase their own utility through the addition of another product. This is a balancing feedback loop, since the installed base of prosumers leads to a decrease in prosumers, through the increased utility of microgrid systems.

Feedback loop B2, the *scarcity effect*, is a typical process emerging from a diffusion reaching its carrying capacity. The rate of growth is reduced through the limitations that appear. In this model, the physical constraint for the diffusion of distributed generation systems is the carrying capacity for PV plants, which is called *PV potential* in the model. This balancing feedback loop is not a network effect.

Indirect network effects arise through the combination of complementary goods (Gupta et al., 1999). In our model, the indirect network effects are modelled as causal effects and not as feedback loops. Feedback modelling of complementary goods would require a larger model boundary than desired for the purpose of this analysis. A network effect of the indirect type emerges in the consumption concept *autarkic prosumer*. Autarkic prosumers combine a distributed generation system with a storage system. In this particular model it is a PV plant and a battery. The utility of the autarkic prosumer concept depends on both components. Changes in the price or the technological effectiveness or their compatibility of both technologies can alter the attractiveness of this concept. An indirect network effect of a similar type arises through the combination of several technologies in the microgrid concept. Here, all PV plants, the CHP units, the wind power plants and the other supporting plants all need to be attractive for an investment. Systems with complementary goods frequently have coordination problems in marketing the products due to the two-way contingency for demand (Gupta et al., 1999). From a transition perspective, this also raises questions of timing. In this model, the indirect network effect between prosumer systems and battery systems is particularly interesting in light of the expected decrease in battery prices (Mulder et al., 2013).

3.3. Model equations

The overarching structure of the model presented in the previous section is modelled by a set of integral, differential and auxiliary equations. In this section, we present the equations used to transfer the systems structure into a model that can be simulated.

The number of households applying a distributed generation concept is captured in stock variables. A stock value is the accumulation of all flows entering and leaving the stock over time, plus the initial value of the stock. As an example, the equation for the stock *prosumers* is shown here:

$$\text{prosumers} = \int_{t_0}^t (\text{change to prosumer} - \text{install storage} - \text{change to microgrid})dt + \text{prosumers}_{t=0} \quad (1)$$

All other stock equations are formulated according to the same principle and therefore not explicitly presented here. The flow equations are defined in the following manner.

$$\begin{aligned} \text{change to concept } X &= \{[\text{households in concept } Y \\ &- (\text{total number of households having applied concept } Y \\ &\times \text{indicated share}_y)] / \text{adjustment time}_x\} \\ &* \text{indicated share concept } X \end{aligned} \quad (2)$$

Concept X stands for the destination concept where the households are heading for. Concept Y represents the concept that the household is currently applying. For instance, when changing to prosumer, the current concept is grid consumer, and the destination concept is prosumer. The adjustment time varies among the different pathways. We assume the following adjustment times: change to prosumer as 1 year, change to autarkic prosumer as 2 years, installation of storage based on an existing prosumer system as 1 year, direct installation of microgrids as 6 years, formation of a microgrid based on existing prosumer systems as 4 years and isolation of an existing microgrid as 2 years. These adjustment times are an aggregation of the time needed for making the investment decision, planning, approval and construction. The indicated shares for the concepts are derived by the following equation:

$$\text{indicated share}_x = \frac{\text{perceived utility}_x}{\sum \text{perceived utility of competing concepts}} \quad (3)$$

The perceived utility of the concept is compared against all other decision options pertaining to of competing concepts, including the concept that the household currently applies. In order to consider path-dependency in decision making it is important that only the concepts that are actually competing against each other are compared. The indicated share should not be distorted by an attractive concept that is not an option at this

decision point. For instance, the decision to become part of an autarkic microgrid is in this model not feasible when being a grid consumer. This means that the model calculates the attributes of nine decision options for the indicated share, perceived utility, NPV and all concept attributes.

Perceived utility is calculated on the basis of the ratio of the NPV of the reference concept (NPV_R) over the NPV of the concept under consideration (NPV_x). Net present value calculations are a common tool to evaluate investment opportunities, also in the energy sector (Helms et al., 2015). The reference concept is always the concept that the household currently applies. Since the NPV covers all costs for future electricity provision, the NPVs for all investment options are negative. Therefore, to achieve a positive utility, the equation is formulated as follows:

$$\begin{aligned} & \text{perceived utility of concept}_x \\ &= \frac{NPV_R}{NPV_x} \times \text{learning effect}_x \\ & \times (\text{scarcity effect} \times \text{attractiveness through density}) \end{aligned} \quad (4)$$

The NPV ratio is multiplied by the learning effect and for some concepts by the scarcity effect and the attractiveness through density effect. The learning effect represents the impact of an increasing information level with a higher number of adopters for the perceived utility. Schelly (2014) analyses the decision criteria of early adopters of PV systems, finding that the most frequently shared decision attribute among PV investors is not economic or environmental considerations, but the information level and the general interest in the technology. Furthermore, she finds that communities of information are a crucial element to motivate investments.

Bollinger and Gillingham (2012) analyse the impact of the peer effect of solar PV systems in more detail. The concept of peer effect is the same as described in network theory under the name learning theory network effect. Bollinger and Gillingham

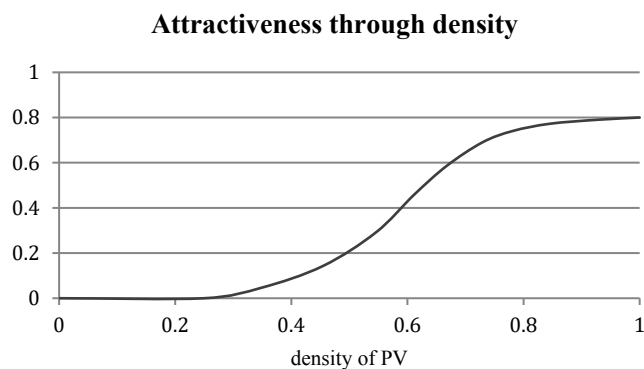


Figure 4: Look-up function used for the attractiveness of microgrids through the density of existing prosumer systems

(2012) analyse the diffusion of solar PV systems in California for different zip codes to determine the impact of the causal peer effect. They find that “an extra installation in a zip code increases the probability of an adoption in the zip code by 0.78 percentage points” (Bollinger & Gillingham, 2012, p. 95) in the average population of the zip code. We apply these results to our simulation model. Due to the model structure, the learning effect coefficient does not influence the adoption rate directly, but alters the perceived utility of the concepts. The following equation is employed for the learning effect, using 0.78 as the learning effect coefficient. This equation results in a linear increase in the learning effect with an increasing share of consumption concepts.

$$\begin{aligned} \text{learning effect}_x & \\ &= (\text{share consumers of concept } X \\ &\quad * \text{learning effect coefficient}) + 1 \end{aligned} \tag{5}$$

All concepts, except of the microgrid deployment based on existing prosumer systems, require the installation of PV plants. Therefore, the *perceived utility of concept X* is multiplied with the *scarcity effect* for PV systems. The *scarcity effect* captures the effect of reduced attractiveness through exhausted potential for PV. First, the PV installations on the house roofs of early

movers are constructed. Lastly, the roofs of laggards and less optimal house roofs are used. Correspondingly, the look-up function is designed. The function maintains a value of one for a long time; as there is no scarce potential, but with the increasing density of PV plants, and therefore declining potential the function drops to zero. This is to ensure that not more PV plants are built

than the total PV potential allows for. The scarcity effect is a function of the PV systems already installed over the regional potential for PV. This function is commonly used in System Dynamics for systems with a carrying capacity (e.g., Sterman, 2000, p. 287). The function capturing this concept is presented in Figure 5.

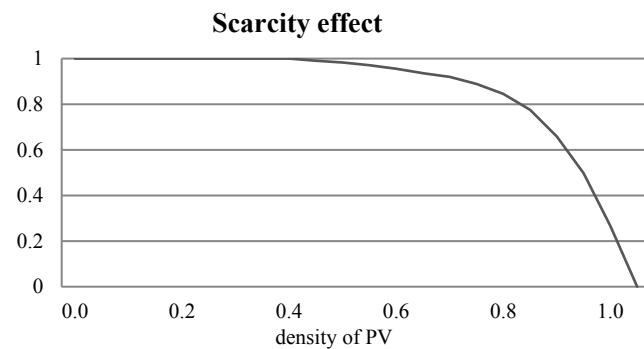


Figure 5: Look-up function used to capture the effect of increased scarcity on the utility of the distributed generation concepts emerging from limited PV potential

$$\text{scarcity effect} = f\left(\frac{\text{total PV installed}}{\text{regional potential PV}}\right). \quad (6)$$

Microgrids are frequently constructed based on existing prosumer systems (Basu et al., 2011). A higher density of prosumer systems therefore increases the attractiveness of the installation of microgrids. The perceived utility of microgrids, which are formed with existing prosumer systems, is altered by the factor *attractiveness of microgrids through density*. The look-up function capturing this effect is shown in Figure 4. The look-up function captures two main points. The first concerns the reasoning that microgrids can only be installed when there is a sufficient density of prosumer systems. It is assumed that the density of PV systems needed for the installation of a microgrid is 25%. This is captured by the point where the function increases above zero at a density of 25%. Secondly, it is assumed that a maximum of 80% of all installed prosumer systems are suitable to be connected to a microgrid, which is ensured by the function stopping at 0.8. In between, we assume a s-shaped increase in the attractiveness of microgrids through increased density.

$$\text{attractiveness through density} = f\left(\frac{\text{installed capacity PV prosumers}}{\text{regional potential PV}}\right) \quad (7)$$

The major input factor for the perceived utility calculation is the NPV. The NPV is calculated according to the standard economic equation, which looks like this:

$$NPV = -\text{Investment costs} + \sum_{t=1}^t \frac{\text{Cash Flow}_t}{(1+i)^t} \quad (8)$$

where t stands for the point of time in simulation and i for the interest rate. In our model, we calculate the NPV of all decision options for distributed generation and the grid consumer model. We use costs determinants suitable for distributed generation systems, including the investment costs, the reimbursement through subsidies, the income that arises through feeding in electricity to the main grid, fixed production costs and costs for the electricity consumption from the main grid at times when the distributed generation system does not provide sufficient electricity. The discounting of all future cash flows uses a *present value factor* combining the summing up and discounting of all future cash flows.

$$\begin{aligned}
NPV_x = & -Investment\ costs_x + Reimbursement_x \\
& + (income\ from\ electricity\ production_x - fixed\ costs_x \\
& - grid\ consumption\ costs_x) \times present\ value\ factor.
\end{aligned} \tag{9}$$

$$present\ value\ factor = \frac{(1 + i)^t - 1}{(1 + i)^t \times i} \tag{10}$$

In contrast to the *prosumer electricity unit costs* suggested by Pillai et al. (2014), a traditional NPV calculation brings the advantage that future cash flows are discounted and not all treated equally, which is important in light of the investment costs. Nevertheless, the way the cash flows are calculated for prosumer systems and microgrids orient along the *prosumer electricity unit costs* calculation by Pillai et al. (2014). *Income from electricity production* is defined by the following equation:

$$\begin{aligned}
income\ from\ electricity\ production_x \\
= total\ electricity\ production_x \times share\ excess\ energy_x \\
\times energy\ price.
\end{aligned} \tag{11}$$

Fixed costs are the sum of all costs appearing only once per year, so in this case just the operating costs.

$$fixed\ costs_x = operating\ costs_x \tag{12}$$

Grid consumption costs arise from the consumption of electricity from the main grid.

$$\begin{aligned}
grid\ consumption\ costs_x \\
= average\ total\ consumption \\
\times share\ consumption\ from\ grid_x \times local\ electricity\ price
\end{aligned} \tag{13}$$

In Table 1, the data used for the NPV calculation in the base run are presented. To facilitate the analysis of the impact of the network effect, we do not present a costs development of the technologies over time. Data points not referenced are assumptions. The investor in this case is a private household. The cost of capital for private investors is assumed to be in the low single-digit range due to their low opportunity costs for capital (Helms et al., 2015). Correspondingly, we assume the interest rate to be 2%. The time frame set for all investments equally is 20 years. A microgrid is assumed to consist of 35 households, all having the consumption of an average household of 4500 kWh per

year. For the reimbursement, we assume a one-time reimbursement for the installation of PV plants as it is currently applied, for instance, in Switzerland (Swiss Energy Regulation¹). Despite this type of policy is known for causing technological lock-in it is finds wide application (Krysiak, 2011). We assume an initial electricity price of 20 rappen per kWh, which consists of the energy price of 10 rappen² kWh and 10 rappen per kWh.

¹Swiss energy regulation, available at <https://www.admin.ch/opc/de/classified-compilation/19983391/201506010000/730.01.pdf>.

² Rappen are the cents of the Swiss franc.

		prosumer	autarkic prosumer	microgrid	autarkic microgrid
Investment	Production plants	PV plant of 10 kWp	PV plant of 13.5 kWp, Battery system of 20 kWh ¹	PV plants of 350 kWp, Wind turbines of 50 kW, CHP of 55 kW, Grid infrastructure and additional support plants ²	Up- scaling of the infrastructure of a microgrid of a factor of +30%
	Investment costs	21'000 CHF ³	28'350 CHF + 24'000 CHF ⁴	735'000 CHF(PV), 110'000 CHF (wind) ⁵ , 60'000 CHF (CHP), 42'000 CHF (grid infrastructure and additional support plants) ²	1'231'100 CHF
One-time reimbursement		8'200 CHF ⁶	10'580 CHF ⁶	287'000 CHF ⁷	358'400 CHF
Fixed costs	Annual operation costs	315 CHF ⁸	608 CHF ⁸	13'905 CHF ⁸	18'077 CHF
Grid consumption costs	share consumption from grid	68% ⁹	0%	20%	0%
Variable income	Total energy production	10'240 kWh ¹⁰	13'824 kWh ¹⁰	577'500 kWh	750'750 kWh
	Share excess electricity	85% ¹¹	0%	60%	0%

Table 1: Data assumptions used in the base run for the different consumption concept

¹ According to (Weniger et al., 2014), it is assumed that a PV system of 13.5 kWp and according to (Mulder et al., 2010), 20 kWh of battery storage is necessary for a household to be autarkic.

² Sontag and Lange (2003, p. 1877) for the necessary size and the costs for the CHP plant and support plants, exchange rate of 1.1 CHF/euro.

³ According to (IRENA, 2015, p. 89). We base our assumption on the PV system costs (total installed PV system costs in residential sector) in Germany, which is 2'100 CHF/kWp.

⁴ Costs for the battery system are calculated based on the Tesla Powerwall system. According to (Mulder et al., 2010), 20 kWh of battery storage is necessary for a household to be autarkic. Therefore, we assume that four packs of 7 kWh of a price of 3'000 CHF are needed to ensure autarky. To match up the life time of PV plants, this investment has to be made twice. <http://cleantech-nica.com/2015/05/07/tesla-powerwall-price-vs-battery-storage-competitor-prices-residential-utility-scale/> (accessed: 29.07.2015)

⁵ Blanco (2009, p. 1374), we take the highest costs of the range of costs for wind turbines, since higher costs might be faced in a residential area. Exchange rate of 1.1 CHF/euro.

⁶ Energieverordnung (Swiss Energy Regulation) available under: <https://www.admin.ch/opc/de/classified-compilation/19983391/201506010000/730.01.pdf>; one-time reimbursement per plant = 1'400 CHF + 680 x 1kWp.

⁷ In the microgrid, it is still assumed that every household does install the PV plant itself and therefore the one-time reimbursements are received correspondingly.

⁸ The operation costs of a microgrid are assumed to 1.5% of the investment costs (Weniger et al., 2014).

⁹ According to (Weniger et al., 2014), based on 2.2 kWp/MWh.

¹⁰ According to (Weniger et al., 2014), the annual energy output is 1'024 kWh/kWp.

¹¹ According to (Weniger et al., 2014), based on 2.2 kWp/MWh.

The local electricity price consists of three parts: the costs for the actual energy consumption, here called energy price, the grid charge and the taxes.

$$\text{local electricity price} = \text{energy price} + \text{grid charge} + \text{taxes} \quad (14)$$

The operator of the distribution grid is usually the local utility company. The arising costs for the grid maintenance are assumed to be exogenous. In the current electricity market, the grid operator covers the costs with the grid charge paid by every consumer for the transmission of every consumed unit of electricity. It is assumed that the grid charge can be adjusted once per year, as it is in the case of Switzerland (Swiss Electricity Supply Act, Art 6. Paragraph 3). This is modelled as an adjustment process of the length of one year between the desired and the actual grid charge. The desired grid charge is calculated according to the formula elaborated by Scheidegger and Gallati (2013).

$$\begin{aligned} & \text{(desired) grid charge} \\ &= \frac{\text{expenses grid} \times \text{share to be covered by grid charge}}{\text{annual total demand from grid}} \end{aligned} \quad (15)$$

The *annual total demand from grid* is the sum of all electricity consumed from the main grid over the year of all households in the different consumption concepts. Autarkic concepts are noted with a *share consumption from grid* of zero, since they do not consume electricity from the main grid.

$$\begin{aligned} & \text{annual total demand from grid} \\ &= \sum_{x=1}^5 (\text{households}_x \times \text{share consumption from grid}_x \\ & \quad \times \text{avg. total consumption}) \end{aligned} \quad (16)$$

The discussed variables with their basic behaviors are shown in the overview graph of the model in Figure 3.

3.4. Model validation and limitations

The presented model was subject to multiple validation tests. We conducted the structure and structure-behaviour tests recommended by Barlas (1996), which are most common in the field of System Dynamics. Formal statistical validation tests were not

conducted. Since the model addresses phenomena in a generic manner that, in addition, will emerge in future, it is not possible to have an actual reference mode to conduct the statistical validation tests. A few pilot projects exist but they are not sufficient in number to build a reliable reference mode. Simulation results of this model should be considered as likely patterns of the transition rather than exact numerical forecasts. In this light, the model should be seen more as a testing environment for “what... if...?” experiments. This model is designed to provide a conceptual framework in the form of a simulation model that brings together distinct pieces of knowledge on the transition of regional energy systems. It allows testing generic structure-behaviour hypotheses of the assumed network effects. Although plausible and empirically grounded initial values are necessary to realistically test these assumptions in the context of decentralisation dynamics, the model does not aim to be calibrated to detailed specific phenomena that happened in the past. However, the model capturing the local decentralisation dynamics can and should be empirically tested, once more real word data on the diffusion of consumer concepts exists.

The model has a couple of limitations. Results of sensitivity tests show that the model reacts very sensitively to changes in the adjustment times used in the flow equations and to the percentages of how much electricity is fed into the grid or consumed from the grid in the different distributed generation concepts. While some of these parameters are well grounded, others are best guesses, since no better data is available. Similar to this issue is the technology constellation of the microgrid used. Microgrids can look very different from one project to another in terms of technology constellation but also in their business models used. The model does not give credit to these aspects and therefore remains very generic.

4. Results

In the following section, we present the simulation results derived from the developed System Dynamics model. As previously mentioned, the analysis focuses on the generic patterns arising in the transition of regional energy systems. Forecasting exact numerous outcomes is not the goal or purpose of this model and study. We start by

presenting the simulation results under the base conditions and then proceed with the analysis of the impact of the discussed network effects.

The simulation analysis is conducted for a hypothetical region. The region consists of 50'000 households. Initially, all households are assumed to consume their electricity from the main grid and are therefore *grid consumers*. The assumptions for the costs of the different consumption concepts are presented in Table 1. The potential for PV plants in the studied region is set to 150 MW. The simulation period starts in year 0 and ends in 10. This time frame is chosen to provide clear visibility of the long-term impacts of the dynamics in the systems.

4.1. Simulation runs

In Figure 6, the simulation results for the different consumption concepts are presented.

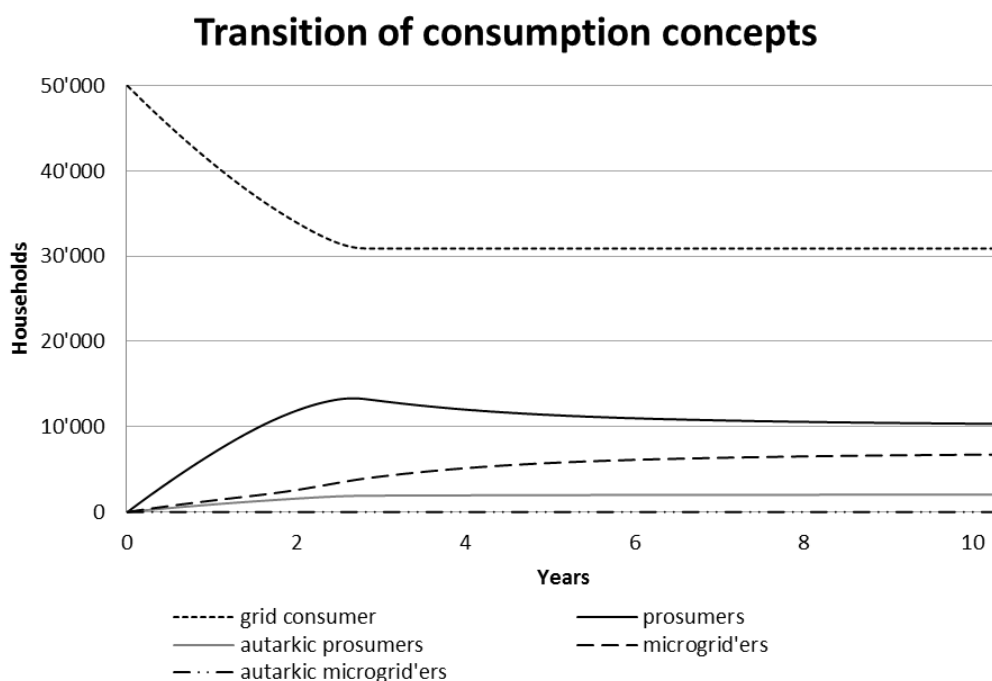


Figure 6: Base run – households in consumption concepts

In the first phase, we observe a strong increase in the number of households choosing the prosumer concept. This boom is supported by the feedback loop R1 *death spiral*. The increasing number of prosumers causes the grid charge to increase and makes prosumer systems even more attractive. This development reaches its peak in the year 3. Already at the beginning of the simulation period, there is a slow increase in

households applying a microgrid concept. The slope of the microgrid growth rate increases when the stock of prosumers reaches its peak. Interestingly, the transition towards microgrids is spread over the two deployment pathways – initially the direct deployment of microgrids dominates (*change direct microgrid*), while afterwards the step-wise deployment of microgrids based on existing prosumer systems becomes more attractive and more frequently applied (*change to microgrid*). This is highlighted in Figure 7. Reasons for this phenomenon are four-fold. First, the step-wise deployment of microgrids requires a density of prosumer systems, which is only realised with the PV boom. Second, through the early direct deployment of microgrids, awareness for this concept was raised and caused to increase the learning effect to increase for microgrids for both deployment pathways. Third, the general boom of distributed generation concepts caused the grid charge to increase, making those concepts even more attractive. Lastly, the combination of the early installation of direct microgrids and the strong increase in prosumer concepts cause a significant reduction in the remaining potential for PV plants, activating the *scarcity effect* feedback loop, which slows down the growth of prosumer systems as well as the direct installation of microgrid systems. However, the extension of prosumer systems to a microgrid due to the prior installation of the PV plant is not affected. Both flows for the different installation pathways diminish towards the end of the period due to high costs and the lack of remaining potential for PV, high costs and lacking reserves for the prosumer systems, which dropped in the course of the numerous step-wise microgrid installations. It is important to understand that these dynamic patterns do not emerge from changing technology prices. These dynamics are all driven by the structure of the system – the network effects gaining in weight and influencing the investment decisions by the consumers.

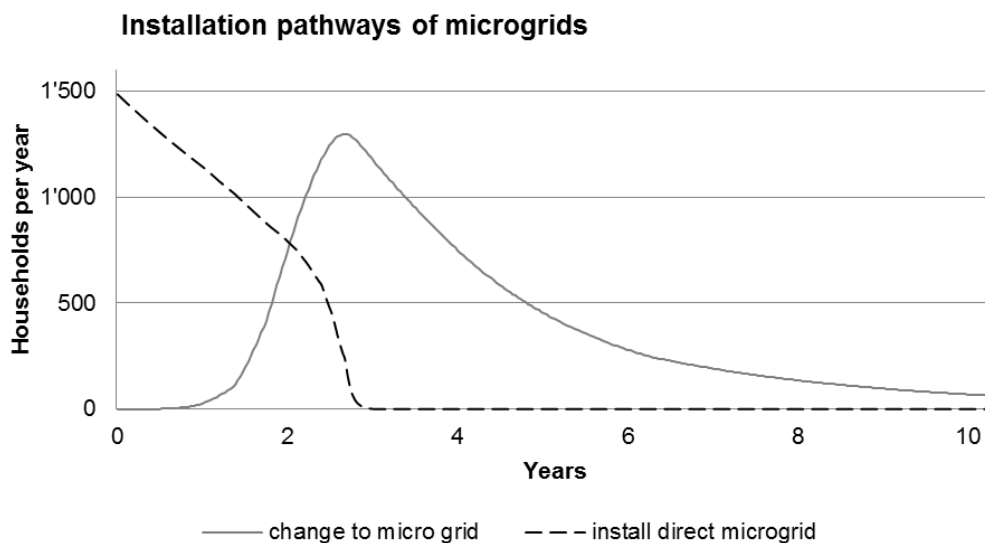


Figure 7: The figure demonstrates the shift between installation pathways of microgrids over time

The autarkic concepts – autarkic prosumers and autarkic microgrids – are low in their perceived utility. The concept of autarkic prosumer finds some applicants, while the autarkic microgrid seems totally unattractive. The transition towards the autarkic prosumer system shows a similar pattern as observed in the transition to microgrids.

4.2. Analysis of the impact of network effects

We analyse the impact of the discussed network effects on the diffusion of the distinct decentral generation concepts. The direct network effects –adjustments of grid charge, the learning theory and the density effect – are modelled as feedback loops. Storage costs and microgrid plant costs are indirect network effects and are captured in the model as simple causalities. We conduct two types of analyses. Firstly, for the analysis of the direct network effects, we deactivate the feedback loops, assuming their influence as constant and not as endogenous. Secondly, for the indirect network effects, costs of storage and microgrid plants, we conduct simulation runs under different cost assumptions. The simulation results are compared with the simulation results from the base run. For the analysis of the impact of the network effects, the model is simulated until the transition has reached its steady-state. These values are used for the analysis presented in Table 2.

Analysing Table 2, we notice the strong impact of network effects on the overall system. All network effects lead to significant changes in the distribution of the households on the various consumption concepts. Interestingly, despite relevant shifts among the other consumption concepts, the number of households applying the grid consumption concepts remains stable within all scenarios. Furthermore, no changes are apparent regarding the concept of autarkic microgrids, as a consequence of insufficient attractiveness.

The network effect *death spiral* works in favour of consumption concepts that consume no or only little electricity from the main grid. When switching this network effect off by putting the grid charge to constant, the number of households with a prosumer system increases, and fewer households in autarkic prosumer systems and microgrids. These results contradict a common perception in energy research that the so-called death spiral frequently leads to an increasing number of prosumers through the adaptation of the grid charge, as these studies do not consider microgrids (see for example Costello & Hemphill, 2014). Here, we in fact experience the opposite. Not adjusting the grid charge leads to more households applying the prosumer system. This leads to a qualitatively different outcome than in the base run, where adjusting grid charge raises the attractiveness of microgrids and therefore reduces the number of prosumers. The deployment of microgrids is very decisive in the energy transition but has been very rarely discussed in the literature so far and should receive more attention in future.

		Grid consumers	prosumers	autarkic prosumers	microgrids	autarkic microgrids	Settling time
Base run		30'900	10'120	2'040	6'940	0	31
Grid charge off (constant at 0.1 CHF/kWh)	absolute difference to base run	30'890	10'940	1'916	6'255	0	30
	% change to base run	-10	820	-124	-685	0	
		0%	+8%	-6%	-10%	0%	
Perfect knowledge (learning effect off)	absolute difference to base run	30'880	9'973	2'121	7'030	0	22
	% change to base run	-20	-147	81	90	0	
		0%	-1%	+4%	1%	0%	
density effect off (constant at 0)	absolute difference to base run	30870	14470	1919	2748	0	32
	% change to base run	-30	4350	-121	-4192	0	
		0%	+43%	-6%	-60%	0%	
direct deployment pathways off (autarkic prosumers and microgrids)	absolute difference to base run	31'000	11'410	482	7'105	0	23
	% change to base run	100	1'290	-1'558	165	0	
		0%	+14%	-54%	+2%	0%	
battery costs +20%	absolute difference to base run	30'850	10'170	1'897	7'093	0	25
	% change to base run	-50	50	-143	153	0	
		0%	0%	-7%	2%	0%	
battery costs -20%	absolute difference to base run	30'960	10'050	2'230	6'785	0	33
	% change to base run	60	-70	190	-155	0	
		0%	-1%	9%	-2%	0%	
microgrid costs +20%	absolute difference to base run	30'910	11'280	2'087	5'725	0	40
	% change to base run	10	1'160	47	-1'215	0	
		0%	11%	2%	-18%	0%	

Table 2: Analysis of the network effects at hand of the absolute number of households in the consumption concepts in year 2040 and the percentage changes compared to the base run

The *learning theory* network effect affects all consumption concepts. Assuming the perfect knowledge with a learning coefficient of zero, we observe fewer households in the prosumer system, which are compensated by the higher number of households in the microgrid concept and in the autarkic prosumer concept. This shows the initially hindering effect in the transition of lacking experience in transitions and the importance of early movers and their role in communicating their experiences. The learning process is crucial in the path creation of a transition. Initial impulses are also seen as necessary in the energy system to overcome the lock-in of the centralised system (Wüstenhagen & Menichetti, 2012).

The *density effect* only directly influences the utility of the microgrid concept. Due to the competition between the consumption concepts, there are also effects on the relative attractiveness of prosumer and autarkic prosumer. Setting off the density effect by putting it to zero, which in fact impedes the pathway for step-wise installation of microgrids, there is a significantly lower number of households applying the microgrid concepts.

Rather counter-intuitive is the effect of the *direct deployment pathways* of autarkic prosumer systems and microgrids. When deleting the direct deployment pathways for autarkic prosumer systems and microgrids, we notice that there are clearly more prosumers, which is to the disadvantage of the autarkic prosumers. Interestingly, there are also more microgridders, even though one installation pathway is cut. The larger number of microgridders emerges due to the increased density of prosumer systems, which raises the attractiveness of microgrid installations based on existing prosumer systems.

The impacts of the *indirect network effects* are rather obvious. Decreases in *battery costs* increase the attractiveness of the autarkic prosumer system and vice versa. Surprisingly, changes in the *costs for plants used for microgrids* have a rather low impact on the system. It is assumed that this is due to the already high attractiveness of microgrid systems. The highest percentage change emerges for the prosumer systems, since they are the intermediates for microgrids and have a low installed base that makes the percentage change as strong.

Network effects of course do not only affect the distribution at the end of the simulation. They also cause changes in the behavioural pattern of the system. In Figure 8, we analyse the variations in the pattern at hand of the number of households in the prosumer consumption system. The stock of prosumers is at a very central and intermediating position in the simulation model. It is therefore particularly interesting to see the changes over time caused by the network effects.

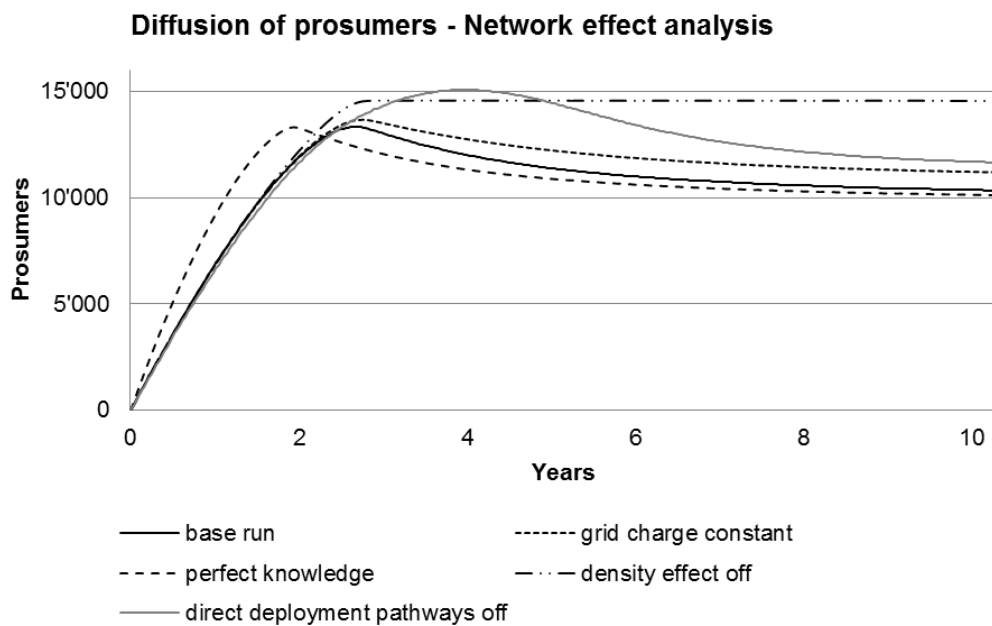


Figure 8: Simulation results for selected scenarios of the stock of prosumers over time

Comparing the base run with the simulation results for the runs where the reinforcing direct network effects are each switched off, assuming they are constant, shows changes in the behaviour patterns. In the simulation run with the network effect *death spiral* switched off, we notice that the increase in prosumers reaches higher levels and declines less. A constant *learning effect* leads to earlier installation of prosumer systems but also enables an earlier and faster decline. This shows that the necessity of learning causes a delay in the adaptation of innovations. The simulation run with the *density effect* switched off results in a higher peak for prosumers and remains at a nearly constant level. Switching off the two direct installation pathways leads to a stronger boom in prosumer systems that also lasts longer than all the other scenarios (except the *density effect* scenario). The indirect network effects with the complementary good storage and CHP plants have a rather low impact and do not bring strong changes to the behaviour

pattern, besides a slightly reduced amount of prosumers due to the higher attractiveness of the other concepts. Therefore, they are not represented in the graph.

We have seen, therefore, that network effects have significant effects on the behavioural patterns of the system. The network effects not only influence the deployment patterns, but the timing of network effects also affect their strength as well as the deployment pattern of the distributed generation consumption concepts.

5. Conclusion

Distributed energy generation systems are becoming increasingly attractive and are being adopted more frequently. These decentralisation dynamics will cause a major transition in regional energy systems. Although increasing shares of prosumer systems and microgrids are having significant impacts on the businesses and strategies of major actors in regional energy systems, decentralisation dynamics and network effects in the transition have not gained much research attention so far.

A System Dynamics simulation model was built to address the question of the likely transition patterns of consumption concepts related to distributed generation. Major drivers for this transition are the network effects between the installed base of the consumption concepts and the development of complementary technologies that influence the utility of the distributed generation concepts as perceived by consumers. We model the direct network effects: the death spiral and learning theory. Indirect network effects between complementary concepts and technologies are addressed between PV systems, storage technologies, support plants for microgrids and the network effect between the installed base of prosumers and the deployment of microgrids.

Simulation results and the analysis of the impact of network effects reveal their high impact on the decentralisation dynamics of a regional energy system in general and on the different consumption concepts related to distributed generation in particular. The System Dynamics simulation model brings multiple insights for energy transition in Europe. First of all, through the generic structure of the model, an improved understanding of likely transition patterns of regional energy systems is gained. Although case-specific conditions may vary, the barriers and drivers, as well as the complex interactions in the

system, remain the same for every regional energy system. Second, we found differences in simulated transition patterns (as demonstrated in Figure 7, Figure 8 and Table 2) that can only be explained by network effects. To our knowledge, this is an aspect that has not been discussed explicitly in energy research to date. Third, pilot projects do have a crucial role in the transition of energy systems as they generate learning effects that accelerate the diffusion and enhance a path creation. Furthermore, the finding of the second phase of the transition with the installation of microgrids brings new insights to likely transitions of regional energy systems. It adds to the discussion on the death spiral, which will be highly relevant for future designs of the grid charge. Overall, this simulation study highlights the necessity of including knowledge from the social sciences in energy transition research.

Our paper makes the following contributions for the practice. The application of the network effect concept on energy systems research in combination with dynamic simulation is novel. By shedding light on the decentralisation dynamics in regional energy systems, new perspectives and options for strategy development in the management of regional energy systems in practice are highlighted. For utilities, understanding the likely patterns of decentralisation dynamics in the supply region is essential for planning of grid and capacity expansion as well as alternative designs for the grid charge. Knowledge on the potential role of future microgrids and the importance of pilot projects for microgrids and on the network effects is crucial for politician. It facilitates strategic energy planning in their municipality and supports selecting the right stakeholders. For technology developers, these results can support timing and choices about which concept to focus on and where attractive business models might emerge.

Further research should be devoted to developing a more detailed simulation framework for the microgrid concept, as the role of microgrids appears to be crucial in the decentralisation dynamics of energy systems. Here, our model remains overly aggregated and simplifying. Important to look at will be the technological constellations of microgrids but also the underlying business models in the deployment and operation of microgrids. Generally, looking deeper into the business models used in distributed generation concept will provide deeper insights in the underlying mechanics of the transition. This will also help to better specify the adjustment times for adaptation.

We hope the results obtained will be useful for both – practitioners in regional energy systems, such as politicians, energy planners, strategy developers in utility companies or technology developers, as well as for research in the field of energy transitions. With our finding on the relevance of network effects in decentralisation dynamics of energy systems and the crucial role of microgrids we hope to contribute to the on-going discussion on energy systems transitions in general and the death spiral in particular.

Acknowledgement

This research was conducted as part of the national research programme of the Swiss Competence Center for Energy Research – Center for Research on Economy, Society and Transition (SCCER CREST, grant number: KTI.2014.0114). We gratefully acknowledge the financing by the Swiss Commission of Technology and Innovation as well as by the Zurich University of Applied Sciences. We thank two anonymous reviewers of the Energy Research & Social Science journal for their valuable feedback that helped us to improve the clarity and quality of this paper. Our thanks also go to Michael Wurzinger and Dr. Juliana Zapata for their thorough revisions.

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Paper II

Squaring the sunny circle? On balancing distributive justice of power grid costs and incentives for solar prosumers

Merla Kubli

Abstract

Solar prosumers are about to revolutionize the power sector. Utilities are challenged in recovering the costs of distribution grids, as parts of their revenue basis decreases through self-consumption. Adjusting the grid tariff sets off a reinforcing feedback loop that increases the attractiveness of solar investments, but also leads to a distribution effect between solar prosumers and conventional consumers. The question is: How to recover distribution grid costs equitable without hampering the diffusion of solar power? Can the two criteria be fulfilled at the same time, or is do we aim for squaring a circle? To address this question, I present a System Dynamics simulation model designed to understand the interactions and assess these competing goals. The occurring distribution effect under the volumetric grid tariff with net purchase and sale appears to be rather limited. Simulation experiments reveal that grid tariff designs strongly influence investments for solar power. A capacity tariff can reduce deviations from the cost causation principle of solar prosumers and incentivizes investments in decentralized storage solutions to reduce peak demand. Nevertheless, also the capacity tariff causes a distribution effect.

Keywords: self-consumption, death spiral, grid tariff design, net purchase and sale, net metering, grid cost recovery

1. Introduction

Renewable energies are about to dramatically change the power sector. Impressive technology learning curves and governmental support programs enhance the increasing penetration of renewable energies. Particularly solar photovoltaics (PV) is developing remarkably (IEA, 2014; IRENA, 2015). PV is highly suitable for decentral generation in small units close to demand and is about to reach grid parity in many countries (IEA, 2014; Karneyeva & Wüstenhagen, 2017; Schleicher-Tappeser, 2012). Grid parity describes the point where decentrally generated solar power reaches the same level as the retail power price. Consequently, installing solar power with self-consumption becomes an attractive investment option for house owners. And so become consumers so-called prosumers – consumers who consume and produce power (Kesting & Bliet, 2013).

Current power systems are designed for centralized generation to supply fully dependent consumers. Costs of the distribution grid infrastructure are most frequently recovered from consumers based on a volumetric grid tariff, which charges the consumers per kWh of used power. A volumetric tariff is a straightforward design to recover the costs of the grid infrastructure, particularly with an increasing demand basis (Costello & Hemphill, 2014; Felder & Athawale, 2014). However, nowadays net demand became less predictable and shows a tendency to decrease through the diffusion of self-consumption concepts and increased investments into energy efficiency (Ruester et al., 2014).

Under a volumetric tariff, solar prosumers can reduce their power bill by avoiding the full retail price for the amount of self-consumed power. The PV bill savings of solar prosumers appear as missing return on the utility company's income statement. To compensate for the missing return, the utility company increases the grid tariff. In return, higher retail power prices increase the attractiveness of self-consumption concepts. This sets off a self-reinforcing feedback loop. Most researchers expect the cost recovery feedback loop – sometimes also called the “death spiral” – to cause the retail power price to rise (Castaneda et al., 2017; Costello & Hemphill, 2014; Darghouth et al., 2016b; Felder & Athawale, 2014).

On the one hand, grid operators perceive this situation as explicitly negative, as recovering the costs of distribution grid becomes increasingly difficult. Increasing the grid tariff usually comes with large administrative hurdles, since grid operators are strongly regulated monopolies. On the other hand, the opportunity of bill savings for solar prosumers fosters the diffusion of PV, hence contributing to national energy and climate policy goals. A distribution effect between conventional consumers and solar prosumers is a potential consequence of adjusting the grid tariff (Eid et al., 2014; Picciariello et al., 2015; Ruester et al., 2014; Satchwell et al., 2015). As the grid assets are highly determined by fixed costs, the current volumetric tariff does not reflect the full costs of supplying prosumers. The issue of cost recovery of distribution grids with solar prosumers is subject to a controversial political debate¹. A capacity tariff is frequently discussed as a potential solution (Costello & Hemphill, 2014; Eid et al., 2014).

In this study, I simulate and quantify two important interdependent aspects: (a) the long-term dynamics between the diffusion of solar prosumer, with and without storage, and the ability of grid operators to recover the costs of distribution grids; (b) the resulting distribution effect and deviations from the cost causation principle for the distinct consumer groups over time. The paper presents a comparative analysis of a volumetric tariff – comparing a net purchase and sale policy with net metering, a capacity tariff and a flat tariff, contributing to the current academic as well as political debate. The analysis is conducted for the situation of a Swiss distribution grid operator.

This paper is structured as follows: in section two, relevant the background literature on PV bill savings, grid tariff designs, PV pricing mechanisms and distributive justice are discussed; in section three, I present the developed simulation model in a conceptual manner, followed by the equations and the developed measures for distributive justice; in the four section, the simulation results are presented and discussed; in the fifth section, I draw the conclusion and discuss the implications for energy policy and the limitations of the study.

¹ For instance in Switzerland addressing the grid tariff design is an important topic in the coming revision of the Swiss electricity law (Swiss Federal Office of Energy, 2015).

2. Background

2.1. PV bill savings under different grid tariff designs and PV pricing mechanisms

Various regulations for self-consumption of distributed generation exist around the globe. The scope of PV bill savings of solar prosumers particularly depends on the applied grid tariff design and PV pricing mechanisms (Borenstein, 2017; Darghouth et al., 2011, 2014; Darghouth et al., 2016a; Eid et al., 2014). Yamamoto (2012) describes three pricing mechanisms for residential PV, two of which are of relevance for self-consumption concepts: *net metering* and *net purchase and sale*. An overview of grid tariffs and pricing design options and the resulting PV bill savings is given in Table 1.

Most literature addresses the net metering system, typically focusing on the impact of different billing periods on the bill savings of solar prosumers (e.g. Darghouth et al., 2011, 2014; Darghouth et al., 2016a; Eid et al., 2014). A notable exception is the study by Eid et al. (2014), which also considers the net purchase and sale system. This is surprising, as many countries apply the net purchase and sale system because of the unbundling regulation for utility companies, separating the grid operation from power generation. Furthermore, only few studies analyze the effect of solar prosumers with storage in a quantitative manner in the context of grid operators allocating the distribution grid costs (Eid et al., 2014; Grace, 2014). However, self-consumption concepts combined with storage can reach much higher self-sufficiency degrees, but also have the potential to be used in a grid-optimized manner (Santos et al., 2014; Veldman et al., 2013).


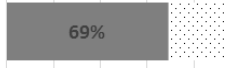
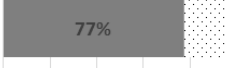
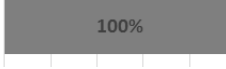
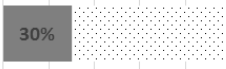

Grid tariff design	PV pricing design options	PV bill savings	Application cases
Volumetric tariff	<i>No self-consumption</i> describes a situation where self-consumption is prohibited by regulatory laws. The situation can also emerge from high feed-in tariffs for renewable energies (subsidies) which are higher than the retail power price or generation costs larger than the retail power price.		Switzerland before 2014
	<i>Net metering</i> allows prosumers to cover demand with the self-generated power for the billing period. The billing period, also called the rolling credit timeframe, can be an hour, a day, a month or even a year (Eid et al., 2014; Ruester et al., 2014). Net metering systems with longer billing period allow for the accounting of larger bill savings, although no direct self-consumption is conducted (Darghouth et al., 2011, 2014; Darghouth et al., 2016ab; Eid et al., 2014).	<i>Daily net metering</i> 	Denmark
		<i>Monthly net metering</i> 	Alaska, Georgia, Oklahoma
		<i>Yearly net metering</i> 	California, The Netherlands, Australia
	The <i>net purchase and sale</i> considers the net power purchased by the consumer from the grid and the net sales of surplus power. Therefore, it only considers time simultaneous self-consumption. A private PV owner can reach a self-sufficiency degree of about 30 percent with direct self-consumption (Weniger et al., 2014). The prosumer saves 30% on her power bill and creates an additional income by selling the surplus power. Surplus generation is sold to the utility for a defined feed-in tariff and can improve the profitability of the PV investment, but is accounted separately.		Switzerland, Italy, Japan
Capacity tariff	A capacity tariff charges consumers based on the maximum peak demand in a specific timeframe. The timeframe for the billing period of a capacity tariff can vary. The PV bill-savings depend on whether the self-consumption system can reduce the maximum peak demand.		Pilot projects in the Netherlands

Table 1: Different grid tariff designs with variants in net metering types and resulting PV bill-savings for solar prosumers (without storage) (data for PV bill-savings is adopted from Eid et al. (2014) and Weniger et al. (2014), application cases from (Commission, 2015; Darghouth et al., 2011; Eid et al., 2014; EURELECTRIC, 2013)).

Several qualitative studies identify the cost recovery of utility infrastructure under increasing self-consumption as a problematic situation that demands for an adjustment in the regulation (Costello & Hemphill, 2014; Felder & Athawale, 2014; Ruester et al., 2014; Schleicher-Tappeser, 2012). The self-reinforcing aspect and developments over time of the cost recovery are only rarely analyzed in a quantitative manner. Notable exceptions are Cai et al. (2013), Darghouth et al. (2016b) and Castaneda et al. (2017). Cai et al. (2013) find that the strength of the cost recovery feedback loop strongly depends on the share of house owners with a higher tolerance for uncertainty. Potential for further research is located in the more realistic representation of the investment decision for PV (Cai et al., 2013). Castaneda et al. (2017) investigate the conditions that lead to a utility death spiral with a System Dynamics simulation model. They find that under the particular setting of the Colombian power market with unlimited net metering and the assumption that prosumers install clearly more distributed generation than what they consume, a utility death spiral is likely to occur. Darghouth et al. (2016b) find that there is a compensating effect through lowering wholesale power prices caused by larger feed-ins of solar power. The merit order effect from solar power can nearly off-set the increase of the tariff for the end-consumers. In contrast to this, Nelson et al. (2012, p. 298) find that customer benefits from the merit order effect from solar PV are “at best transient, and the overall effect on welfare is adverse”. In this respect, it is decisive whether utility companies really pass on the wholesale price advantage to end-consumers, which depends on the applied utility regulation. In a regime with an integrated service regulation for utilities, as applied in the United States and the study by Darghouth et al. (2016b), reduced wholesale power prices can trigger the described compensating effect. In a regime with unbundling of power generation from the grid operation, as applied in Europe (Eid et al., 2014), the two effects play out in separate business units and therefore can only be considered as indirectly compensating. Most of the literature on the cost recovery of distribution grids assumes an integrated utility service system. In this study, I focus on the situation of a grid operator under the unbundling regulation with a net purchase and sales system for PV remuneration. To address the differences, I simulate the net metering system in a scenario as a comparison. Variants in grid tariff design are tested.

2.2. Distributive justice of power grid costs

Regulatory authorities aim for distributive justice among the power consumers, when defining regulations for cost recovery of power distribution grids. However, what is perceived as fair, is subject to personal views and preferences, as nicely explained by Tabi and Wüstenhagen (2017). When it comes to recovering costs from distribution grids, there seems to be a consensus that an equity principle should be applied. The cost causation principle is one of the most frequently named equity principles for ideal tariff design for power distribution grids¹, intending that consumers pay for the costs they cause (DNV GL, 2015; Picciariello et al., 2015). Furthermore, the efficiency principle is considered to incentivize efficient use of power, as well as efficient operation and investments for powers grids (DNV GL, 2015; Green, 1997).

Nelson et al. (2011) analyze the taxation burden of a gross feed-in tariff as well as a net feed-in tariff for solar PV for different consumer segments. They measure the distribution effect as the impact of the feed-in tariffs on the annual bills, as well as a share on the household income. Eid et al. (2014), in contrast, measure the occurring distribution effect² caused by self-consumption as the share of lost income of utilities, considering different net metering designs. Satchwell et al. (2015) and Castaneda et al. (2017) choose a similar approach by calculating the impacts on retail power rates of solar PV under net metering with different utility regulations and settings. Satchwell et al. (2015) assume the deployment rate of solar PV as an exogenous input factor, while Castaneda et al. (2017) simulate the PV diffusion based on a bass diffusion model. A consumer oriented measurement of the distribution effect between conventional consumers and prosumers is applied in Picciariello et al. (2015), focusing on achieving cost-causality of consumers under different PV deployment scenarios.

No comprehensive study was found that covers the full dynamics of the cost recovery feedback loop, considering the diffusion of solar prosumer including storage and prosumer communities, which evaluates the distribution effect and deviation from the cost causation principle for distinct consumer groups.

¹ See for example Swiss Electricity Law (Schweizer Stromversorgungsgesetz), Art. 14, paragraph 3.

² In the study by Eid et al. (2014) the distribution effect is called “potential for cross-subsidy”.

3. Method and model

To simulate the interplay between the diffusion of self-consumption concepts and the grid tariff level I chose a System Dynamics simulation approach (Forrester, 1961; Sterman, 2000). System Dynamics is particularly suitable to endogenously simulate feedback processes and dynamics over time. The simulation model is designed, calibrated and simulated for the particular circumstances of a Swiss grid operator. Switzerland applies an unbundling regulation for utilities, separating the grid operation from the power generation business. For PV plants with an installed capacity smaller than 30 kWp a net purchase and sale policy is in place. The policy is complemented by an investment grant, covering 30% of PV investment costs. The conceptual model framework of Kubli and Ulli-Ber (2016) was used as a basis, but was refined to a more realistic representation of the system. I present the extended model along its dynamic structure, the equations, data and the validation with four additional cases.

3.1. Causal structure of the simulation model

The model captures, besides the conventional consumption concepts of grid consumers, four self-consumption concepts: solar prosumers, solar prosumers with storage, solar prosumer communities and solar prosumer communities with storage. Consumers are categorized in three consumers groups – single-family houses, multi-family houses and commercial customers – due to essential differences in the investment decision and significantly different self-sufficiency levels (Weniger et al., 2014). The consumer groups are to be understood as a consumer unit sharing the same grid connection (the inhabitants of one house). The respective owners are in charge of taking the investment decisions. I assume that prosumer communities are only realized within a multi-family house, as it is currently legally allowed in Switzerland. Consumers can adopt to self-consumption concepts through different decision pathways (see box (a) in Figure 1). A grid consumer can decide to invest in a prosumer concept or a storage prosumer concept, or just remain a conventional grid consumer. Prosumers can enhance their system by installing a storage technology, such as a battery, to become a prosumer with storage. The characteristics of the self-consumption concepts for the three consumer groups are presented in Table 2.

	Installed capacity	Share consumption from grid ¹	Net demand in kWh/a ²	Share excess energy ¹	Peak Demand in kW ³	Optimized peak demand ⁴
Grid consumer [SFH]		100%	4'520		6 kW	5.5 kW
Grid consumer [MFH]		100%	24'408		25 kW	23 kW
Grid consumer [CC]		100%	90'000		100 kW	90 kW
Prosumer [SFH]	10 kW PV	65%	2'938	80%	6 kW	5 kW
Prosumer [MFH]	20 kW PV	70%	17'086	65%	25 kW	21 kW
Prosumer [CC]	30 kW PV	70%	63'000	10%	90 kW	72 kW
Storage prosumer [SFH]	10 kW PV 9 kWh battery	25%	1'130	60%	4.2 kW	3 kW
Storage prosumer [MFH]	20 kW PV 35 kWh battery	38%	9'275	75%	17.5 kW	12.5 kW
Storage prosumer [CC]	30 kW PV 35 kWh battery	65%	58'500	0%	70 kW	50 kW

Table 2: Characteristics of the consumption concepts (SFH: single-family house, MFH: multi-family houses, CC: commercial customers

¹ Share consumption from grid and the share excess energy is based on Weniger et al. (2014) – for exact values for one family houses, for multi-family houses and commercial customers the source was used as a guidance. The term “share consumption from grid” is the residual of the self-sufficiency degree (which is sometimes used within this text).

² The annual consumption is based on the information from BKW Energie AG for their supply area. The consumption of a commercial customer is an assumption.

³ Values for peak demand are well-informed assumptions. I assume that the peak demand for a one family house and multi-family house remains the same with the PV plant. For commercial customers it is assumed that the peak demand can be reduced as generation times coincidence with PV generation. According to Santos et al. (2014), a battery used for self-consumption optimization can help to reduce the peak demand to 70% of the original peak demand.

⁴ Based on Veldman et al. (2013), the peak of normal residential electricity use can be reduced by 8% applying load control. For prosumer, I assume the peak demand can be reduced through demand shifting by additional 10% compared to a grid consumer. Based on Santos et al. (2014), a battery applied with a focus on peak demand reduction can help to reduce the peak demand to 50% of the initial demand.

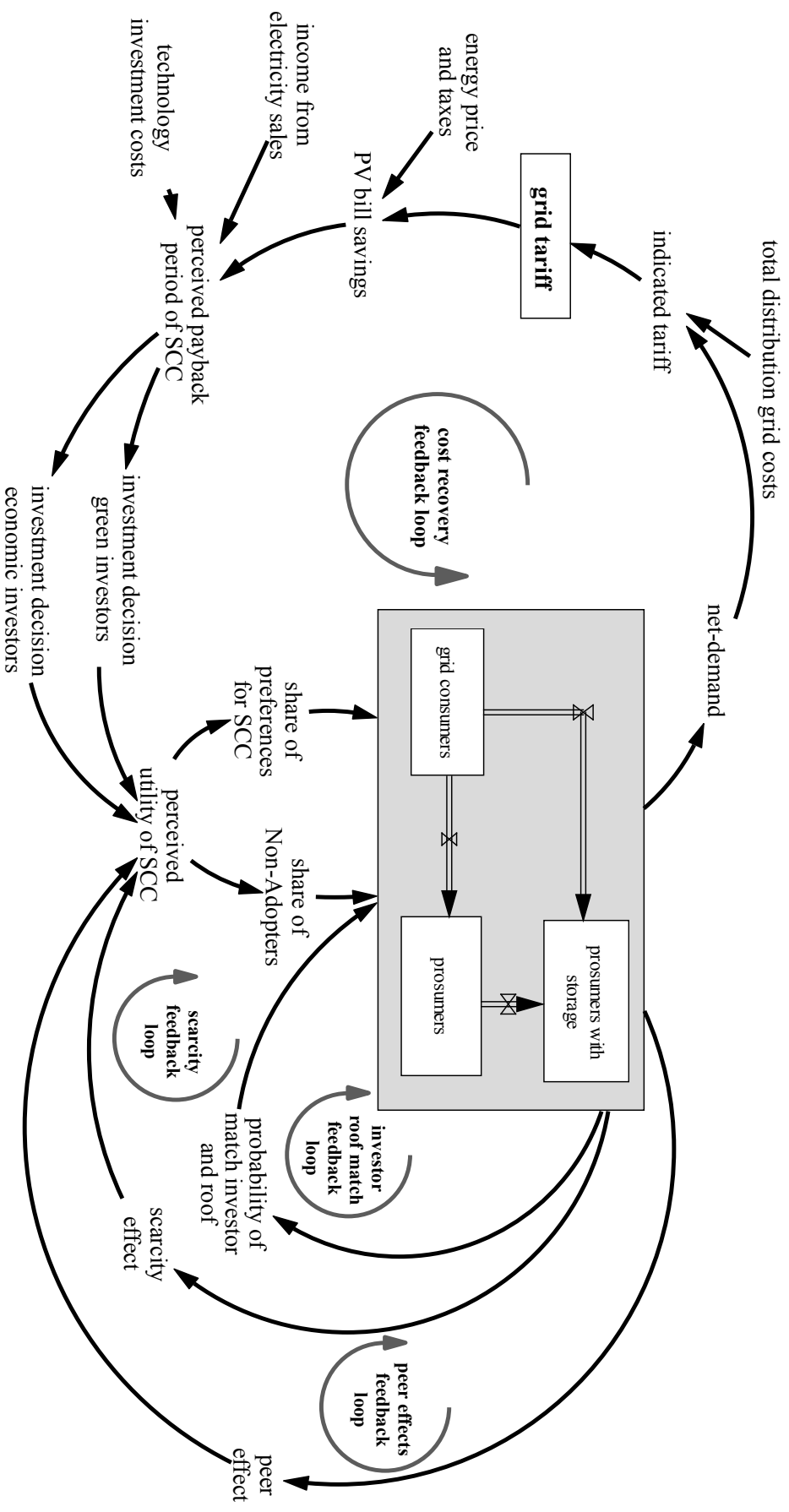


Figure 1: Feedback structure of the simulation model, capturing the cost recovery feedback loop (self-consumption concepts are abbreviated as SCC). The cost recovery feedback loop and the peer effects feedback loop are reinforcing, while the scarcity feedback loop and the investor roof match feedback loop have a balancing character.

The endogenous simulation of the cost recovery feedback loop of distribution grids with the interplay between the diffusion of solar prosumers and the cost recovery allows to analyze the dynamics of the distribution effect. The simulation model contains four major feedback processes, presented in the conceptual model in Figure 1 – the cost recovery feedback loop, the peer effect, the probability of investor-roof match and the scarcity effect. The model structure builds on the foundation of network theory. For the detailed discussion of the theoretical foundations and the reasoning of the feedback structure based on network theory, I refer to Kubli & Ulli-Ber (2016).

The *cost recovery feedback loop* is triggered by the constellation of the consumers and the applied self-consumption concepts, as these determine net demand. Net demand and total grid costs, as well as the tariff design define the indicated grid tariff. The attractiveness of self-consumption concepts is determined by several factors. Karneyeva and Wüstenhagen (2017) define the economics of decentrally installed PV plants by the savings and the income, resulting from the self-sufficiency level and sales of excess energy. Savings come from avoiding the grid tariff but also from power costs. The tariff design and level influence the attractiveness of self-consumption concepts by defining how much can be saved by self-consuming. Income comes from the remuneration for surplus generation and potential subsidies influence the profitability of self-consumption concepts. Most relevant costs factors are the investment costs, operating costs and, in the case of prosumer communities, also measuring and administrative costs are considered.

Insights from behavioral decision theory and empirical studies in the energy field are used to achieve a realistic representation of the decision-making process. People make their decisions based on the perceived level of attributes relevant for their decision (Tversky & Kahneman, 1974), in this case the perception of the payback period. The decision process for the investment in a self-consumption concept is structured as a sequential decision process (Johnson, 1984), separating the decision whether a switch of concept is generally worthwhile from the selection of the concrete concept. Besides economic considerations, Particularly for private house owners investing in renewable energy technology, other factors are frequently more relevant (Helms et al., 2015). In the model, I distinguish between two investor types – the investors deciding based on economic criteria – the “economic investors” – and the investors that also consider non-

financial benefits besides the payback period – the “green investors”. Empirical research in the energy field supports this segmentation and the relevance of non-financial factors, such as perceived self-sufficiency (Ebers & Wüstenhagen, 2015; Korcaj et al., 2015; Salm et al., 2016). Empirical research finds that the payback period is the most frequently chosen concept for investment decisions by private investors; other concepts such as the net present value (NPV) or the internal rate of return (IRR) are less frequently applied (Ebers & Wüstenhagen, 2015, p.16).

Learning from peers has a significant impact on the perceived attractiveness of self-consumption concepts (Bollinger & Gillingham, 2012), which is captured in the *peer effect feedback loop*. This feedback loop describes the positive influence from neighbors with a PV plant on the considerations of the investor.

Not every house is suitable for PV installation. Interested investors may not always be those with the most suitable rooftops, limiting the probability of the match between the investor and the roof. This is captured with the *probability of investor-roof match feedback loop*, which is assumed to slow down the diffusion process.

The scarcity effect feedback loop takes into account the geo-physical limits of the diffusion to the technical potential for PV deployment.

3.2. Model structure and equations

The model structure and equations are presented along the three essential elements of the cost recovery feedback loop: the investment decision and diffusion of solar prosumers (3.2.1), the economics of solar prosumer concepts (3.2.2) and the grid tariffs (3.2.3). The feedback loops – investor-roof match feedback loop, the peer effect feedback loop and the scarcity effect feedback loop – are described under 3.2.1, as they influence the investment decision respectively the diffusion process. Table 6 in Appendix B provides a list of notations for the variables in the equations with the corresponding input data.

3.2.1. Modelling the investment decision and diffusion of solar prosumers

The stocks measure the number of households, respectively commercial customers, applying a certain consumption concept (consumption concept $c \in \{grid\ consumer = gc, prosumer = p, storage\ prosumer = sp; reference\ concept = rc\}$). Stocks are an integration of the in- and out-flows plus the initial values. The flows describing the adoption rate (ar) of the decision options for self-consumption concepts ($d \in \{prosumer, storage\ prosumer, storage\ installation; competing\ decision\ option = dc\}$) are formulated as:

$$ar_{d,i} = \max(C_{c=rc,i} - NC_{c=rc,i}, 0) * sp_{d,i}/at_{d,i} \quad (1)$$

where, i represents the consumer groups ($i \in \{single - family\ house = SFH, multi - family\ house = MFH, commercial\ customer = CC\}$). $C_{c=rc,i}$ are the consumers applying the reference consumption concept (e.g. grid consumer) per consumer group, and $NC_{c=rc,i}$ are the consumers of the reference concept not willing or able to adopt a different consumption concept. $sp_{d,i}$ are the shares of a consumer group with distinct preferences for the different decision options. $at_{d,i}$ are the adjustment times for the adoption, which are specific for the different decision options and consumer groups. $at_{d,i}$ for the decision options prosumer and storage prosumer are defined as follows:

$$at_{d=prosumer, storage\ prosumer; i} = atb_i * ec_{i=MFH} * (1/pr_i) \quad (2)$$

$$at_{d=install\ storage; i} = atb_i \quad (3)$$

where atb_i is the base adjustment time for each consumer group. The time delay is derived with an optimization procedure designed for calibration (see documentation and values in Table 8 in Appendix D). $ec_{i=MFH}$ is variable capturing the additional coordination effort needed for multi-family houses when they need to form a self-consumption community, increasing at by 20%. pr_i is the probability of the investor roof match and causes at to increase when more and more roofs suitable for PV are already used:

$$pr_i = sr_i - (PPV_i/C_i) \quad (4)$$

sr is the share of roofs suitable for PV, PPV the retail consumers and commercial customers, respectively the prosumers, that already have a PV plant and C the total number of households and commercial customers. With the link from the prosumers (PPV)

to the adoption adjustment time for solar prosumers ($at_{d=prosumer,storage\ prosumer; i}$) the investor-roof match feedback loop is closed.

$$NC_{d,i} = TC_{c=rc,i} * (1 - (u_{d,i} * bi)) \quad (5)$$

NC , the consumers not willing or able to change, are defined by $TC_{c=rc,i}$, the total consumers that ever applied the reference concept (the respective initial value plus the accumulation of the inflows over time), $u_{d,i}$, the perceived utility of the decision option and bi , the base share of investors. $u_{d,i} * bi$ represent the share willing to change per decision point – people who perceive the decision options as attractive and are generally willing to invest in renewable energies. bi is a share of 57% willing to invest in renewable energies independent from the profitability of the investment, derived from empirical data from Balcombe et al. (2014).

$u_{d,i}$ is also used to determine $sp_{d,i}$, the share of preferences. A multi-nominal logit model is used:

$$sp_{d,i} = 1/(1 + \exp(-\beta * (u_{d,i} - u_{d=dc,i}))), \quad (6)$$

where $u_{d,i}$ is the perceived utility of the decision option under consideration and $u_{d=dc,i}$ the perceived utility of the competing decision option. β determines the responsiveness to changes in the perceived utility.

The perceived utility $u_{d,i}$ is a construct combining multiple factors:

$$u_{d,i} = (uei_{d,i} * sei_i + ugi_{d,i} * (1 - sei_i)) * (1 + pe_i) * se_i * f_{iv}(I_{d,i}) \quad (7)$$

where,

$$pe_i = TPPV_i / C_i \quad (8)$$

$$se_i = f_{se}(TPPV_i / ((C_{c=p; i} + C_{c=sp; i}) * cPV_i)). \quad (9)$$

uei is the perceived utility by economic investors, ugi is the perceived utility by green investors. sei is the share of investors deciding on the basis of economic criteria, pe the peer effect and se the scarcity effect. $sei_{i=SFH,MFH}$ has a value of 69% for single-family house owners and multi-family house owners (Ebers & Wüstenhagen, 2015, p.

16). For commercial customers, I assume that all are investing based on economic criteria.

The peer effect (pe), using a peer effect coefficient of 0.0469 (Bollinger & Gillingham, 2012) multiplied with the share of consumers with a PV plant, increases the perceived utility. This closes the peer effect feedback loop. The scarcity effect (se) is defined by a function (f_{se}) of the share of the used PV potential. $TPPV_i$ is the technical potential of PV for the consumer groups, respectively their house roofs. Prosumers and storage prosumers ($C_{c=p} + C_{c=sp}$) install a certain capacity of PV (cPV). cPV uses the values for installed capacity from Table 2. f_{se} is described in Figure 11 in Appendix C.¹

The effect of investment costs is captured in the function of investment volume (f_{iv}) altered by the total investment volume (I). The function s displayed in Figure 2, using empirical data from (Ebers & Wüstenhagen, 2015).

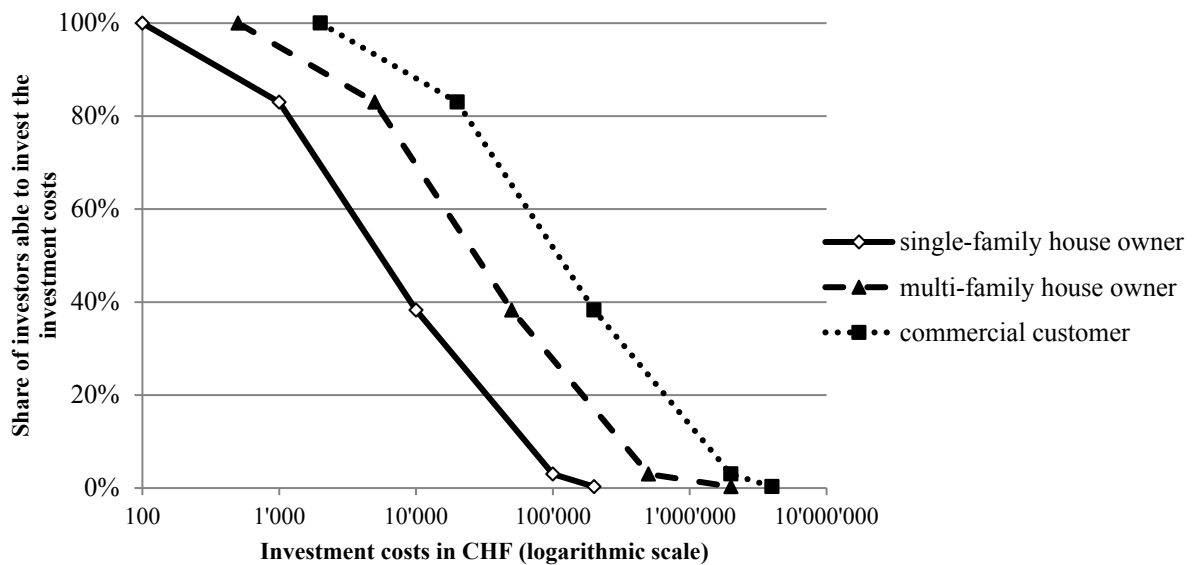


Figure 2: Effect from investment volume (based on Ebers and Wüstenhagen (2015) for single-family houses)

As human beings base their decisions on their perceptions of the relevant criteria, which they usually slowly adjust (Tversky & Kahneman, 1974), a perception delay of the payback period is included in the model. I assume an adjustment time of 2 years.

¹ For more detailed descriptions of the scarcity effect feedback loop and the peer effect feedback loop I refer to Kubli and Ulli-Ber (2016).

The perceived utility by economic investors is:

$$uei_{d,i} = f_{tl}(PPP_{d,i}; tl_d) * f_{ppc=ei,i}(PPP_{d,i}) \quad (10)$$

with $f_{tl}(PPP_{d,i}; tl_d)$ being the function for the effect from technology life time and $f_{ppc=ei,i}(PPP_{d,i})$ capturing the heterogeneity among investors in terms of their tolerance for the perceived payback period ($PPP_{d,i}$). $f_{ppc=ei,i}$ for single-family houses and multi-family houses were derived again from the survey data by Ebers and Wüstenhagen (2015), whereas slight adjustments were made for commercial customers. Figure 3 displays the share of investors that accept a particular payback period.

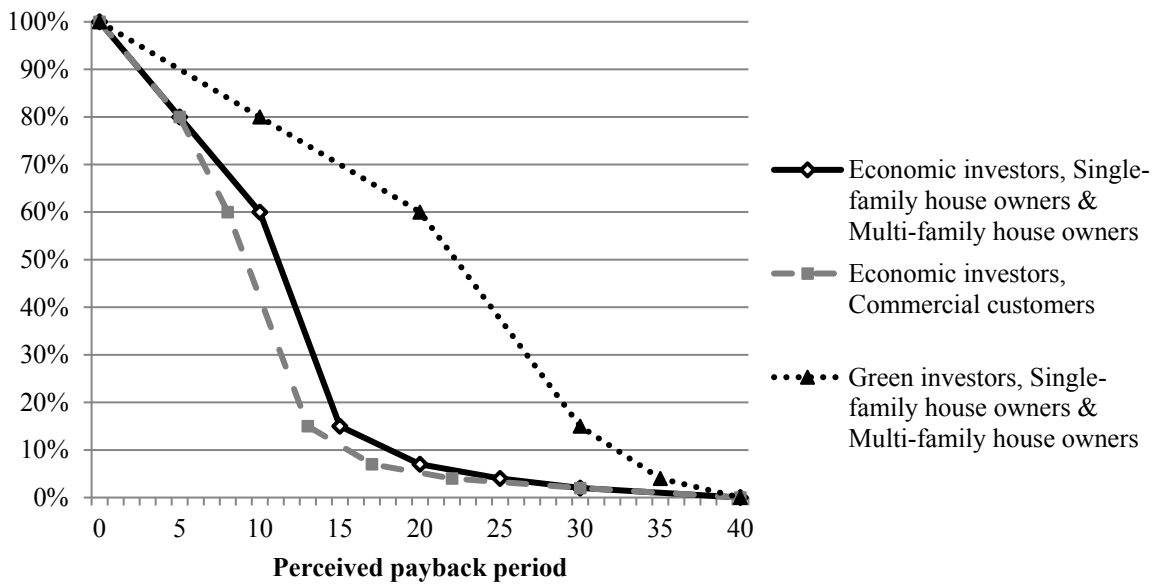


Figure 3: Functions for the tolerance of the perceived payback period (adjusted from Ebers and Wüstenhagen (2015))

f_{tl} simply ensures that no investments are taken that take longer to payback than the technology is optimistically expected to last. I assume technology lifetimes (tl) of 35 years for PV and 20 years for batteries (Weniger et al., 2014).

The utility of green investors is determined as follows:

$$ugi_{d,i} = \min(f_{ppc=gi,i}(PPP_{d,i}) + f_{ss}(1 - scg_{d,i}); 1) \quad (11)$$

where $f_{ppc=gi,i}(PPP_{d,i})$ represents the function described in Figure 3, and f_{ss} the function deriving the effect of self-sufficiency on the investment decision of green investors. Various studies indicate that there is a perceived benefit from increased self-

sufficiency (Ebers & Wüstenhagen, 2015; Jager, 2006; Korcaj et al., 2015), detailed empirical insights, however, are not available (yet) to the knowledge of the author. I assume f_{ss} , based on $(1 - scg)$, which is 1 minus the share of consumption from grid, as presented in Figure 4. I assume that the pure possession of a PV plant, which generates only for the grid, increases the perceived utility of the investment by 10%. Actual self-consumption of solar power raises the perceived value, until it reaches a maximum of 1 under full self-sufficiency.

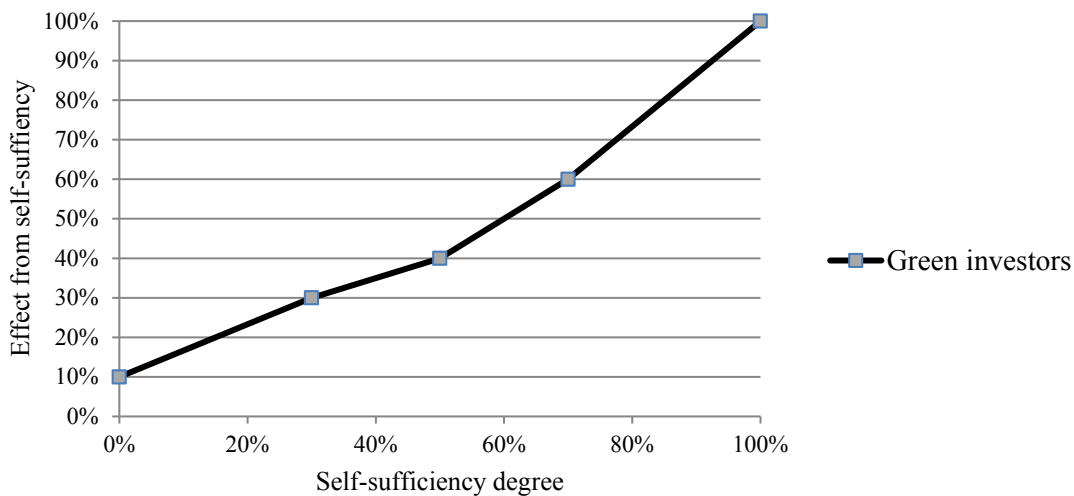


Figure 4: Function self-sufficiency effect for green investors

3.2.2. Modelling the economics of self-consumption concepts

The core of the economic assessment of the self-consumption concepts is the payback period:

$$PP_{a,i} = (IT_{a,i} - G_{a,i} + M_{a,i})/aCF_{a,i} \quad (12)$$

where $(IT - G + M)$ equals to the total investment volume I , consisting of the technology investment costs (IT), the investment grant (G), which is a policy parameter¹, and the costs for the measuring infrastructure (M), if this is legally required. aCF is the annual cash flow that is expected to arise. For self-consumption concepts aCF consists of four essential parts:

¹ In Switzerland an investment grant policy for PV plants smaller than 30 kWp is in place. The investment grant covers 30% of the investment costs. The investment grant replaced a fixed feed-in tariff policy.

$$aCF_{d,i} = (ie_{d,i} - ie_{dr,i}) + (eb_{d,i} - eb_{dr,i}) + (gb_{d,i} - gb_{dr,i}) - (oc_{d,i} - oc_{dr,i}) \quad (13)$$

The annual cash flow consists of the income from power sales (ie), savings on the power bill (eb), the savings on the grid usage bill (gb) and the additional operating costs (oc). A crucial element of the definition of the cash flow variables is the comparison to the reference concept (marked with “dr” in the subscript).

The income from power sales (ie) is based on the amount of power generated by the self-consumption system (ge), the share of excess power (sx) and the price received for power that is fed into the grid (p_{PV}).

$$ie_{d,i} = ge_{d,i} * sx_{d,i} * p_{PV} \quad (14)$$

ge , the generated power from the self-consumption concept is calculated based on the installed capacity of PV (c_{PV}) and the annual generation of 1 kW installed PV of 1024 kWh (Weniger et al., 2014). sx is defined by the values for share excess power in Table 2.

For p_{PV} I use historical data from the Canton of Berne and from 2017 on the value remains on 14.78 rappen¹, consisting on the feed-in tariff of 9.78 rappen plus a price for the certificate of origin of 5 rappen.

The retail power price (p_{retail}) consists of three essential parts:

$$p_{retail} = p_e + gt_{vol} + t \quad (15)$$

the price for the pure power (p_e), the volumetric grid tariff (gt_{vol}) and the taxes (t). For p_e historical data is used and from 2017 a constant of 9 rappen. The taxes (t) are a constant of 1.5 rappen.

The power bill, containing only the costs for the power itself without costs for grid tariffs, is defined as follows:

$$eb_{d,i} = aec_i * scg_{d,i} * p_e \quad (16)$$

where, aec is the annual power consumption of the consumer independent of a self-consumption concept and scg the share of consumption from the grid as defined

¹ Rappen is the cent of the Swiss franc.

above. scg uses the values from Table 2; aec corresponds to the consumption of the grid consumers in Table 2.

The grid bill (gb) arises from the different grid tariffs that can be allocated for grid usage.

$$gb_{d,i} = gb_{vol_{d,i}} + gb_{flat_{d,i}} + gb_{cap_{d,i}} \quad (17)$$

The annual operational costs (oc) are defined by a share of 1.5% of the investment costs (Weniger et al., 2014, p. 85).

3.2.3. Modelling the grid tariff designs and cost recovery

The volumetric grid tariff is defined by the total grid costs that are to be covered in one year (GC)¹ and the total annual net-demand to the grid (AND):

$$gt_{vol} = (GC * s_{gt vol}) / AND \quad (18)$$

A share ($s_{gt vol}$) is included in the equation to determine which share of GC is to be recovered from the volumetric grid tariff. In the base case, the scenario “volumetric tariff”, $s_{gt vol}$ is set to 100%. An adjustment process of one year is assumed to change the tariff from the current level to the new desired level, as utilities are usually only allowed to change the tariffs once per year². The annual net demand (AND) is defined as follows:

$$AND = \sum_{c=1}^m \sum_{i=1}^n (C_{c,i} * scg_{c,i} * aec_i) \quad (19)$$

where $C_{c,i}$ are all consumers categorized into the applied consumption concepts (c) and the consumer group (i). The share of consumption from grid $scg_{c,i}$ corresponds to $scg_{d,i}$, described in equation (15), but has reallocated subscripts to the corresponding consumption concepts.

The grid usage bill for the volumetric tariff for a consumer is defined as follows:

¹ I here refer to the costs for the lowest grid level (in Switzerland grid level 7) after the cost roll. The cost roll is a mechanism that allocates the grid costs of all grid levels to the grid levels where the beneficiaries are.

² For example in Swiss Electricity Law (Schweizer Stromversorgungsgesetz), Art. 6, paragraph 3.

$$gb_{vol_{d,i}} = gt_{vol} * scg_{d,i} * aec_i .^1 \quad (20)$$

To enable the analysis of alternative grid tariff designs I built in: a) a flat tariff, charging the consumers based on an annual fixed price for the grid connection, and b) a capacity tariff, based on the maximum peak demand in the year (mc).

The flat grid tariff is defined as:

$$gt_{flat} = (GC * s_{gt\ flat}) / \sum_{c=1}^m \sum_{i=1}^n (HH_{c,i}) \quad (21)$$

leading to this grid bill for a consumer of:

$$gb_{flat_{c,i}} = gt_{flat} \quad (22)$$

The capacity grid tariff is defined by:

$$gt_{cap} = (GC * s_{gt\ cap}) / \sum_{c=1}^m \sum_{i=1}^n (mc_{c,i}), \quad (23)$$

leading to a grid bill:

$$gb_{cap_{c,i}} = gt_{cap} * mc_{c,i}. \quad (24)$$

The capacity tariff may incentivize prosumers to adapt a grid friendly behavior. Prosumers can do so by shifting their consumption to the times when the PV plant generates. Prosumers with storage can manage the storage to reduce the peak demand. Operating the battery targeted towards a peak demand reduction leads to a reduced self-consumption (Santos et al., 2014). I assume a reduction of the self-sufficiency degree of 20% for storage prosumers. I assume that prosumers adopt peak optimized behavior (t_{pob} stand for trigger peak optimized behavior) when it is profitable for them, taking the annual return as a reference:

$$t_{pob} = \text{if } (aCF_{d,i,optimized\ peak} > aCF_{d,i,normal\ peak}) \text{ then } (mc_{c,i,optimized\ peak}) \text{ else } (mc_{c,i}) \quad (25)$$

Potential adjustments are delayed with a fixed delay of half a year.

¹ Here scg is again used with the subscript “d” to maintain consistency with the following use of the variable in equation (16).

3.3. Data, calibration and validation with five cases

The model is applied for the case of the supply area of the utility company BKW in the Canton of Berne, Switzerland. The utility company BKW provided data for the grid costs and the grid structure. The developments of the technology costs for PV and battery are based on the predictions of IRENA (2015), estimations for the increase in grid costs on Swiss Federal Office of Energy (2013). Details on the data input are provided in Table 6 in Appendix C.

For validation the suggested procedure by Barlas (1996) was taken as a reference. An emphasis was placed on including the expertise of practitioners. During the model development, meetings were held with the project partners from BKW Energie AG. Within the setting of the TREES approach (Ulli-Beer et al., 2017), the model and results were discussed in workshops with participants from multiple utility companies, technology developers and public authorities. Results were also discussed with researchers within the Swiss research project SCCER CREST, which resulted in a white paper publication for the practitioner audience (Ulli-Beer et al., 2016).

Four additional cases were simulated for validation: the municipality of Frutigen (a rural municipality), Wohlen (a suburban municipality) and Ostermundigen (an urban municipality), all located in Switzerland, as well as Bavaria in Germany. Bavaria was selected, as Germany is more advanced in the PV diffusion than Switzerland. Regional specific data for the initial values of solar prosumers, settlement pattern, average power consumption and the PV potential were adjusted for the validation cases. Furthermore, for Bavaria the different regulatory setting and PV and battery support policies were implemented. Comparing the simulation with historic data reveals a good model fit, as indicated by R^2 in Table 3. The high R^2 for all validation cases indicates that the model structure is well suited to explain the diffusion dynamics of solar prosumers for different regions. Nevertheless, the differences in the derived adjustment times for the regions (Appendix C) reveal that there are further regional specific factors, which are not captured in the model. The consumer group specific R^2 shows that there are differences on how well the model captures the investment decision of different customer groups. As the used empirical data is oriented towards the investment decisions of single-family house owners, it is not surprising that the model fit is better for this segment.

Application case		Validation cases			
		Frutigen	Wohlen	Ostermündigen	Bavaria
	BKW				
Single-family houses	0.97	0.97	0.96	0.96	0.96
Multi-family houses	0.84	0.60	0.94	0.87	0.98
Commercial customers	0.89	0.96	0.91	0.89	0.97
Overall	0.90	0.84	0.94	0.90	0.97

Table 3: Goodness of fit for the simulated cases and consumer groups¹

3.4. Measures for distributive justice

Simulation results are evaluated for distributive justice along two major measures: the distribution effect and the deviation from the cost causation principle. The equity principle based on cost causation is assumed as the relevant criteria for fair distribution of grid costs, as commonly applied in utility regulations (as discussed under 2.2). Furthermore, the diffusion of solar prosumers indicates the effectiveness principle in respect to achieving energy and climate policy goals.

Distribution effect: The distribution effect measures the strength of the cost recovery feedback loop. The term represents the percent increase of the grid tariff caused by solar prosumers, independent of increasing costs of grid infrastructure:

$$\begin{aligned}
 & \textit{distribution effect} \\
 & = (gt_{simulation} - gt_{without decentralization}) / gt_{without decentralization}
 \end{aligned} \tag{25}$$

Deviation from the cost causation principle: The deviation from cost causation principle measures the contribution of a consumer to the cost of the distribution grid relative to the costs caused by the respective consumer. In concrete terms, the deviation from cost causation is defined as follows:

¹ For the R² calculations historical data from 2009¹ to 2016 was used for the Swiss cases¹ and 2009 to 2015 for Bavaria.

$$\begin{aligned}
& \text{deviation from cost causation principle}_{c,i} \\
&= \left[\left(\frac{gb_{c,i}}{(mc_{c,i} + 30\% * mc_{c,i}) * gt_{con}} \right) \right. \\
&\quad \left. - \left(\frac{gb_{c,i,t=0}}{(mc_{c,i} + 30\% * mc_{c,i}) * gt_{con}} \right) \right] \tag{26}
\end{aligned}$$

where gt_{con} , the connection size grid tariff, which is the theoretical grid tariff if when all consumer would pay based on their effectively caused costs, defined as:

$$gt_{con} = GC / \sum_{c=1}^m \sum_{i=1}^n (mc_{c,i} + 30\% * mc_{c,i}). \tag{27}$$

The contribution to the cost recovery of the distribution grid is defined as the costs paid for grid usage over a year by the consumer, equaling the grid usage bill (gb). I here define the caused costs as the costs for the effective connection size necessary, determined by the peak demand (mc) plus a reserve assumed of 30%. I initialize the term to zero to focus on the distribution effect arising from self-consumption¹. The measure shows the deviation from perfect cost causation (which would be a value of zero) for a customer with the respective consumption concept in percent (%).

4. Results

For the analysis, I simulate five scenarios, described in Table 4. The simulation covers the years 2015 until 2050 and consider the circumstances of the supply area of BKW, but sets the initial values of solar prosumers to zero. Values are presented to give an idea of likely outcomes and should be understood as a what if-analysis (Zagonel et al., 2004), rather than an exact forecast.

First, I compare the scenario “volumetric tariff with net purchase and sale” with the “volumetric tariff with net metering” scenario to analyze the difference between the current regulatory setting in Switzerland versus a setting, as it can be found in the US. I assume a yearly billing period to simulate the most extreme case possible, leading to

¹ As a consequence of the initialization of the cost causation term, the values for relative distribution multiplied by the number of households per consumption concept will not sum up to zero, as one would expect from a cross financing.

100% PV bill savings of grid costs (see Table 1) and excess power is compensated with the power price (p_e). Second, I present simulation experiments with alternative grid tariff designs – a flat tariff, a capacity tariff and a capacity tariff with the option for consumers to implement peak demand optimization.

Scenarios	Volumetric tariff, net purchase and sale	Volumetric tariff, net metering	Flat tariff	Capacity tariff	Capacity tariff with option for peak reduction
Grid tariff design	Volumetric	Volumetric	Flat	Capacity	Capacity
Metering design	Net purchase and sale	Net metering with yearly billing period	Net purchase and sale	Net purchase and sale	Net purchase and sale
PV Reimbursement	Investment grant for PV	No investment grant	Investment grant for PV	Investment grant for PV	Investment grant for PV
Consumption optimization principle	Self-consumption optimization	Self-consumption optimization	Self-consumption optimization	Self-consumption optimization	Determined by the consumers

Table 4: Overview on the scenario settings

4.1. Diffusion of self-consumption concepts

Scenario: Volumetric tariff with net purchase and sale

The scenario volumetric tariff, presented in Figure 5, involves the most likely diffusion behavior under the current Swiss regulation. Single-family houses adopt the prosumer as well as the storage prosumer concept, with a majority remaining with the prosumer concept. Multi-family houses first have a similar adoption for both concepts, while over time the storage prosumer concept becomes dominant. A shift in the dominating concept can be observe among the commercial customers. At first, a strong adoption of the prosumer concept occurs. After 2020, the storage prosumer concept becomes more attractive for commercial customers, due to decreasing battery prices and the increasing grid tariff. The number of prosumers drops, as commercial customers are updating their systems with batteries. The retrofitting process also occurs at the other con-

sumer groups, but is not as pronounced. Overall, there is a strong diffusion of self-consumption concepts. Considering the storage prosumer concept appears to be very relevant, as larger shares of consumers invest in concepts that combine PV and storage.

Important factors for the diffusion of the self-consumption concepts are the investment decision function, considering different benefits from the self-consumption concepts, and the general increase in the overall grid costs. The effect of non-financial factors in the investment decision is particularly evident in the case of single-family houses. “Green investors” serve as early adopters, decisively contributing to market development. If all single-family houses would invest based on only economic criteria, diffusion would lag behind the reference until 2025 and could only catch up to the level of the scenario “volumetric tariff with net purchase and sale” until the end of simulation. The overall increase in grid costs is the major driver for the increase in the volumetric grid tariff, and not the distribution effect, in contrast to what is sometimes discussed in previous research and political debates. The overall increase in grid costs contributes 92% to the total increase of the volumetric tariff. Particularly, the storage prosumer concept finds less adopters among single-family houses and commercial customers with constant grid costs. For multi-family houses, the storage prosumer concept is already attractive without a strong increase in the grid tariff.

Scenario: Volumetric tariff with net metering

Relating to the academic discussions, I compare the volumetric tariff with net purchase and sale policy to a scenario with a net metering policy with yearly billing (Figure 5). The net metering policy has considerable effects on the adoption of the self-consumption concepts. The net metering policy shifts the attractiveness to the solar prosumer concept without storage, since through net metering the stored power has the same value as the excess power. Consequently, there are no additional incentives to invest in a storage prosumer concept¹.

¹ There is an adoption of the storage prosumer concept, although under the net metering policy no financial incentive exists for storage installation, due to the functioning of the logit function implemented and the effect of investors also considering non-financial aspect.

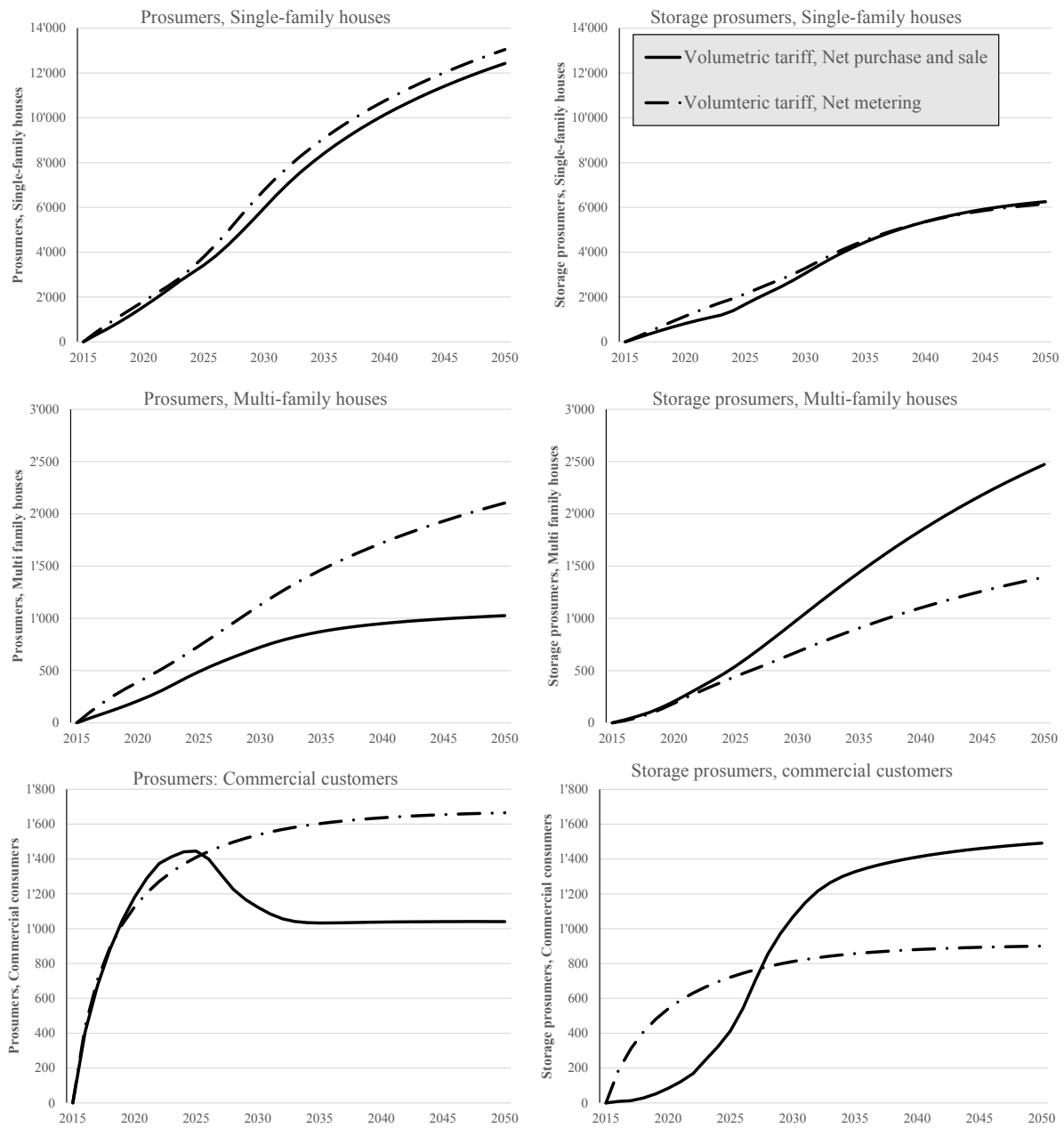


Figure 5: Diffusion of the self-consumption concepts under the scenarios with a volumetric grid tariff: net purchase and sale and net metering

4.2. Distribution effect, installed PV capacity and deviations from the cost causation principle

Distribution effect and installed PV capacity

In Figure 6, the resulting distribution effect (see definition under 3.4) (a) and the capacity expansion of PV over time in (b) are presented. In the scenario volumetric tariff with the net purchase and sale policy, the distribution effect increases to a level of 8,4%, meaning that the volumetric grid tariff increased by 8.4% caused by the diffusion of self-consumption concepts (respectively 0.26% per year). The distribution effect makes a contribution of one-eighth in the total increase of the tariff of 70% over the 35 years. The remaining of the increase is caused by grid expansion, operation and measurement. A very different picture results under the net metering policy. Under the net metering policy, the increase in the grid tariff caused by the diffusion of solar prosumers reaches 24% in 2050. Through the bill savings of solar prosumers the diffusion has a much stronger impact on the grid tariff. Obviously, when applying shorter billing periods a lower distribution effect would result.

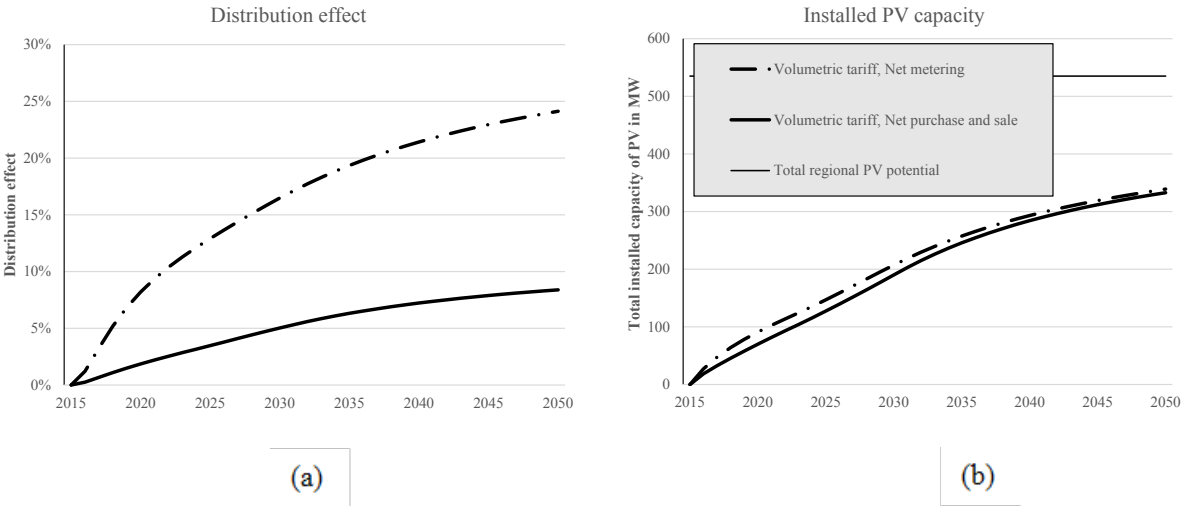


Figure 6: Distribution effect (a) and the installed capacity of PV (b) under the volumetric tariff with net purchase and sale and the net metering scenario

The total capacity expansion of PV over time look similar across the scenarios, ranging between 333 to 339 MW as an installed capacity in 2050. This equals 62% to 63% of the technical potential. While the capacity expansion is only slightly stronger, the net metering policy leads to a considerably higher distribution effect, as we just saw. Therefore, research results on the distribution effect under the net metering system

should not be transferred to a net purchase and sale system. Targeted research for both policy settings is necessary.

Deviations from the cost causation principle

The deviations from the cost causation principle is evaluated for the year 2050 in Figure 7 for the scenario volumetric tariff with net purchase and sale. Prosumers and storage prosumers benefit from avoiding grid tariff costs through self-consumption. The deviation from the cost causation principle varies among the different consumer groups and consumption concepts, as there are differences for the peak demand and the self-sufficiency degree. Storage prosumers have, in the case of single-family houses and multi-family houses, a stronger deviation from the cost causation principle. As the avoided costs through large self-sufficiency are higher than the reduced caused costs, the deviation from cost causation is even larger. Commercial customers show better values in the deviation from the cost causation principle, as they can more effectively reduce the peak demand with the self-consumption concept. Conventional grid consumers have a positive value in the cost causation term due to the distribution effect. In the case of BKW in the year 2050, grid consumers pay 35 CHF (a single-family house), 242 CHF (a multi-family house) and 824 CHF (a commercial customer) per year extra due to the distribution effect¹. In the average single-family house live 2.8 people², resulting in extra costs per person of 12.50 CHF in the year 2050. Consequently, the cross financing between prosumers and conventional consumers is rather limited. However, whether the amount of the cross financing is socially accepted, is left open for future empirical studies.

¹ I assume no inflation.

² <http://www.bfs.admin.ch/bfs/portal/de/index/themen/01/02/blank/key/bevoelkerungsstand/02.html> (Accessed: 14.3.2016)

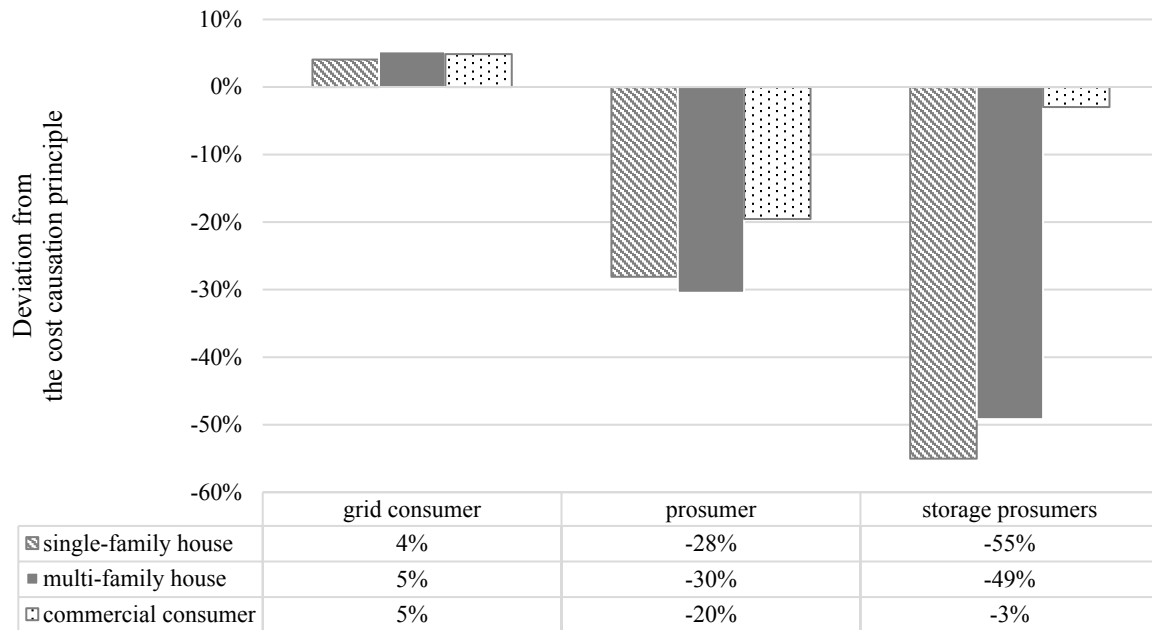


Figure 7: Deviation from the cost causation principle in 2050 for the scenario volumetric tariff with net purchase and sale. Positive numbers indicate that the consumers pay more than what they cause on costs for their connection size, and vice versa.

4.3. Simulation of alternative grid tariff designs

Current discussions consider alternative grid tariff designs as an option to reduce the deviation from the cost causation principle of self-consumption concepts. I test two options: (a) a flat tariff, charging all consumers connected to the grid with the same monthly tariff; (b) a capacity tariff, charging the consumers based on the peak consumption of power per year. The capacity tariff can set incentives for consumer to take measures to reduce their peak demand. In the scenario “capacity tariff with option for peak reduction” (c), storage prosumers can shift to a peak demand reducing behavior, based on the definition in equation (24). The resulting diffusion patterns of prosumers and storage prosumers are presented in Figure 8.

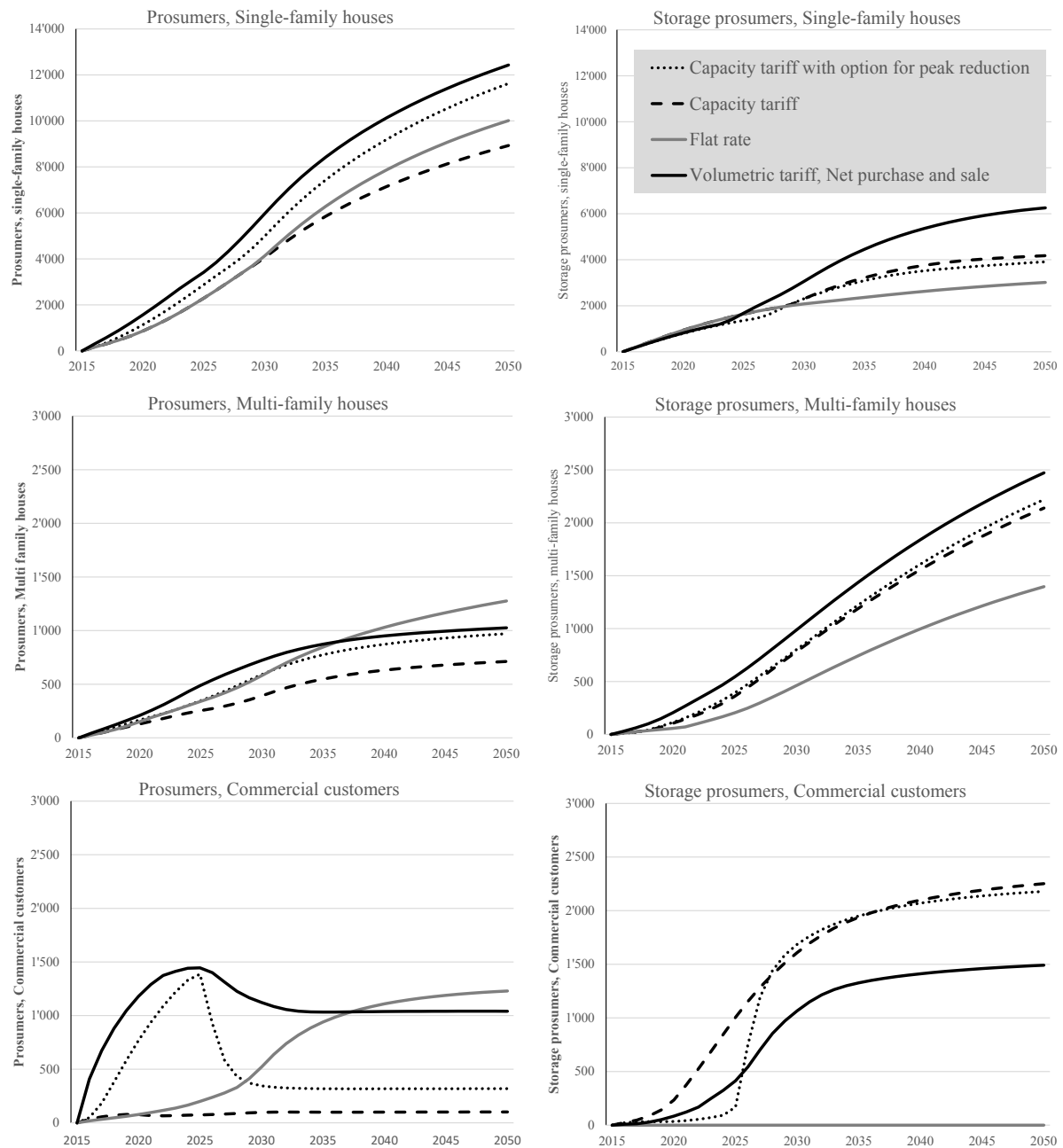


Figure 8: Diffusion of self-consumption concepts under the volumetric tariff with net purchase and sale, the flat tariff and the capacity tariff, with and without the option for peak demand reduction

The flat tariff

The flat tariff generally sets fewer incentives for self-consumption concepts. With the flat tariff, only the avoided power price can be accounted as savings. The sales of excess power remain, as well as the non-financial benefits. Therefore, the adoption of the storage prosumer concept is considerably lower, or zero in the case of commercial

customers. Consumers still adopt the prosumer concept, as the concept still becomes profitable and gains from the comparably low attractiveness of the storage prosumer concept. Overall, a much lower installed capacity of PV results under the flat tariff (Figure 9b).

The capacity tariff

The main incentive of the capacity tariff is targeted towards a reduction of the peak demand. For this reason, the storage prosumer gains on relative attractiveness. However, the adoption of the storage prosumer concept is lower than in the base run for the cases of single-family houses and multi-family houses. As the peak demand is not reduced relatively less than the saved share with self-consumption, a lower adoption and less installed capacity of PV results (Figure 9b).

In the scenario “capacity tariff with option for peak reduction”, peak reduction is profitable already for the beginning for single-family houses and multi-family houses, for prosumers as well as storage prosumers. Only for commercial customers with the storage prosumer concept, it is not profitable to adopt the grid-optimized behavior at first. Since demand shifting is profitable for commercial consumers with the prosumer concept from the beginning of the simulation, commercial customers strongly adopt the prosumer concept at first and then, later on, shift to the storage prosumer concept. It is important to note that the scenario does not include technical costs for demand shifting to reduce peak demand, such as devices for smart control, which might alter the cost evaluation.

The scenarios with alternative grid tariff designs clearly highlight that adjustments in the grid tariff lead to significant changes in the attractiveness of the self-consumption concepts and therefore influence the speed and form of diffusion. The tested flat tariff and capacity tariff (with and without option for peak reduction) cause lower investments in PV capacity (Figure 9b), having a negative effect on reaching renewable energy policy targets.

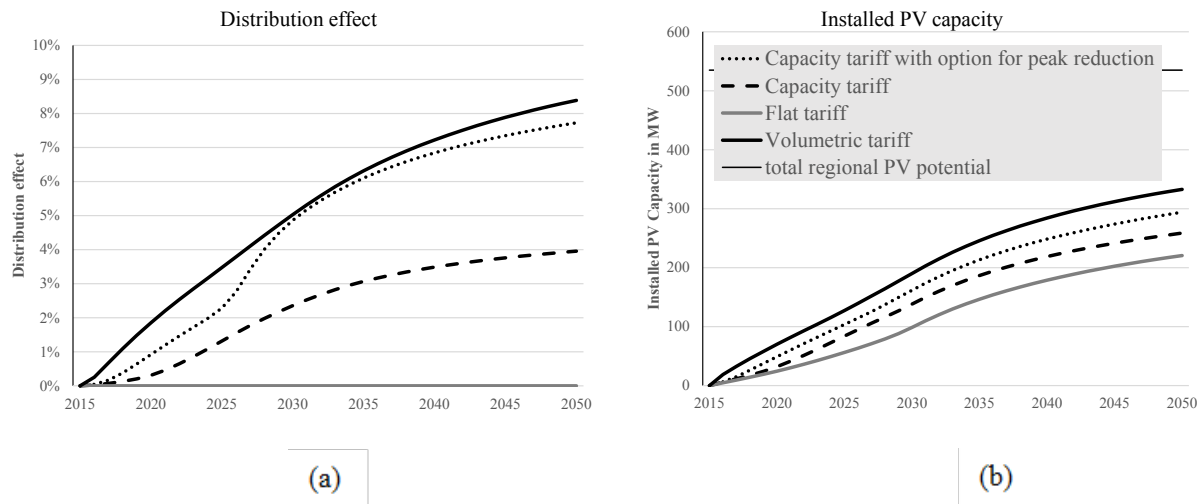


Figure 9: Distribution effect (a) and installed PV capacity (b), under the volumetric grid tariff with net purchase and sale, the flat tariff and the capacity tariff, with and without the option for peak demand option.

Deviation from the cost causation principle under alternative grid tariff designs

Looking at the distribution effect resulting from the alternative grid tariff designs tested in Figure 9, we note that the alternative tariffs cause a weaker distribution effect than the volumetric grid tariff. Under the flat tariff, no increase in the tariff occurs, as all consumers remain connected to the grid. However, Figure 10 demonstrates that there are still consumers disadvantaged under the flat tariff. Storage prosumers, who reduce their peak demand, now pay more for the grid than the costs they actually cause.

The capacity tariff, on the other hand, does not lead to a deviation from the cost causation principle (Figure 10), as the caused costs were defined based on the effectively needed connection size. However, under the capacity tariff the distribution effect still raises (Figure 9a). Due to the existing grid infrastructure, reductions in peak demand are not automatically translated to a smaller connection size. Therefore, the overall grid costs are still recovered from the customer base. Consequently, conventional grid consumers still pay more due to the diffusion of self-consumption concepts. When storage prosumers adopt a grid friendly behavior by reducing their peak demand, the distribution effect is even larger and close to the distribution effect under the base run (Figure 9a).

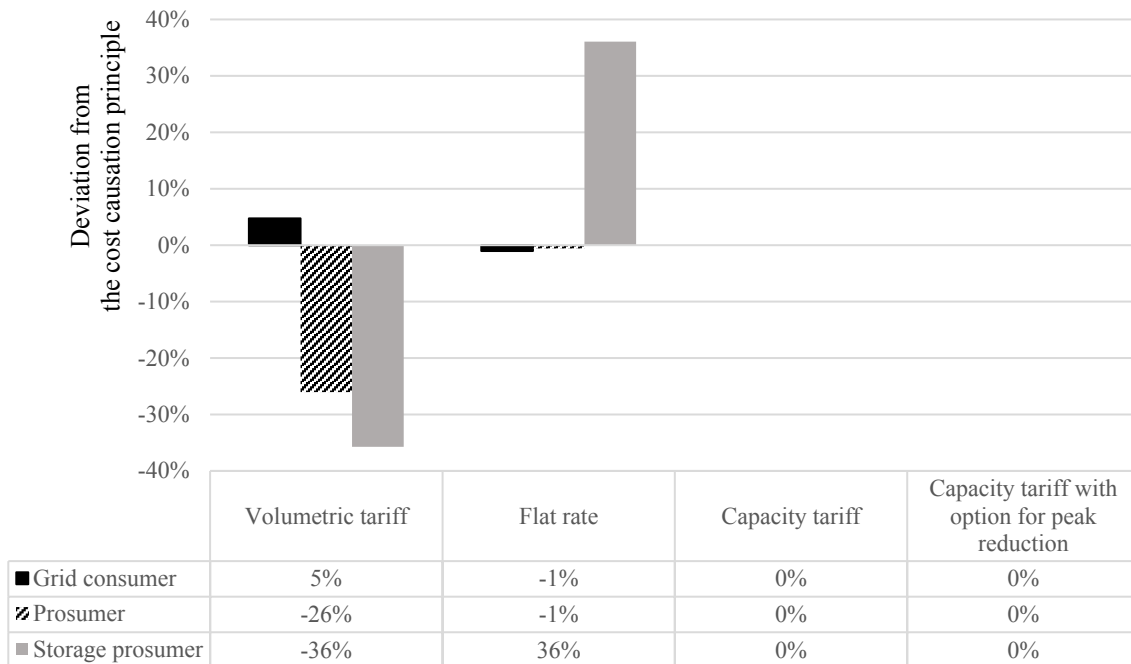


Figure 10: The deviation from the cost causation principle under the volumetric tariff with net purchase and sale, the flat tariff and the capacity tariff, with and without the option for peak demand reduction.

5. Conclusion

Self-consumption of locally generated power increasingly challenges the ability of utility companies to recover costs of their distribution grid. As solar prosumers can avoid part of the grid costs under the volumetric grid tariff, costs are distributed differently among customers, leading to a distribution effect and deviations from the cost causation principle. In this study, I investigated the scope of the distribution effect and the deviation from the cost causation principle of grid consumers, solar prosumers and solar prosumers with storage. Furthermore, I tested currently discussed alternative grid tariff designs in a System Dynamics simulation model.

The simulation results indicate a strong diffusion of solar prosumers in all simulated scenarios. Storage appears to play a crucial role in the analysis of the cost recovery of distribution grids. Prosumers with storage diffuse widely among the consumer groups. The scenario “volumetric tariff with net purchase and sale” leads to an increase of the volumetric grid tariff caused by self-consumption of 8.4%, with an installed base

of PV of 333 MW in 2050. In the case of the simulated Swiss utility company, conventional grid consumers would pay 12.5 CHF per year more due to the distribution effect. Important to keep in mind is that also initially there are deviations from the cost causation principle, due to differences between the net consumed power and the used grid connection size. Net metering provides stronger incentives for consumers to adopt the prosumer concept, but is less attractive for additional storage installation. Under the net metering policy, a much larger distribution effect arises, reaching a level of 24% in 2050. The differences in results between net metering and the net purchase and sale policy highlight the need for policy specific evaluation of the distribution effect caused by self-consumption. This study contributes to the academic as well as political debate on distributive justice of power grid costs by (a) highlighting this difference and (b) shedding a particular focus on the unbundling system with a net purchase and sales policy.

Alternative grid tariff designs are discussed as potential solutions to resolve the distribution effect and the deviation from cost causation. I tested a flat tariff and a capacity tariff, with and without option for peak reduction through load shifting, for their impact on the diffusion of self-consumption concepts, the distribution effect and deviation from the cost causation principle of the self-consumption concepts. The flat tariff prevents a self-consumption induced increase of the grid tariff, but lowers the attractiveness of self-consumption and hinders diffusion. The PV capacity expansion under the capacity tariff is smaller than under the volumetric tariff, but sets incentives for consumers to invest and adopt a behavior that reduces peak demand, leading to a relatively stronger adoption of the storage prosumer concept. The capacity grid tariff successfully reduces the deviations from the cost causation principle, as consumers pay for the effectively needed connection size. Nevertheless, the capacity tariff still increases due to self-consumption diffusion, as the grid infrastructure already exists and has to be amortized. Therefore, the distribution effect, which considers historic costs, still increases, indicating that conventional grid consumers pay more than they would if there was no diffusion of self-consumption. Considering that consumers can invest in a peak demand optimized behavior, by shifting demand and adjusting the storage management, the distribution effect increases to a level even higher, only slightly lower than under the volumetric grid tariff.

Recommendations for energy policy

Overall, the findings of this study confirm that a distribution effect occurs under the volumetric grid tariff with a net purchase and sale policy, but it is moderate in scope. Therefore, under the net purchase and sale policy, distributive justice should not overly dominate debates. In contrast, the results highlight the importance of the tariff design induced investment incentives for self-consumption. Changes in the attractiveness of the self-consumption concepts have a strong effect on the diffusion of solar prosumers. Governments should not only focus on keeping the distribution effect in a tolerable range, but put an emphasis on whether the grid tariff design incentivizes an efficient and sustainable development of the power system. A capacity-based tariff sets incentives in the right direction of reducing peak demand, but also causes a distribution effect. When considering a shift in the tariff design, the costs and benefits should be weighted carefully.

It is worth noting, that the overall benefit of solar power arises on a societal level by avoiding negative external costs of fossil fuels (Krewitt, 2002). Generally, contributions to a renewable energy provision should be compensated in an appropriate manner on the power side and contributions to an efficient use of grid infrastructure should be rewarded on the grid side. Concerning future grid expansions is efficient to use the locally generated power on site, or in the same grid level, to reduce the need for grid expansions. Current tariff designs and policies only consider the building level for self-consumption, but do not allow and incentivize self-consumption within a grid level. In a future energy system, with larger penetration of decentralized energy generation on lower levels of the grid, grid costs may consider which grid levels were needed to transmit and distribute the power to the consumer by considering the origin of the power. Enabling this would require a change of the current structure of the cost allocation of power grids. Currently, a top-down cost roll, from generation on the highest levels of the grid to consumers on the lower levels of the grid, is applied. As we expect increasing bi-directional flow of power in future, a system that considers how intense the separate grid levels are used would be desirable for cost efficient grid development. Obviously, transitioning to this system requires major changes and takes time. However, a grid level specific tariff based on intensity of usage of the grid level would set the right incentives to ensure optimal use of local resources and incentivize efficient future grid expansions.

Decentral generation and storage plants could, for instance, be used for flexibility provision at the distribution grid level instead of self-consumption optimization on a building scale.

Furthermore, as built grid connections remain for decades, it is important to support including decentral energy generation with low peak demand right when new buildings are constructed. In this manner, the expansion of the grid infrastructure can be reduced, resulting in cost savings.

Limitations and further research

Estimating the caused costs of a consumer is a particularly delicate task. I here assumed the effectively used connection size as the determinant. Defining the caused costs by the effectively needed capacity implies that a change of a grid consumer to a storage prosumer concept, which effectively reduces peak demand, would also reduce the caused costs. In practice, this would require reducing the connection size, which would cause extra costs. Furthermore, in reality, the caused costs depend on the impacts on the entire grid infrastructure. For a more accurate measurement, a technical simulation of every individual consumer based on the caused marginal costs in the particular grid setting would be required. Calculating the effectively caused costs on the grid with a Reference Network Model, as it was conducted by Picciariello et al. (2015), is beyond the scope of this study. Nevertheless, what defines the “true” costs of a consumer is subject to a controversial debate. For instance, one could argue that the historically caused costs should be considered in the measure of cost causation as well. Literature on economic regulation in fact already stated earlier that the “true” costs of a customer cannot be determined unambiguously in a system with economies of scale (e.g. Kes-sides et al., 1995).

The simulation model defines the self-consumption concepts by a fixed technology constellation in installed capacity and type. However, realistically these constellations are adjusted with changes in technology prices and incentives. Additionally, in future, district solutions – such as microgrids or district prosumer communities or district batteries – will play a crucial role. Further research should target both aspects, by building an endogenous model structure enabling the dynamic adjustment of the self-consumption concepts and include district solutions.

Acknowledgement

This research was conducted as part of the national research program of the Swiss Competence Center for Energy Research – Center for Research on Economy, Society and Transition (SCCER CREST, grant number: KTI.2014.0114) in a collaboration with BKW Energie AG. I gratefully acknowledge the financing by the Swiss Commission of Technology and Innovation and BKW Energie AG. My thanks go to Frederik Schneider for the fruitful project collaboration and to Dr. Silvia Ulli-Beer for her guidance in the project, the numerous discussions and her valuable feedback. My thanks also go to Prof. Dr. Rolf Wüstenhagen for his detailed feedback that helped to improve the clarity and quality of this paper. I am grateful for the comments by an anonymous reviewer of Energy Policy, who helped to sharpen the focus of the manuscript and make it better understandable for a wider audience. Furthermore, I am honored to be awarded with the best student paper for this work at the European conference of the International Association of Energy Economics in Vienna in 2017.

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Appendix

Appendix A. General Simulation settings

The model was implemented in the Software Vensim DSS, Version 6.4E. Model settings are described in Table 5.

Initial time	2009
Final time	2050
Time step	0.0078125
Units for Time	Year
Integration Type	Euler

Table 5: Model settings in Vensim

The simulations and optimizations were executed on a DELL Latitude E7270 laptop. No significant computing costs are needed. The simulation and optimization time are below one minute.

Exogenous data was imported through CIN files, to allow easy exchange of the data sets for the different simulated regions.

Appendix B. Data inputs

Table 6 lists the used notations for the variables and data inputs applied.

Abbreviation	Subscript elements	Subscript
c	Grid consumer = gc, Prosumer = p, Storage prosumer = sp; Reference concept = rc; economic investors = ei; green investors = gi	consumption concept
d	Prosumer, storage prosumer, storage installation; competing decision option = dc	decision option
i	single-family house = SFH, multi-family house = MFH, commercial consumer = CC	consumer groups
Abbreviation	Variable	Value
	Population [people]	824'054
$C_{c=gc; i=SFH}$	Grid consumers, single-family houses, initial [houses]	166'600
$C_{i=gc; i=MFH}$	Grid consumers, multi-family houses, initial [houses]	23'280
$C_{c=gc; i=CC}$	Grid consumers, commercial consumers, initial [houses]	8'206
$C_{c=p; i}$	Prosumers (SFH, MFH and CC), initial [houses]	0
$C_{c=sp; i}$	Storage prosumers, (SFH, MFH and CC), initial [houses]	0
	Total PV potential [kW]	535'100
$TPPV_{i=SFH}$	PV potential, single-family houses [kW]	308'200

$TPPV_{i=MFH}$	PV potential, multi-family houses [kW]	100'600
$TPPV_{i=CC}$	PV potential, commercial customers [kW]	126'300
c_{PV}	installed capacity of PV per concept [kW]	Table 2
sr	share of roofs suitable for PV [dimensionless = dmnl]	0.32
p_e	Power price (from 2017 on, before historical data) [CHF/kWh]	0.09
t	taxes on electricity [CHF/kWh]	0.015
GC	Total grid costs, initial (historical data until 2016) [CHF/a]	217'354'163
	Annual growth of total grid costs (for 2017 and later) [dmnl]	0.03
p_{PV}	Price for PV power [CHF/kWh]	0.1478
IT	investment costs [CHF/kW]	Longitudinal data
G	investment grant (governmental policy) [CHF/kW]	Longitudinal data
M	Costs for measuring infrastructure [CHF/a]	664.2
$atb_{i=SFH}$	base adjustment time, single-family house [years]	3.26246
$atb_{i=MFH}$	base adjustment time, multiple-family house [years]	5.43202
$atb_{i=CC}$	base adjustment time, commercial consumer [years]	0.939081
β	beta of the logit model [dmnl]	4.74309
$ec_{i=MFH}$	additional coordination effort needed to form a self-consumption community [dmnl]	1.2
bi	base share of investors [dmnl]	0.57
$sei_{i=SFH, MFH}$	share of investors deciding on the basis of economic criteria, SFH and MFH [dmnl]	0.69
$sei_{i=CC}$	share of investors deciding on the basis of economic criteria, CC [dmnl]	1
pe	peer effect [dmnl]	0.0469
aec	annual total power consumption [kWh/a]	Table 2
scg	share of consumption from the grid [dmnl]	Table 2
sx	share excess power [dmnl]	Table 2
mc	peak demand [kW]	Table 2
tl_{PV}	technology lifetime, PV [years]	35
$tl_{battery}$	technology lifetime, battery [years]	20
s_{gt}	share of the total grid costs that shall be covered by the respective grid tariff [dmnl]	scenario variable
Non-linear functions		
f_{iv}	function of investment volume	Figure 2
f_{pp}	function of tolerance for payback period	Figure 3
f_{ss}	function effect from self-sufficiency	Figure 4
f_{se}	function of the scarcity effect	Figure 11
f_{tl}	function effect from technology life time	Equation 10

Auxillary variables		
C	Consumers	endogenous
ar	adoption rate	endogenous
at	adjustment times of adoption for the decision options [years]	endogenous
$NC_{c=rc}$	non-adopters in the reference concept [houses]	endogenous
sp_d	shares of preferences for the different decision options [dmnl]	endogenous
pr	probability of the investor roof match [dmnl]	endogenous
PPV	consumers with a PV plant [houses]	endogenous
$TC_{c=rc}$	total consumer in the reference concept ever [houses]	endogenous
u_d	perceived utility of the decision option [dmnl]	endogenous
$u_{d=dc}$	perceived utility of the competing decision option [dmnl]	endogenous
uei	perceived utility by economic investors [dmnl]	endogenous
ugi	perceived utility by green investors [dmnl]	endogenous
se	scarcity effect [dmnl]	endogenous
PPP	perceived payback period [years]	endogenous
PP	payback period [years]	endogenous
I	total investment volume [CHF]	endogenous
aCF	annual cash flow [CHF/a]	endogenous
ie	income from power sales [CHF/a]	endogenous
eb	power bill [CHF/a]	endogenous
gb	grid usage bill [CHF/a]	endogenous
oc	operating costs [CHF/a]	endogenous
ge	generated power from the self-consumption concept [kWh/a]	endogenous
p_{retail}	retail power price [CHF/kWh]	endogenous
gt_{vol}	volumetric grid tariff [CHF/kWh]	endogenous
gt_{flat}	flat rate grid tariff [CHF/connection]	endogenous
gt_{cap}	capacity grid tariff [CHF/kW]	endogenous
gt_{con}	connection size grid tariff [CHF/kW]	endogenous
AND	annual net demand [kWh/a]	endogenous
t_{pob}	trigger for peak optimized behavior [dmnl]	endogenous

Table 6: List of notations and data inputs

The function of the scarcity effect (f_{se}) looks as described in Figure 11.

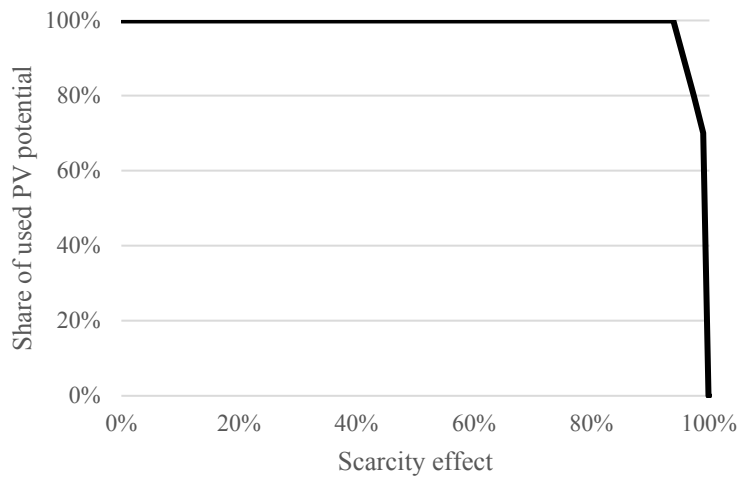


Figure 11: Function of the scarcity effect (f_{es})

Appendix C. Optimization settings to determine atb_i and β

The applied optimization settings for the Vensim optimize function are presented in Table 7.

Calibration type	Policy
Payoff Variable	R2 overall [maximize; weight 1]
Timing	Final
Optimizer	Powell
Random Type	Default
Maximum Simulations	1000
Optimization parameters	AT base[single-family house] AT base[multi-family house] AT base[industry] beta
Model Settings: Initial Time	2009
Model Settings: Final Time	2016 (Swiss cases: BKW, Frutigen, Wohlen, Ostermundigen) 2015 (Bavaria)

Table 7: Optimization settings

The payoff variable «R2 overall» was implemented into the model structure, determining the R^2 of the historical data of the number of prosumers in each consumer group and the simulated data.

To avoid optimization results origin from local optima, which are not realistic an iterative approach as applied. Constraints were set to reach values for atb_i between 0 and 50; and for β between 0 and 20. I assumed that adjustment times longer than 50 years are not realistic. Furthermore, a β of more than 20 leads to overly extreme switches of the logit function, which are not considered a realistic representation of investor decision making either. In case optimization results appear that showed values for the optimization parameter exactly the same as the constraints values, then the constraints were narrowed until “free” values were received. Afterwards the results were used as initial values for a last optimization run with the original constraints to retrieve the desired optima in the realistic sphere. Initial values and results are presented in Table 8.

	BKW	Frutigen	Wohlen	Oster- mundigen	Bavaria
Initial values					
AT base[single-family house]	3.10951	1	6.41983	15.7564	1
AT base[multi-family house]	4.96525	1	11.5474	48.1234	1
AT base[industry]	1.06982	1	2.21999	4.2768	1
beta	3.3988	1	6.0042	13.0528	-- ¹
Optimization results					
AT base[single-family house]	3.26246	2.85874	5.977	15.7564	0.967126
AT base[multi-family house]	5.43202	0.912162	11.5645	48.1234	1.05663
AT base[industry]	0.939081	1.85872	2.46112	4.2768	0.954974
beta	4.74309	6.20507	6.02995	13.0528	-- ¹

Table 8: Optimization initial values and results

¹ In the case of Bavaria no stable optima were found in the sphere defined as realistic, when the beta was part of the optimization. Therefore, the beta value was set fixed to the assumed value of 5.

Paper III

The flexible prosumer: Measuring the willingness to co-create distributed flexibility

Merla Kubli, Moritz Loock, Rolf Wüstenhagen

Abstract

Rising shares of fluctuating renewables increase the need for flexibility in the power market. At the same time, the emergence of the prosumer has created new opportunities for co-creation of distributed flexibility. As of yet, there is surprisingly little empirical analysis in terms of whether individuals are actually ready to co-create flexibility, and if so, under which conditions these resources can be mobilized by grid operators or electricity supply companies. We address this gap in the energy economics literature with three studies analyzing in total 7'216 individual decisions in a series of choice experiments with 902 study participants in three main domains of residential energy prosumption: (1) solar PV plus storage, (2) electric mobility, (3) heat pumps. We develop a novel measure of the prosumers' willingness to co-create flexibility, and solicit their preferences for power supply contracts with varying levels of flexibility to derive implied discomfort costs. Our results indicate that current and potential electric car and solar PV users exhibit a higher willingness to co-create flexibility than heat pump users. Reaping the potential in those two domains requires taking the prosumer perspective into account when designing policy instruments and creating adequate business models.

Keywords: solar photovoltaics, battery storage, vehicle-to-grid, consumer behavior, business models, smart grid.

1. Introduction

Matching supply and demand over time is a key challenge in power markets. In traditional electricity markets, demand has largely been taken for granted, while the necessary flexibility has been built into the supply side through peak power plants and centralized storage. Increasing shares of fluctuating renewable energies have enhanced the need for flexibility to avoid imbalances in the power system. Established and new companies develop novel business models to provide flexibility (Helms et al., 2016). Decentralization trends in the energy market offer new opportunities for matching supply and demand in a distributed manner. Distributed flexibility provision can take different forms: Shifting demand and supply over time and/or building up local storage capacity. Successfully mobilizing flexibility in distribution grids can help to delay or avoid investments in extending centralized grid infrastructure (Gordijn & Akkermans, 2007; Veldman et al., 2013), resulting in cost efficient energy systems and allowing smooth integration of renewables (Denholm & Hand, 2011). While centralized sources of flexibility (e.g. gas-fired power plants or hydropower reservoirs) are well understood, the tendency of decentralized electricity consumers becoming prosumers (producers and consumers at the same time, cf. (Bergman & Eyre, 2011; Kotler, 1986; Toffler, 1980) provides a potentially valuable source of – so far underutilized – flexibility (Gordijn & Akkermans, 2007; Kubli, 2018; Veldman et al., 2013). Decentral prosumers can provide flexibility by optimizing the timing of their electricity production and consumption, and by making decentralized storage available (e.g. through investing in batteries or providing heat reserves through a more flexible heating behavior). A better understanding of whether and under which conditions prosumers are actually ready to contribute to flexibility provision is important if these resources are to be mobilized.

This paper empirically investigates prosumers' willingness to co-create flexibility with a series of studies across three main domains of energy use: (a) solar PV plus storage, (b) electric vehicles, (c) heat pumps. By conducting three choice experiments with a unique sample of actual and potential flexible prosumers in Switzerland (N=902), we aim to answer the following two research questions:

1. To what extent are prosumers willing to co-create flexibility?
2. Are there differences between the three technology domains?

Our paper makes three main contributions to the extant literature on smart grids and flexibility in the power market. First, we answer the call for “putting people in the loop” (e.g. Sowe et al., 2016) and for revealing determinants of social acceptance of smart grids (Wolsink, 2012), by investigating the preferences of end users as important agents in the diffusion of distributed flexibility. Second, we develop an innovative way of operationalizing and measuring the willingness to co-create flexibility. Third, we provide a pilot application of this measurement instrument that can serve as a role model for policymakers and energy companies who seek to effectively engage prosumers.

This paper is structured as follows. In the second section, we discuss existing literature on distributed generation, energy consumer preferences, and the role of prosumers in co-creating flexibility. In the third section, we introduce our methodological approach. Section 4 presents the results of the three studies and a discussion, while section 5 concludes the paper with implications for energy policy and flexibility business model design, as well as a section on limitations and further research.

2. Literature review

2.1. Energy system flexibility and smart grids

As Lund et al. (2015, p. 799) point out, energy system flexibility is “definitely a ‘hot topic’”. Their review of close to 400 academic publications presents a comprehensive overview of all the available options to integrate increasing shares of renewables in the grid, from large-scale centralized to small-scale decentralized, from supply-side to demand-side, and across a range of different time horizons. As another indication of the “hot” nature of this topic, the European Commission under its Horizon 2020 research programme is currently investing 337 million Euros of R&D funding in projects related to accelerating smart grids and storage deployment.¹ While there is an increased understanding of the large technical potential of distributed flexibility, previous attempts to assess the market potential are handicapped by the lack of reasonably fine-grained empirical data (Kondziella & Bruckner, 2016). This is particularly true for the emergence of decentralized battery storage, which could

¹ http://www.h2020-bridge.eu/wp-content/uploads/2017/06/BRIDGE_presentation_EUSEW17.pdf

potentially revolutionize the power market (Agnew & Dargusch, 2015; Ebers & Wüstenhagen, 2015; Kubli, 2018), but are still in a nascent stage of market development. As a result, there is currently a wave of search processes for viable business models to deploy distributed flexibility options like demand response, energy management systems, electricity and thermal storage, and distributed solar photovoltaics (Burger & Luke, 2017). While both the need for and the potential of distributed flexibility options are now widely acknowledged, whether or not business models in this realm will be economically viable ultimately depends on whether they create customer value. This is increasingly understood by policymakers and business model developers, as evidenced for example by the creation of a Working Group on customer engagement in the above-mentioned EU initiative.² The following section contributes to this debate by offering a structured review of starting points for investigating prosumer preferences for flexibility co-creation.

2.2. Consumer preferences for electricity, demand response and the rise of the prosumer

The literature on preferences of energy consumers has gradually evolved from the traditional view of taking demand as given towards including aspects of flexibility and the rise of the prosumer (Figure 1).

² <http://www.h2020-bridge.eu/working-groups/customer-engagement/>

Demand	variable	Demand Response	Flexible Prosumer
	fixed	Conventional Consumer	Conventional Prosumer
		no	yes

Distributed Generation

Figure 1: From conventional consumer preferences towards flexible prosumers

Traditional studies investigating consumer preferences have focused on explaining consumer choice in liberalized electricity markets, determining the role of factors like price and contract duration (Burkhalter et al., 2009). It was found that switching behavior has remained below expectations in many markets, pointing to the nature of electricity as a low involvement product and the strong role of routines and inertia in electricity consumer behavior (Herbes & Friege, 2017). One factor that has been found to be relevant is the electricity mix, in that offering electricity products with a high share of renewables can be a way to overcome customer inertia (Kaenzig et al., 2013; Roe et al., 2001; Tabi et al., 2014). By measuring respondents’ stated preferences, these studies provide insights into consumers’ willingness to pay for changes in the attributes of electricity products.

A second stream of research looks at consumers’ willingness to participate in demand response programmes, i.e. to allow utilities to shift some of their demand in time (Cappers et al., 2010; Torriti et al., 2010), to develop consumer segment-specific product and service offerings (Kaufmann et al., 2013) or to advance detailed understanding of personal traits as drivers of consumer acceptance of smart grids (Gamma, 2016) such as for instance perceived control over appliances (Moser, 2017). A common finding is that consumers request a relatively high financial incentive in order to voluntarily sign up for demand response programmes, and the likelihood of participation increases if required changes in daily routines are minimized (Annala,

2015). Apart from stated preference surveys, there are also some analyses of revealed preferences, for example tracking the behavior of participants in pilot programmes (e.g. Wemyss et al., 2016). A common finding of these studies is that the individual and societal advantages of participating in a demand-response program are not obvious to consumers, unless they actually get a chance to experience what this implies in everyday life (Dütschke & Paetz, 2013). Paterakis et al. (2017, p. 887) even conclude that “the greatest challenge is related to the successful engagement of customers in demand response programs”, illustrating the need for further research on end-user preferences.

A third stream of research, represented by the lower right quadrant in Figure 1, investigates what makes consumers become actively engaged in their energy supply, i.e. to become prosumers. A popular theme here is to explore determinants of homeowners’ decision to install solar photovoltaics on their roof (Curtius et al., 2017; Rai & Robinson, 2013; Sigrin et al., 2015). There is mixed evidence on the role of traditional socio-demographic factors like income, education and environmental awareness (for a review, see Dharshing, 2017, p. p. 115). In contrast, preferences for independence and peer effects have been shown to be effective drivers of installing solar PV (Bollinger & Gillingham, 2012; Dharshing, 2017; Kubli, 2018; Kubli & Ulli-Ber, 2016; Rode & Weber, 2016).

The fourth quadrant in Figure 1 represents the logical combination of quadrants two and three, namely prosumers actively engaging in flexibility provision. Such flexible prosumers go beyond the electricity production activities of conventional prosumers (which for instance, install a solar photovoltaic system on their roof and feed the electricity into the grid). Flexible prosumers in turn co-create flexibility by different means. A well-known example is demand response and the flexible timing of consumption (e.g. through smart appliances, smart heat pumps or smart charging of batteries). However, also the production of electricity can now be flexible, as for instance PV-battery systems allow prosumers to be more flexible in regard to when to feed electricity into the grid. Also novel heating systems facilitate the emergence of flexible prosumers and enable the utilization of heat reserves for ancillary services.³ Empirically, this space is surprisingly uncharted territory, but given the future

³ <http://www.nano-tera.ch/projects/360.php>

importance of flexible prosumers, it is important to close this gap and learn more about what influences prosumers' willingness to co-create flexibility. What would be of particular interest is a quantification of the premium required by prosumers to give up full autonomy, as this implies that the prosumer incurs a cost of discomfort (Good et al., 2015; Pournaras et al., 2014). The next section of our paper outlines the methodological approach to tackle this important question.

3. Methodology and data

Borrowing from previous studies investigating preferences related to consumers' electricity choice, demand response and becoming a prosumer, we investigate prosumers' willingness to co-create flexibility with choice experiments. Choice experiments have been widely applied in energy economics and related fields (Aravena et al., 2016; Chau et al., 2010; Heinzle & Wüstenhagen, 2012; Kaenzig et al., 2013; Lüdeke-Freund & Loock, 2011; Lüthi & Wüstenhagen, 2012; Park et al., 2013; Salm, 2017; Sammer & Wüstenhagen, 2006; Tabi et al., 2014; Tabi & Wüstenhagen, 2017), but for the purposes of the present paper, two important methodological challenges have to be addressed. First, distributed flexibility is a rather complex technological phenomenon, which average electricity customers may be unfamiliar with. Second, the number of flexible prosumers is still somewhat limited. To address the first challenge, we have decided to focus our experimental design on a choice situation that is more familiar to customers, namely the choice of an electricity product. To address the second challenge, the easiest solution would be to wait until the number of prosumers is larger than it is today. This, however, would be unsatisfactory because knowing more about the (emerging) preferences of flexible prosumers at an early point in time can provide valuable information for business model design and energy policy. Our approach here was to carefully craft three subsamples of respondents who can be expected to become early adopters of the concept of flexible prosumers in the respective domain of energy use. The following sections will explain both aspects of our methodological approach in more detail.

3.1. Choice experiments

Choice experiments are a popular method to elicit consumer preferences. They are based on classical random utility theory, assuming that individuals seek to maximize their utility, which can be described as the sum of the part-worth utilities for the different attributes of a choice object (Lancaster, 1966; Louviere et al., 2010). A popular application is the development of new products, where actual purchasing behaviour cannot be observed yet and hence revealed preference data is not available (Hensher et al., 2005). A choice experiment consists of a number of choice tasks, in which respondents have to select their preferred option from a range of choice objects (e.g. products or services), which are described by their most important attributes. Repeating the choice task with varying attribute levels requires respondents to make trade-offs between desired attributes, and hence allows to effectively elicit their underlying preferences. In this study, we use choice-based conjoint (CBC) analysis (Sawtooth, 2017), which is the most widely-applied method in the family of choice experiments. We designed the CBC experiment in an iterative process, which included refining the CBC design in various steps among the three researchers, soliciting feedback from energy experts, and a pretest of the online questionnaire. The final CBC design is discussed in detail in section 3.2.

The respondents of the three studies received an online questionnaire with 8 choice tasks where they are asked to select their most preferred power supply contract. The number of required choice tasks were defined based on Sawtooth (2009b). The choice tasks are a randomized constellation of the defined attribute levels (see Table 1 and Table 2). No adaptation of the constellations is made based on the previous selections of the respondents.

To derive part-worth utilities and attribute importances, we use Hierarchical Bayes (HB) estimation. Estimation based on HB is one of the standard procedures for CBC studies, and is reported to reach superior hit rates of individual choices and higher choice share validations compared to alternative estimation approaches (Moore, 2004; Orme, 2000; Sawtooth, 2009a). For validation purposes, we compared the estimation results based on HB with logit estimations. As the estimated coefficients showed no important differences, similar as in model comparisons of previous research (Wuebker

et al., 2015), we did not include the results of the logit model in the paper. The data is available on request from the authors and has been presented to the reviewers.

3.2. Experimental design

Choice experiments in the area of new product development have to strike a balance between realistically mirroring the possible features of the (future) product and not overstressing the respondents' imagination. While smart grids and distributed resources are a hot topic in expert circles, these issues are not very familiar to the average electricity consumer as mass market-diffusion is yet to come. And yet, it is the final consumer who is the ultimate bottleneck in the adoption of distributed flexibility. We solved this issue by embedding our object of interest, the flexibility option, in a choice context that is familiar to respondents, namely choosing between different electricity tariffs. The rationality here is that even solar prosumers with storage will usually not strive for full autarky, as it is in most cases more economical to stay connected to the electricity grid so that backup power can be acquired in times where consumption exceeds own production. Hence we explained to respondents that what they are choosing from is the supply contract for their residual electricity needs. Table 1 shows the overarching design of the choice task for all three studies. The electricity offering is described by four attributes with four levels each, and each respondent had to complete eight choice tasks.

Attributes	Levels			
Power costs per month	110 CHF ⁴	90 CHF	70 CHF	50 CHF
Use of flexibility	Super Flex*	Flex Medium*	Flex Light*	No Flex*
Power mix	100% uncertified grey power	100% nuclear power	100% hydro power	100% solar power
Contract duration	4 years	2 years	1 year	Can be cancelled anytime

Table 1: Attributes that describe the power contract including flexibility provision

**) For details of the flexibility attribute for the three studies, see Table 2 below*

Apart from the usual attributes of electricity contracts like monthly power cost, electricity mix and contract duration, which we adapted from Burkhalter et al. (2009) and Kaenzig et al. (2013), these choice tasks included a flexibility option with four levels, which are described in more detail below. The general idea is that a contract with this option allows the supplier to intervene in the prosumers' normal demand pattern to mobilize distributed flexibility, implying that the customer gives up some autonomy and control over her infrastructure.

The ideal-type flexible prosumer would be characterised by high electricity consumption, distributed generation, and local storage, which enables fast and high-capacity buffering between production and consumption. In order to bring our experimental design as close as possible to real decision-making and to answer our second research question, we surveyed specific subsamples in three domains and adapted the flexibility attribute levels in the choice task correspondingly. The closest approximation to such ideal-type flexible prosumers which already operate on today's energy markets are owners of PV-battery systems, electric vehicles and heat pumps. Consequently, these are the target groups for our empirical analysis:

⁴ 1 CHF = 0.86 EUR = 1.01 USD (as of December 17, 2017)

1) Owners of PV plus battery systems, who can offer flexibility by storing local generation and allowing the utility to access the battery

2) Electric vehicle owners, where flexibility is related to shifting charging times and accessing the battery when the vehicle is connected to the grid

3) Heat pump owners, where flexibility is provided by load shifting of the heat pump operation, making use of the thermal storage capacity of the building

It is important to note that energy companies and prosumers have opposing interests when it comes to the provision of flexibility. From the utilities' point of view, these options increase their flexibility in matching demand and supply. From the prosumers' point of view, in contrast, accepting the flexibility option implies a discomfort. By adopting four levels, from "No Flex" to "Super Flex", our experimental design mirrors the continuum between a contract design that maximizes the degrees of freedom for the supplier and one that minimizes the discomfort for the prosumer, as displayed in Figure 2. As our choice experiments measure the prosumers' preferences, we expect increasing levels of flexibility to translate into decreasing part-worth utilities of this attribute, reflecting a rising cost of discomfort.

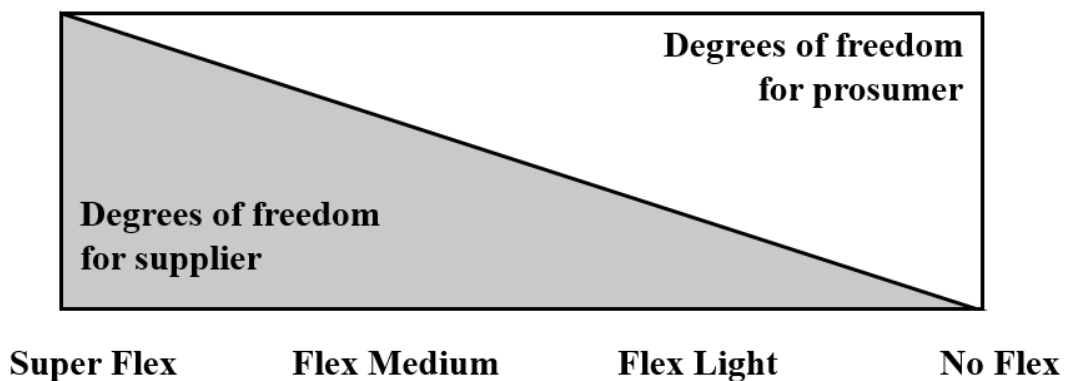


Figure 2: Flexibility attribute and the trade-off between supplier and prosumer freedom

The specific levels of the flexibility attribute for each of the three technology domains are presented in Table 2. In line with our objective to measure prosumer (rather than supplier) preferences, these levels are described in terms of the degrees of discomfort that they imply for the customer.

3.2.1. Study 1 – PV plus battery

We assume that in the absence of a flexibility option, the solar prosumer would run the system to maximize self-consumption and have full control over its production and consumption data. By allowing the utility to intervene and operate the battery according to its flexibility needs, the prosumer faces two inconveniences: a decreasing share of self-consumption (Santos et al., 2014), and granting the utility data access. The levels of the flexibility attribute describe different shades of those aspects. From No Flex to Super Flex, the self-consumption rate decreases from 75% to 30% (Weniger et al., 2014). In terms of data use, the levels increase from no data access to transmission of consumption data that is used for forecasting, reflecting potential privacy concerns (Efthymiou & Kalogridis, 2010).

3.2.2. Study 2 – Electric vehicles

In the “No Flex” scenario, the user has full control over the charging level of her EV battery. With increasing levels of the flexibility attribute, the EV owner will face two inconvenient consequences: A car that is not fully charged when she wants to use it, and increased wear and tear of the battery due to additional discharging cycles caused by the utility. In the Super Flex scenario, only 40% charging level is guaranteed, implying a significant discomfort if the car does not have sufficient range for certain trips, and an unlimited number of discharging cycles per day may occur, implying lower battery lifetime.

3.2.3. Study 3 – Heat pumps

In contrast to a “No Flex” scenario, increasing levels of the flexibility attribute imply constraints on the provision of heating and warm water, which allows the utility to react to temporary shortages in electricity supply. To express those inconveniences in terms that are familiar to respondents, we operationalized this as deviations from a desired room temperature, set at 22° Celsius,⁵ and constraints in the duration of hot showers per day. At the “Super Flex” level, only a room temperature of 16° Celsius was

⁵ Note that the survey was done in a Northern hemisphere context, where it is reasonable to assume that higher (rather than lower) room temperatures are positively correlated with comfort. To validate this assumption, the questionnaire included a separate question on preferred room temperature, which confirmed our baseline of 22° Celsius.

guaranteed, and hot showers could be limited to five minutes per day. The other levels of the flexibility attribute gradually released those constraints.

Technology domain	Levels of the attribute “Use of flexibility”			
Study 1: PV+battery	Super Flex 30% PV Self-Consumption; consumption data transmitted and used for forecasting	Flex Medium 45% PV Self-Consumption; consumption data transmitted	Flex Light 60% PV Self-Consumption; only data on battery charging level transmitted	No Flex 75% PV Self-Consumption; no data transmitted
Study 2: Electric vehicles	Super Flex Guaranteed charging level 40%; Unlimited amount of discharging cycles per 24 h	Flex Medium Guaranteed charging level 60%; max. 3 discharging cycles per 24 h	Flex Light Guaranteed charging level 80%; max. 1 discharging cycle per 24 h	No Flex No access to battery for the utility
Study 3: Heat pumps	Super Flex Guaranteed room temperature 16°; 5 min. hot shower per day	Flex Medium Guaranteed room temperature 18°; 10 min. hot shower per day	Flex Light Guaranteed room temperature 20°; 15 min. hot shower per day	No Flex Guaranteed room temperature 22°; Unlimited hot shower per day

Table 2: Levels of the attribute “Use of flexibility” in the three technology domains

In choosing the specific levels of the flexibility attribute, we considered prosumer, supplier and technological perspectives. We wanted to make sure that the levels spanned a spectrum of feasible options in each domain, while also including levels that would stretch the prosumers’ comfort zone. At the same time, we attempted to

design the experiment in a way that would represent similar amounts of flexibility across the three domains.⁶

3.3. Sample

Our total sample consists of 902 respondents in German-speaking Switzerland, conducting eight choice tasks each, resulting in a total dataset of 7'216 experimental decisions. Respondents were recruited through the consumer panel of a leading Swiss market research agency⁷ in December 2016. The sample consisted of three subsamples, one for each technology domain, with N=300 to 301 each. The target population were actual or potential prosumers, split up in three technology domains: PV plus batteries⁸, electric vehicles and heat pumps. A screening question was used to make sure that every respondent either owned one of these devices or intended to buy one in the next three years. If respondents owned (or were interested in buying) more than one of the systems, they were assigned to the group that had the lower response rate until the three samples reached similar size. As Table 3 in the appendix shows, between one third and half of the respondents in any particular domain were also interested in the other technologies, supporting our conjecture that we selected the technologies that will form important cornerstones for the rise of the flexible prosumer. Table 4 in the appendix presents the socio-demographic characteristics of the three subsamples.

4. Results and discussion

In the following, we report the results of the three studies along two main factors: the relative importances of the attributes and the part-worth utilities for attribute levels. Subsequently, we conduct a qualitative comparison of the three studies based on the willingness to co-create flexibility.

⁶ We estimated the amount of flexibility provided per day assuming a 10 kW PV system and 10 kWh battery storage in the solar case, a 40 kWh battery in the electric vehicle case, and a heat pump with a daily consumption of 20 kWh, and applied domain-specific availability factors, reflecting, for example, the fact that electric vehicles, in contrast to stationary PV-battery systems, are not connected to the grid all the time.

⁷ <https://www.intervista.ch/panel/?lang=en> - The overall panel includes nearly 70'000 consumers.

⁸ The monthly electricity cost for this subsample includes the cost of battery leasing.

4.1. Study 1 – PV and Batteries

In Figure 3a, we present the relative importances of the attributes for study 1 addressing the domain of energy use of PV and batteries. The relative importance describes the weight of an attribute in the average respondent's decision. Importances sum up to 100% over the four attributes included in our choice experiment. The part-worth utilities for individual attribute levels are presented in Figure 3b. They can be interpreted as the change in average respondents' preference relative to the average level of a given attribute, *ceteris paribus*. Positive values indicate increasing utility, negative values express decreasing utility. The ideal product would combine no flexibility, a green electricity mix, and the possibility to cancel anytime with the lowest power costs of 50 CHF per month, and the part-worth utilities indicate under which conditions respondents' would accept less desired attribute levels.

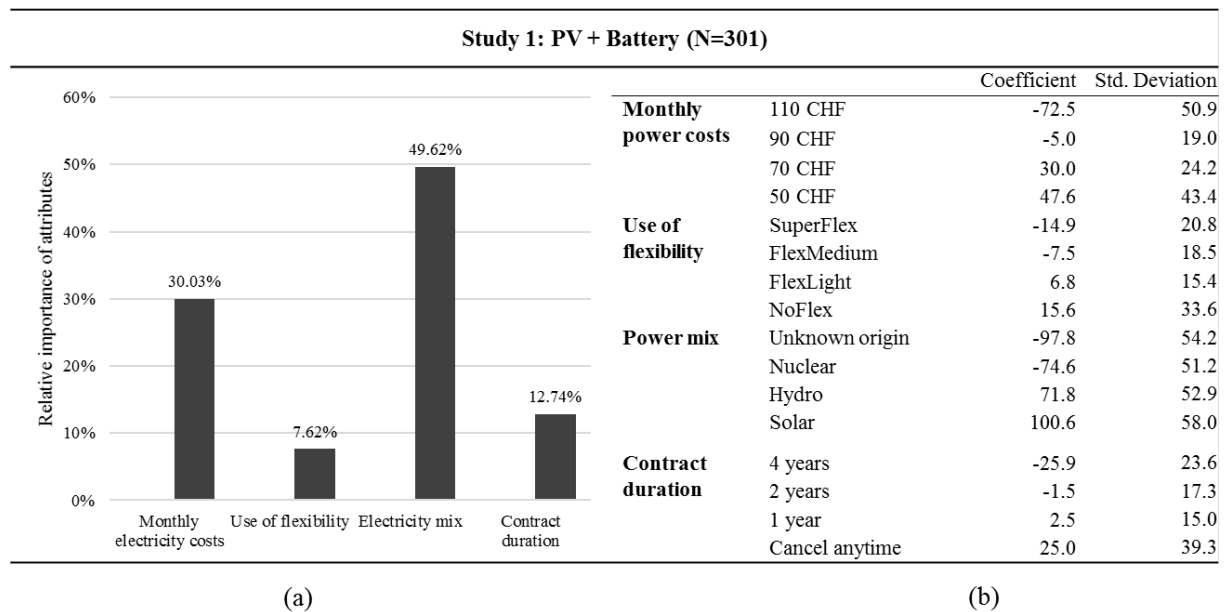


Figure 3: Importances and part-worth utilities of study 1: PV and battery

Respondents of study 1 put the highest importance on the attribute “power mix”, when deciding for a power supply contract. The flexibility attribute in contrast received the lowest importance, indicating that respondents do not react particularly sensitively to the discomfort that would be implied by providing flexibility with the battery.

4.2. Study 2 – Electric vehicles

Figure 4 displays the results from study 2 focussing on providing flexibility with electric vehicles.

While the EV respondents also exhibit relatively low sensitivity for the flexibility attribute, it is remarkable to observe the concave function of the part-worth utilities for different levels of the flexibility attribute, suggesting that the acceptability of flexibility options shows a sharp drop if guaranteed charging levels decline below 60% of a full charge.

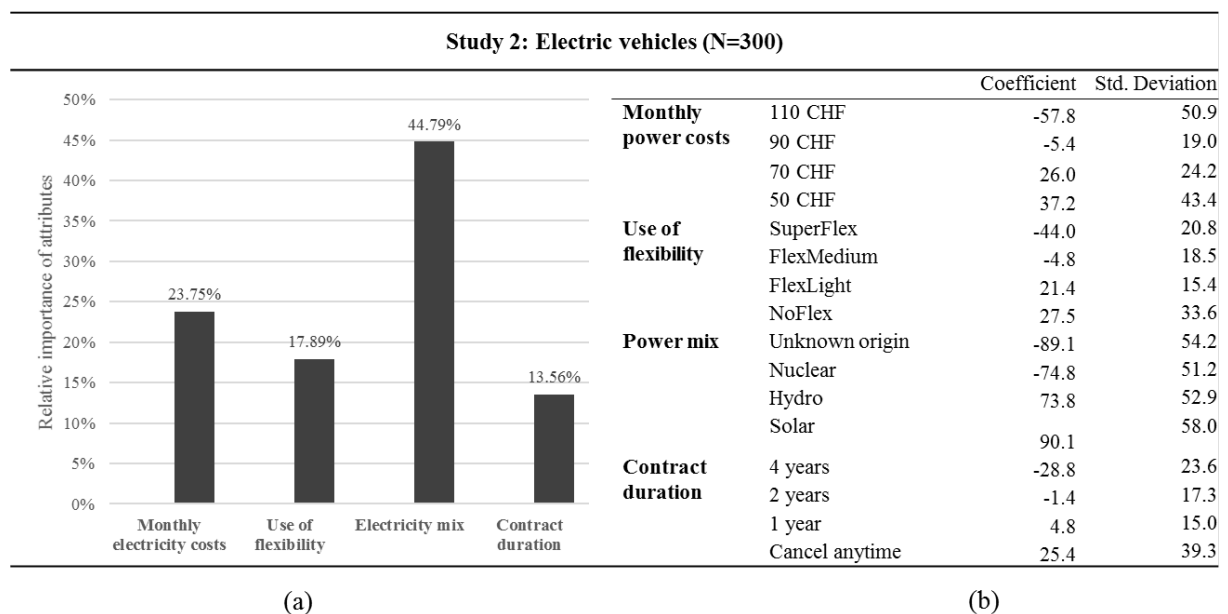


Figure 4: Importances and part-worth utilities of study 2: Electric vehicles

4.3. Study 3 – Heat Pumps

Figure 5 highlights the findings for study 3 which surveyed actual and potential heat pump customers. Unlike in the other two studies, the attribute “use of flexibility” is the most important attribute for this subsample. This indicates that heat pump customers are very sensitive to changes in levels of this attribute.

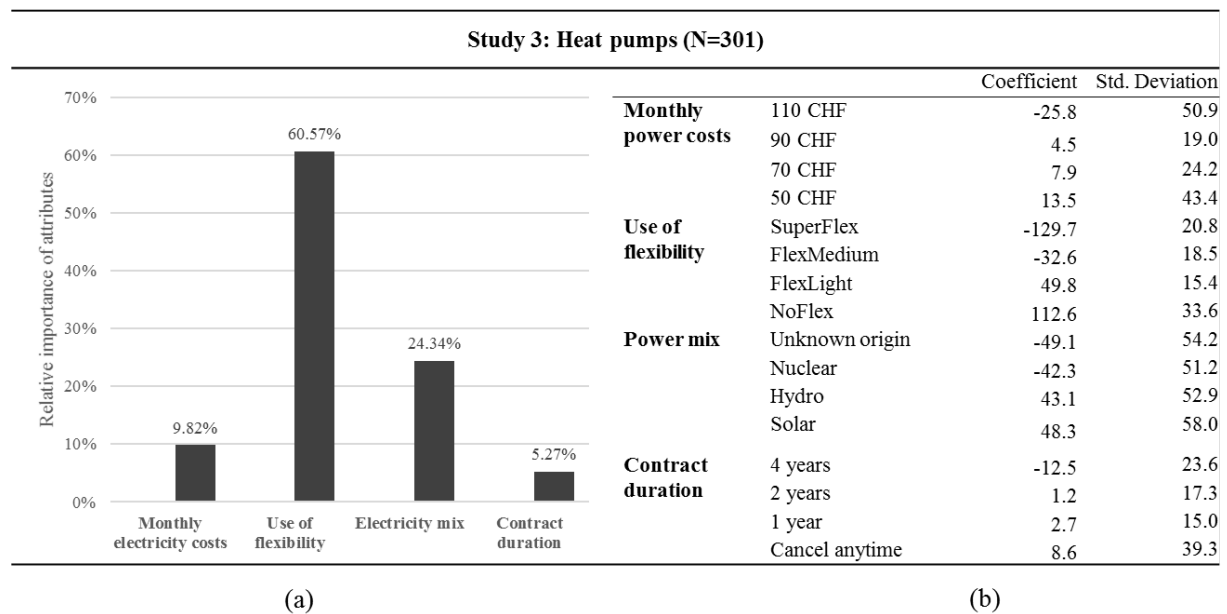


Figure 5: Importances and part-worth utilities of study 3 - Heat pumps Qualitative comparison across Studies

4.4. Qualitative comparison across studies

The design of the three studies was defined in a manner that providing flexibility implies critical trade-offs for the respondents. At the same time, the attributes were set so that a similar amount of flexibility is provided with the attribute levels across the three studies. We therefore aim for a qualitative comparison across the three studies.

As can be seen from Figure 3 and Figure 4, the PV and EV studies show a similar ranking of attribute importances, with electricity mix and monthly cost being the two most important attributes. The attribute use of flexibility is comparatively less important for these respondents, and even the least important attribute in the PV plus battery study. Given our operationalization of flexibility as reflecting varying levels of discomfort, this suggests that current and potential PV plus battery owners perceive the lowest level of inconvenience from the flexibility options included in the experiment. Quite to the contrary, as can be seen in Figure 5, flexibility is by far the most important attribute for the heat pump owners, followed by electricity mix and monthly cost. Across all studies, the importance of contract duration is rather limited, suggesting that – all else being equal – respondents prefer shorter contract duration, but this preference is relatively weak compared to the other attributes.

Apart from the differences in importances discussed above, the preference order within attributes is remarkably consistent across the three studies. For example, when it comes to the attribute *electricity mix*, owners of EV, PV and heat pumps all prefer renewable energies like solar and hydro over nuclear power or electricity of unknown origin.

Finally, we can also express the results of the flexibility attribute in monetary terms, as a willingness-to-accept the discomfort of sharing control over one's energy use. We calculate this required flexibility premium with a fixed cost coefficient and on the basis of average preference levels (Sillano & Ortúzar, 2005), by dividing mean-centered utilities by the monetary coefficient of the monthly power costs (MC). We applied the following definitions:

$$WTCC = \frac{\beta_{flex,max} - \beta_{flex,j}}{MC} \quad (1)$$

$$MC = \frac{\beta_{pc,max} - \beta_{pc,min}}{PC_{max} - PC_{min}} \quad (2)$$

where $\beta_{flex,j}$ represents the part-worth utility value of the flexibility attribute at level j and $\beta_{flex,max}$ indicates the highest part-worth utility value within the flexibility attribute (corresponding to the “no flex” option in all three studies). MC is the linear monetary coefficient, which is the ratio of the minimum and maximum values of the part-worth utilities of the attribute “monthly power cost” ($\beta_{pc,max} - \beta_{pc,min}$) to the levels of that same attribute ($PC_{max} - PC_{min}$). Using study 1 (PV+battery) as an example, respondents would ask for 4.40 CHF to shift from the NoFlex option to FlexLight⁹. As *Figure 5* shows, the implicit discomfort cost ranges from 3.85 to 45.16 CHF per month for electric vehicle users and 4.40 to 15.24 CHF per month in the PV plus battery case. Especially for the LightFlex and MediumFlex levels, moderate discounts on the electricity bill would allow utilities to access affordable flexibility. In

⁹ This is calculated using the part-worth utilities from *Figure 3*. $MC = (\beta_{pc,max} - \beta_{pc,min}) / (PC_{max} - PC_{min}) = 47.6 - (-72.5) / (110 \text{ CHF} - 50 \text{ CHF}) = 120.1 / 60 \text{ CHF} = 2.00167 \text{ CHF}^{-1}$. $WTCC_{FlexLight/NoFlex} = (\beta_{flex,j} - \beta_{flex,max}) / MC = ((15.6 - 6.8) / 2.00167) \text{ CHF} = 4.40 \text{ CHF}$.

contrast, the implicit discomfort cost for actual and potential heat pump owners is prohibitively high, exceeding the average monthly power cost in all cases except for the NoFlex scenario.

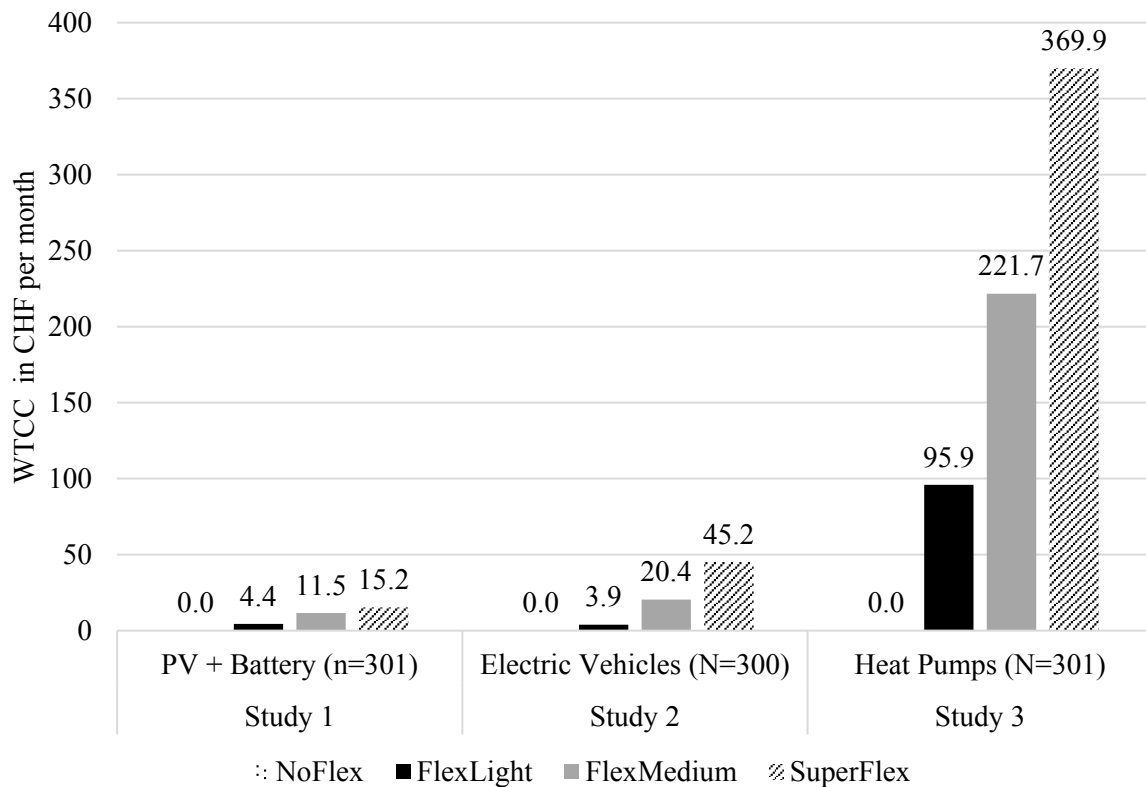


Figure 6: Implicit Discomfort Cost (Willingness-to-Co-Create) for Flexibility

5. Conclusion and implications for energy policy

Increasing shares of renewable energies create new challenges for balancing supply and demand, but in combination with the rise of the prosumer, they also offer opportunities for providing distributed flexibility. In this paper, we have emphasized the important role of the prosumer in co-creating flexibility. By conducting a series of choice experiments with 902 actual and potential flexible prosumers across three domains of energy use, we confirm that there is actually a positive willingness to co-create flexibility. It is important to note that prosumers do not prefer flexibility per se, but they are willing to accept certain levels of inconvenience in exchange for higher utility through other product attributes, e.g. a cheaper or greener electricity tariff. In our experimental setting, we also find differences between the three domains, in that

prosumers with PV plus battery systems and electric vehicle owners appear to be more willing to provide flexibility than heat pump owners. This suggests that even similar levels of technical flexibility provision may result in different reactions by prosumer, based on domain-specific discomfort cost. Apart from the specific use context, the way in which the consequences of flexibility provision are being framed may also influence prosumers' willingness to co-create distributed flexibility. For example, describing the consequences of flexibility provision in the heat pump sample as influencing room temperature and hence being closely linked to personal comfort levels may have emphasized the inconvenience in more concrete terms than the reduced charging levels of the car battery in the EV sample.

To our knowledge, this is the first study that systematically investigates consumers' willingness to co-create flexibility across three domains of energy use. The paper highlights novel opportunities to advance the search processes for smart grid solutions and flexibility business models by putting "humans in the loop". The paper provides for instance data and insights for more accurate energy system modeling based on consumers' willingness to co-create flexibility. Optimization and simulation models in the energy domain often operate based on static models of human agency, whereas accuracy of energy system modeling can be increased by considering empirical insights on consumer decision making (Eichler et al., 2016; Kubli, 2018).

In terms of *implications for energy policy*, this paper confirms that there is indeed significant potential for distributed flexibility if prosumers' preferences are successfully addressed. Policymakers looking for ways of integrating high shares of renewables can therefore be encouraged to look beyond centralized solutions for the provision of flexibility (e.g. capacity markets for large power plants). Our study helps to take the prosumer perspective into account when designing policy instruments for distributed flexibility provision. Our findings also highlight the importance of prosumer heterogeneity across different domains of energy use, indicating that there may not be a one-size-fits-all solution to incentivizing the emergence of distributed flexibility provision. We would caution, though, that drawing policy conclusions from the latter insight is a non-trivial task: For example, sticking to opt-in models of flexibility provision, where consumers voluntarily decide whether or not they want to offer

flexibility, would maximize consumer choice, but may at the same time be an obstacle towards maximizing the system benefits of distributed flexibility.

In terms of *implications for energy business model design*, our study provides three main insights. First, energy companies looking for low-hanging fruit in terms of mobilizing distributed flexibility resources may be well advised to target prosumers with PV plus batteries and drivers of electric vehicles. Heat pump owners, in contrast, appear to be more reluctant to provide flexibility, at least if it has the kind of direct impact on their personal comfort that our study design implied. Hence acquiring distributed flexibility is more costly in some domains than others. Second, another way of looking at the higher willingness to provide flexibility among EV drivers and solar prosumers is that they might be less opposed to more automated modes of flexibility provision, such as the “smart camouflage” business model described by Curtius et al. (2012, p. 70 f.). Third, our findings also suggest that prosumers expect to be compensated for the cost of discomfort that providing flexibility implies for them. Such compensation can take the form of lower monthly electricity bills, but also higher levels of other desirable product attributes, like the share of renewables in the electricity mix.

As an early contribution to an emerging research stream, our study is subject to *limitations* that can be the starting point for *further research* in this important domain. First, our study highlights the importance of taking a contingent view on the potential that flexible prosumers offer. Such a contingency perspective argues that the potential contribution of flexible prosumers to the power system can only be assessed by looking at the distinct specifics in which the flexible prosumer operates. While naturally it is important to consider features of the technological set-up (e.g. the capacity of the batteries or heat-pumps and the infrastructure, including specifics of charging systems or heating system configurations) our study shows how important also behavioral aspects are. Flexible prosumers differ considerably in how much they are willing to provide flexibility. It is an urgent need for future studies to consider and control for this important insight. The model that emerges from our study is that the flexibility potential that is attributable to prosumer behavior is contingent to distinct, prosumer related costs. In our study, different technological set-ups provide high (heating) or low (batteries) discomfort costs, which in turn determine the behavior-based flexibility potential.

Figure 6 depicts the model which provides important guidance for future research on prosumer behavior in the energy sector.

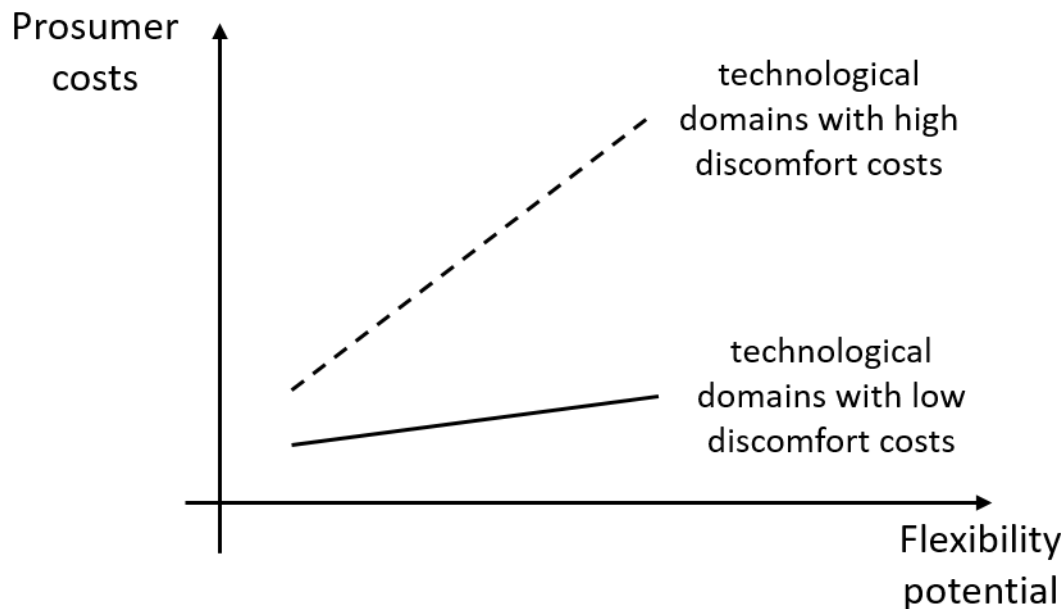


Figure 7: A contingent view on flexibility potential with distributed prosumers

Second, while we observe significant differences in prosumers' willingness to provide flexibility between the three technology domains, our analysis can only provide limited insights into the underlying reasons for those differences. Further research could investigate whether the preference for a given flexibility option is in fact explained by its impact on personal comfort levels, or whether other situational or personal factors play a role. Third, while we have attempted to design comparable choice contexts across the three domains, our findings are clearly influenced by how we operationalized the flexibility attribute in the three choice experiments. Future research can validate our findings with different ways of operationalizing flexibility. This implies two directions: First, it would be desirable to identify a commonly agreed upon technical measure to compare the potential of distributed flexibility options across different domains of energy use. Second, domain-specific studies could test different ways of describing the implications of distributed flexibility options on prosumer discomfort, and thereby disentangle framing effects from the underlying variations in preferences. Such research would have direct benefits for designing flexibility products and services.

Finally, while we see consumer preferences as an important, so far neglected, determinant of the emergence of distributed flexibility markets, it would certainly be valuable in further research to combine this perspective with insights from electricity market modellers, electrical engineers and regulation specialists. Such interdisciplinary collaboration would also allow to iteratively design and test further flexibility options beyond the three specific cases mentioned in this paper.

Acknowledgements

The authors gratefully acknowledge funding from the nano-tera project HeatReserves, the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 646476 (EMPOWER) and from SCCER CREST and SCCER Mobility, which are financially supported by the Swiss Commission for Technology and Innovation (CTI). We thank Gianni Operto and Thomas Kubli for their expert advice on the technical assessment of flexibility options included in the choice experiments, as well as Stefanie Hille and Nina Hampl for their helpful methodological advice. Furthermore, we like to thank three anonymous reviewers for their valuable feedback on an earlier version of this manuscript. All remaining errors are our own.

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Appendix

Actual & Owners of...	Potential	PV + Battery (N=301)		Heat Pump (N=301)		Electric Vehicle (N=300)	
		N	%	N	%	N	%
...are also interested in...							
Solar PV				125	42%	136	45%
Heat Pump		87	29%			95	32%
Electric Vehicle		128	43%	114	38%		

Table 3: Prosumers express interest in further energy technologies across three domains

Study	PV+ (N=301)	PV in %	EV (N=300)	EV in %	HP (N=301)	HP in %
Male	183	61%	194	65%	174	58%
Female	117	39%	106	35%	127	42%
Average age (years)	51.4		48.1		49.5	
Owner of technology	176	59%	56	19%	255	85%
Interested in technology	124	41%	244	81%	46	15%
Urban	72	24%	80	27%	44	15%
Agglomeration	167	56%	160	54%	168	56%
Rural	61	20%	59	20%	87	29%
Number of people per household	2.49		2.46		2.50	
Rental flat	71	24%	147	48%	70	23%
Rental house	9	3%	10	3%	16	5%
Own Flat	36	12%	41	13%	48	16%
Own House	183	61%	110	36%	175	57%
Education						
Compulsory education	1	0.3%	3	1.0%	2	0.7%
Secondary education	153	51.2%	135	45.0%	161	53.7%
Tertiary education	141	47.2%	161	53.7%	135	45.0%
none	4	1.3%	1	0.3%	2	0.7%
Monthly household income						
Less than 4'500 CHF	24	8%	21	7%	13	4%
Between 4'501 and 6'000 CHF	20	7%	27	9%	19	6%
Between 6'001 and 9'000 CHF	77	27%	72	25%	64	22%
Between 9'001 and 12'000 CHF	62	21%	57	20%	72	24%
More than 12'000 CHF	51	18%	54	19%	63	21%
No answer	55	19%	59	20%	65	22%

Table 4: Socio-demographic characteristics of the three studies

Curriculum Vitae



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Education

- 08/2015 - **Ph.D. Candidate in Management**, University of St. Gallen
- 08/2012 – 07/2014 **European Erasmus Mundus Master in System Dynamics**,
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- 08/2008 – 07/2011 **Bachelor of Arts in Business and Economics**, University of
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Professional Experience

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- 08/2014 – **Research associate**
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- 07/2011 – 03/2012 **Research intern**
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