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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.

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 [26,31,47]. Therefore, current energy systems show strong decentralisation tendencies [3,15,54]. 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 [50] and largely influence the decision-making process of small-scale investors to invest in prosumer systems or to form a microgrid [43,47]. Insights from the social sciences, as such, are chronically underrepresented in energy research [48]. 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 [25] 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

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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 Hagiu [19] 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 [17,49], 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 ([4], 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 [35] 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 [15,44]. 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” [2, p. 201]. The transition towards distributed generation is observed on the entire European continent [15] 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 [56] and Helms et al. [20] 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. Fig. 1 displays the categorisation of the distributed generation concepts discussed below.

Prosumers are entities in the electricity system that consume and produce electricity [26]. 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 [10,38]. 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 [47]. 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 [10,47]. 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 [6,10]. Furthermore, several simulation studies are conducted in the area of distributed generation systems. Hiremath et al. [21] and Manfren et al. [30] 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. [36]. It discusses the case of the village of Zernez (Switzerland). Here, different technology constellations for fossil-free energy provision to the village

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

Fig. 1. Categorisation of distributed generation concepts.

are analysed on the basis of the energy hub concept. Further, simulation models address technical aspects of prosumer systems or microgrid systems [22]. Hiremath et al. [21] 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 the 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 [6,10,47]. This study makes a contribution to fill this research gap.

2.3. Simulation models in transition research and the energy sector

Manfren et al. [30] 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 [23]. The difficulty arises, as Holtz et al. [23] 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 [23]. 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 [25]. 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 of high utility for the consumers only through a large network [40]. In the energy sector, investments are made for a very long time horizon, causing lock-in effects for future decisions [53]. 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 they are absolutely crucial. Simulations of network effects have been made in a couple of studies, usually looking at one particular network effect [1]. The relevance of network effects was also demonstrated with simulation in earlier versions of our work [28].

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 p. 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 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. [30], and links to the emerging field of societal transition modelling [23]. 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 system are critical in understanding the transition patterns of regional energy systems. System Dynamics [17,49] 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 [13,16]. Some of these System Dynamics simulation models address aspects of distributed generation systems, such as the diffusion of PV plants [32,42] or the diffusion of CHP plants [7]. The method is also used for strategy development for utility companies in the framework of energy market liberalisation [14]. In addition, System Dynamics is applied as a method for simulation-based theory-building

[12,39,41,45]. 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 [29,52, 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 notification 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 [50]. 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.

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. [6] 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. Fig. 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.

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. Fig. 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 [1]. Network effects start to form in the pervasive diffusion of an innovation, that is, when the market share of the good reaches 5% to 50% [52, Chapter 2, p. 29].

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 [44]. 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. [18] 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) [11]. 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 and Rosenkopf [1] 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 [1]. In marketing literature this effect is usually called the peer effect (e.g. Bollinger and Gillingham [9]). In System Dynamics, the concept of the word-of-mouth effect [49] or familiarity effect [51] is more common. In contrast to the learning theory, the main argument for the word-of-mouth effect is the exposure to advertising, which is referring to awareness rather than the actual information level. In this model, it is assumed

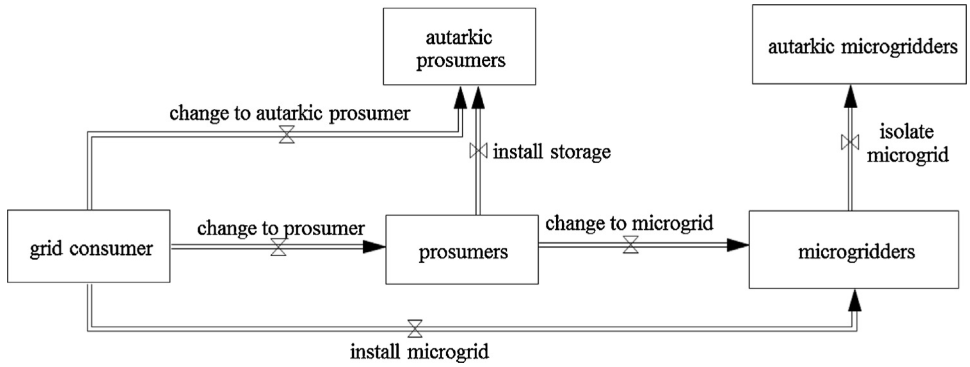

Fig. 2. Structure of the stocks for consumption concepts in the model.

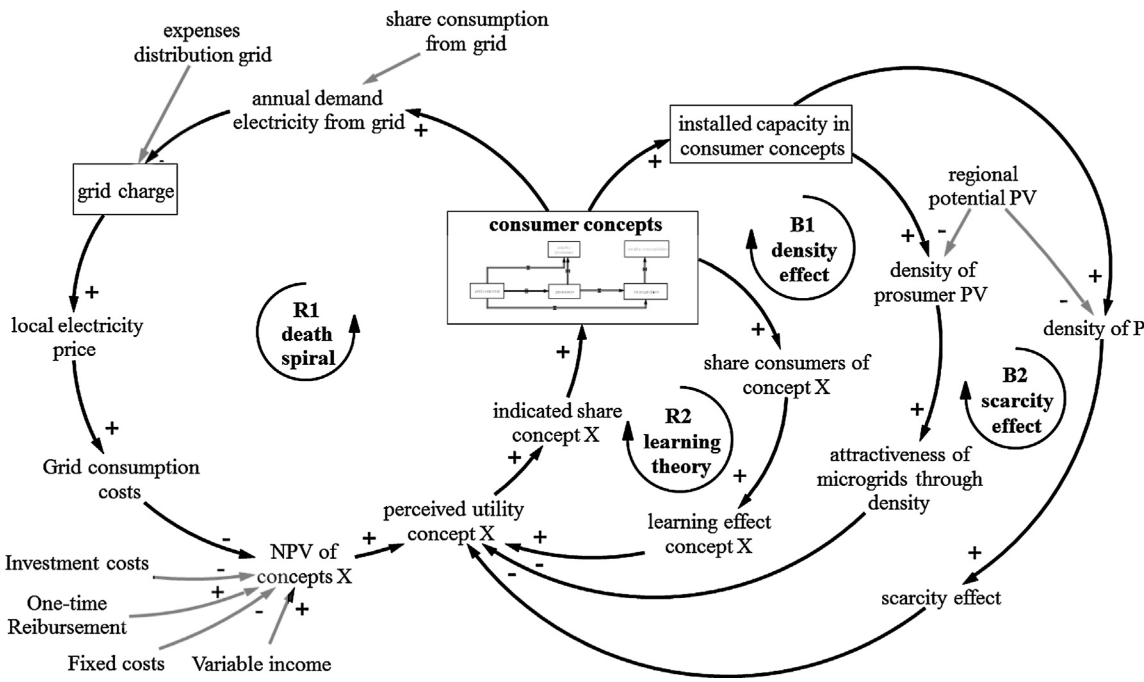

Fig. 3. Overview of the feedback loops represented in the model.

that a higher information level leads to a more positive evaluation of the concepts. This theory is supported by Basu et al. [6] for the case of microgrids, who mention a lack of experience and information as barriers for the deployment of microgrids. Bollinger and Gillingham [9] 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 [1] distinguish between four types of fad theories. They suggest that the motivation for adoption is driven by the assumption that others have better knowledge; 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 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 [18]. In our model, the indirect network effects are modelled as causal effects and not as feedback loops. Feedback modelling of complementary goods would require larger model boundaries 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 [18]. 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 [34].

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 system 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:

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

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.

$$\text{change to conceptX} = \frac{\text{households in conceptY} - (\text{total number of households having applied conceptY} \times \text{indicated share}_y)}{\text{adjustment time}_x} \times \text{indicated share conceptX}. \quad (2)$$

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:

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

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 [20]. 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:

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

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 [43] 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 consideration, 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 [9] 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 [9] 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” [9, 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.

$$\text{learning effect}_x = (\text{share consumers of concept X} \times \text{learning effect coefficient}) + 1 \quad (5)$$

All concepts, except of the microgrid deployment based on existing prosumer systems, require the installation of PV plants.

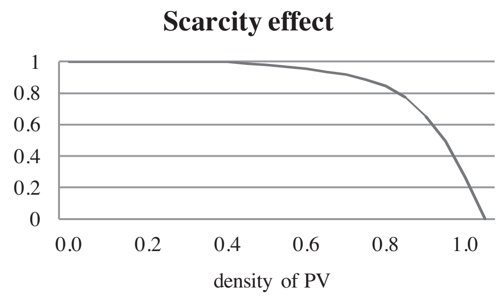

Fig. 4. Look-up function used to capture the effect of increased scarcity on the utility of the distributed generation concepts emerging from limited PV potential.

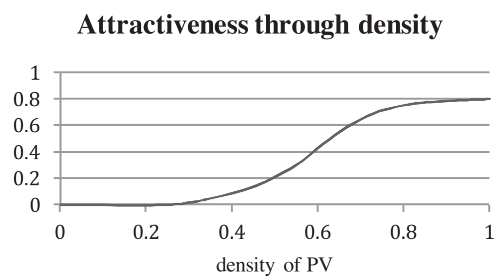

Fig. 5. Look-up function used for the attractiveness of microgrids through the density of existing prosumer systems.

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 [49], p. 287). The function capturing this concept is presented in Fig. 4.

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

Microgrids are frequently constructed based on existing prosumer systems [6]. 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 Fig. 5. 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.

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

The major input factor for the perceived utility calculation is the NPV. The NPV is calculated according to the standard economic equation:

$$\text{NPV} = -\text{Investment costs} + \sum_{t1}^{t} \frac{\text{Cash Flow}_t}{(1+i)^t}, \tag{8}$$

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.

$$\begin{aligned}\text{NPV}_x &= -\text{Investment costs}_x + \text{Reimbursement}_x\\&\quad +(\text{income from electricity production}_x - \text{fixed costs}_x\\&\quad -\text{grid consumption costs}_x) \times \text{present value factor}\end{aligned} \tag{9}$$

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

In contrast to the prosumer electricity unit costs suggested by Pillai et al. [37], 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. [37]. Income from electricity production is defined by the following equation:

$$\begin{aligned}&\text{income from electricity production}_x = \text{total electricity production}_x\\&\quad \times \text{share excess energy}_x \times \text{energy price}\end{aligned} \tag{11}$$

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

$$\text{fixed costs}_x = \text{operating costs}_x \tag{12}$$

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

$$\begin{aligned}&\text{grid consumption costs}_x = \text{average total consumption}\\&\quad \times \text{share consumption from grid}_x \times \text{local electricity price}\end{aligned} \tag{13}$$

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 effects, 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 [20]. 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

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

		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[a]	PV plants of 350 kWp, Wind turbines of 50 kW, CHP of 55 kW, Grid infrastructure and additional support plants[b]	Up- scaling of the infrastructure of a microgrid of a factor of +30%
	Investment costs	21,000 CHF[c]	28,350 CHF + 24,000 CHF[d]	735,000 CHF(PV), 110,000 CHF (wind)[e], 60,000 CHF (CHP), 42,000 CHF (grid infrastructure and additional support plants)[b]	1,231,100 CHF
One-time reimbursement		8200 CHF[f]	10,580 CHF[f]	287,000 CHF[g]	358,400 CHF
Fixed costs	Annual operation costs	315 CHF[h]	608 CHF[h]	13,905 CHF[h]	18,077 CHF
Grid consumption costs	share consumption from grid	68%[i]	0%	20%	0%
Variable income	Total energy production Share excess electricity	10,240 kWh[j] 85%[k]	13,824 kWh[j] 0%	577,500 kWh 60%	750,750 kWh 0%

[a] According to [55], it is assumed that a PV system of 13.5 kWp and according to [33], 20 kWh of battery storage is necessary for a household to be autarkic.
[b] Sontag and Lange [46, p. 1877] for the necessary size and the costs for the CHP plant and support plants, exchange rate of 1.1 CHF/euro.
[c] According to IRENA [24, p. 89]. We base our assumption on the PV system costs (total installed PV system costs in residential sector) in Germany, which is 2100 CHF/kWp.
[d] Costs for the battery system are calculated based on the Tesla Powerwall system. According to Naill [33], 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 3000 CHF are needed to ensure autarky. To match up the life time of PV plants, this investment has to be made twice. http://cleantechnica.com/2015/05/07/tesla-powerwall-price-vs-battery-storage-competitor-prices-residential-utility-scale/ (accessed: 29.07.2015).
[e] Blanco [8, 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.
[f] Energieverordnung (Swiss Energy Regulation) available under: https://www.admin.ch/opc/de/classified-compilation/19983391/201506010000/730.01.pdf; one-time reimbursement per plant = 1400 CHF + 680 × 1 kWp.
[g] 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.
[h] The operation costs are assumed to 1.5% of the investment costs [55].
[i] According to Verbong and Geels [55], based on 2.2 kWp/MWh.
[j] According to Verbong and Geels [55], the annual energy output is 1024 kWh/kWp.
[k] According to Verbong and Geels [55], based on 2.2 kWp/MWh.

applied, for instance, in Switzerland (Swiss Energy Regulation[1]). Despite this type of policy is known for causing technological lock-in it finds wide application [27]. We assume an initial electricity price of 20 rappen per kWh, which consists of the energy price of 10 rappen[2] kWh and 10 rappen per kWh.

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.

$$\text{local electricity price} = \text{energy price} + \text{grid charge} + \text{taxes} \tag{14}$$

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 [42].

$$\text{(desired) grid charge} = \frac{\text{expenses grid} \times \text{share to be covered by grid charge}}{\text{annual total demand by grid charge}} \tag{15}$$

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.

$$\text{annual total demand from grid} = \sum_{X=1}^{5} (\text{households}_X \times \text{share consumption from grid}_X \times \text{avg.total consumption}) \tag{16}$$

The discussed variables with their basic behaviours are shown in the overview graph of the model in Fig. 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 [5], 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.

[1] Swiss 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.

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

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 Ref. [11]). 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.

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 expe-

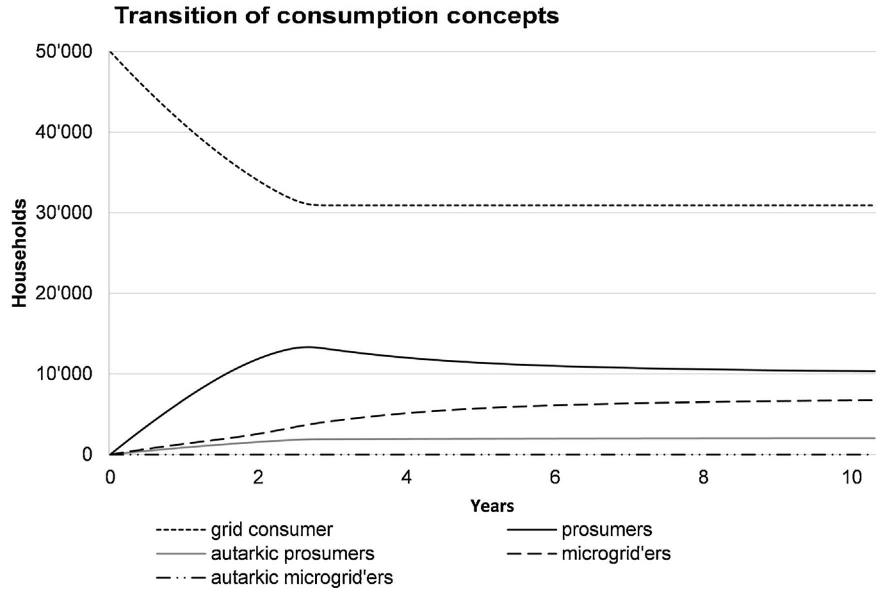

Fig. 6. Base run–households in consumption concepts.

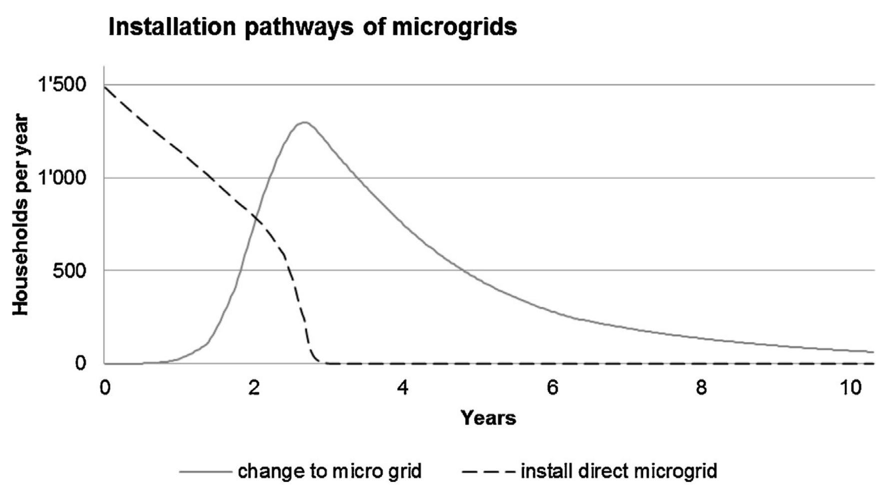

Fig. 7. The Fig. demonstrates the shift between installation pathways of microgrids over time.

rience 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 [56].

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 Fig. 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.

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

Table 2
Analysis of the network effects at hand of the absolute number of households in the consumption concepts in their steady-state and the percentage changes compared to the base run.

		Grid consumers	Prosumers	Autarkic prosumers	Microgiders	Autarkic microgriders	Settling time
Base run		30,900	10,120	2040	6940	0	31
Grid charge off	Absolute	30,890	10,940	1916	6255	0	30
(constant at 0.1	Difference to base run	−10	820	−124	−685	0	
CHF/kWh)	% Change to base run	0%	8%	−6%	−10%	0%	
Perfect knowledge	Absolute	30,880	9973	2121	7030	0	22
(learning effect off)	Difference to base run	−20	−147	81	90	0	
	% Change to base run	0%	−1%	4%	1%	0%	
Density effect off	Absolute	30,870	14,470	1919	2748	0	32
(constant at 0)	Difference to base run	−30	4350	−121	−4192	0	
	% Change to base run	0%	43%	−6%	−60%	0%	
Direct deployment pathways off	Absolute	31’000	11’410	482	7105	0	23
(autarkic prosumers and	Difference to base run	100	1290	−1558	165	0	
microgrids)	% Change to base run	0%	14%	−54%	2%	0%	
Battery costs +20%	Absolute	30’850	10,170	1897	7093	0	25
	Difference to base run	−50	50	−143	153	0	
	% Change to base run	0%	0%	−7%	2%	0%	
Battery costs -20%	Absolute	30,960	10,050	2,230	6785	0	33
	Difference to base run	60	−70	190	−155	0	
	% Change to base run	0%	−1%	9%	−2%	0%	
Microgrid costs +20%	Absolute	30,910	11,280	2087	5725	0	40
	Difference to base run	10	1160	47	−1215	0	
	% change to base run	0%	11%	2%	−18%	0%	

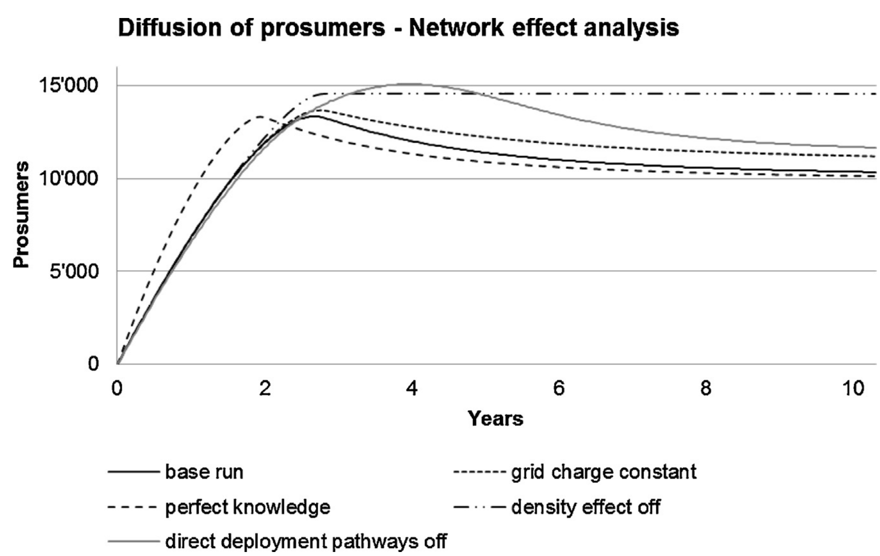

Fig. 8. Simulation results for selected scenarios of the stock of prosumers over time.

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 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 Figs. 7 and 8, 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 politicians. 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 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.

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