TRANSITION PATTERNS OF DISTRIBUTED ENERGY GENERATION CONCEPTS CONSIDERING NETWORK EFFECTS

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ABSTRACT

Distributed generation is becoming increasingly important in energy systems, causing a transition of regional energy systems. These decentralisation dynamics are difficult to predict in their scope and timing and therefore become a major challenge for political decision makers, utility companies and technology developers. Network effects are crucial in these decentralisation dynamics, strongly influencing the dominance of the various concepts of distributed energy generation. Network effects emerge between technologies, the installed base of a concept and actor-specific decision criteria.

A System Dynamics simulation model is built, capturing the consumer concepts related to distributed generation as well as arising network effects, to analyse likely transition dynamics in regional energy systems. The direct network effects of grid charge adjustment, learning theory and an effect due to density as well as indirect network effect between storage technologies and combined heat and power systems in microgrids are represented in the model. Preliminary simulation results on the transition of the distributed generation concepts are shown and will be analysed in further research on the specific impact of network effects on the transition patterns. This paper aims to make a contribution to the field of energy transitions by translating theories on network effects of the economic literature to the energy systems simulation and by discussing and simulating relevant network effects as relevant drivers of the dissemination of distributed energy generation concepts and the related consumer concepts.

Keywords: *regional energy systems, transition, network effects, distributed generation, simulation, System Dynamics.*

INTRODUCTION

Current energy systems show strong decentralisation tendencies [1, 2]. This development is driven by the integration of new renewable energies, which are suitable for local and small scale installation, into the energy system. In this context, prosumer and microgrid concepts become attractive [3-5]. Despite the significance for the energy transition and the growing number of regional initiatives, decentralisation dynamics and network effects in the transition of distributed generation systems has enjoyed little attention in research so far. However, early strategy development and stakeholder engagement is crucial for successful deployment of these concepts and to avoid high costs of late adaptation.

We hypothesise that deployment patterns of prosumer systems and microgrids strongly depend on regional-specific initial conditions; as well as early co-ordinated initiatives in general - and network effects in particular. Network effects are defined as the dependency of the product utility on the network size as well as the positive effect of coalitions with other products [6]. We presume that network effects are decisive for the dominance of a particular concept and can promote distributed generation systems to a breakthrough, which otherwise would not happen on a comparable scale. Hence, a better understanding of evolving network effects is critical for choosing early on the right investment strategy and partners.

We apply System Dynamics [7], a causal modelling approach focussing on feedback mechanisms in a system, to simulate likely deployment pathways of distributed generation systems, integrating five essential network effects. A detailed understanding of likely decentralisation dynamics in a region is essential for production planning, business model development and grid maintenance for utilities, producers of technological components and the political governance of a region. The novelty of this paper is the application of the network theory on the field of energy transitions as well as the combination with the System Dynamics simulation approach.

BACKGROUND

Energy transitions are a widely discussed topic in the scientific literature. Today, new renewable energies that favour the distributed generation of energy are about to transform the energy system [8]. Distributed generation is defined as an “electric power source connected directly to the distribution network or on the customer site of the meter” [9]. Within these decentralisation dynamics, different consumer concepts related to distributed generation emerge and become increasingly attractive. Prosumer systems and microgrids are frequently analysed in a technological manner [10, 11]. Also simulation studies are conducted in the area of distributed generation systems. Hiremath et al. [12] and Manfren et al. [13] provide useful overviews of simulation models applied at various levels of decentralised energy systems and their planning. Hiremath et al. [12] observe that most of these simulation models use an optimization technique to find the ideal constellation of technologies for the specific area. However, these approaches do not provide an explanation and analysis addressing the co-evolution and the diffusion processes of these concepts. This is surprising since in liberalised network industries, such as the electricity sector, a co-evolution between technology and institutions is decisive to avoid incoherence and instability in the system [14]. Network effects are considered as major determinant of diffusion processes [15] and play a crucial role in the co-evolution between technology and institutions. Qualitative discussions of benefits and challenges of distributed generation systems [4, 10, 11] provide valuable insights into relevant aspects of the diffusion. To our knowledge, a formal quantitative analysis of likely diffusion patterns of these concepts has not yet been provided in the literature.

METHOD

A System Dynamics model is built addressing the issue of likely transition patterns of consumption concepts related to distributed generation in energy regions applying a consumer perspective. Analysing processes within in the energy system is essential to consider the consumer perspective due the importance of consumer or households decisions of how to consume and produce electricity [16]. Simulation is useful and essential for this study to support the complex thought experiments that could not just be conducted mentally. With our simulation approach, we address the need highlighted by Manfren et al. [13] for innovative simulation models analysing transition aspects for decentralised energy systems, taking into account the complex interlinkages between technology, actors, the economy and institutions as. We chose System Dynamics as considered the most suitable modelling and simulation technique to address this issue, since multiple feedback processes, delays and the state of the systems are critical to understand the transition patterns of regional energy systems. System Dynamics [7] is a simulation and mapping method based on causal modelling. 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. System Dynamics finds applications as a planning, analysis and policy design method in various areas of the wide field of energy research [17].

The model presented here is generic in its structure. We aim to model typical patterns that can arise from the decentralisation dynamics of regional energy systems. The model captures four distributed energy generation concepts: prosumers, autarkic prosumers, microgrids and autarkic microgrids. Microgrids are a cluster of producer units that are installed close to multiple consumer units and are connected through a small scale grid with a single node to the main grid [11]. Autarkic concepts are assumed to be completely decoupled of the main grid. These distributed generation concepts are compared to the standard consumption concept, here called “grid consumer”, which are purchasing the required electricity from the main electricity grid. The investment decision made by consumers is based on a utility assessment of the concept, based on the economic aspects in form of the net present value of the concepts, which is enriched by non-economic factors of learning, practical aspects and a scarcity effect.

The model captures five network effects, three in form of feedback loops and two as simple causalities. Figure 1 highlights the central feedback loops captured in the model.

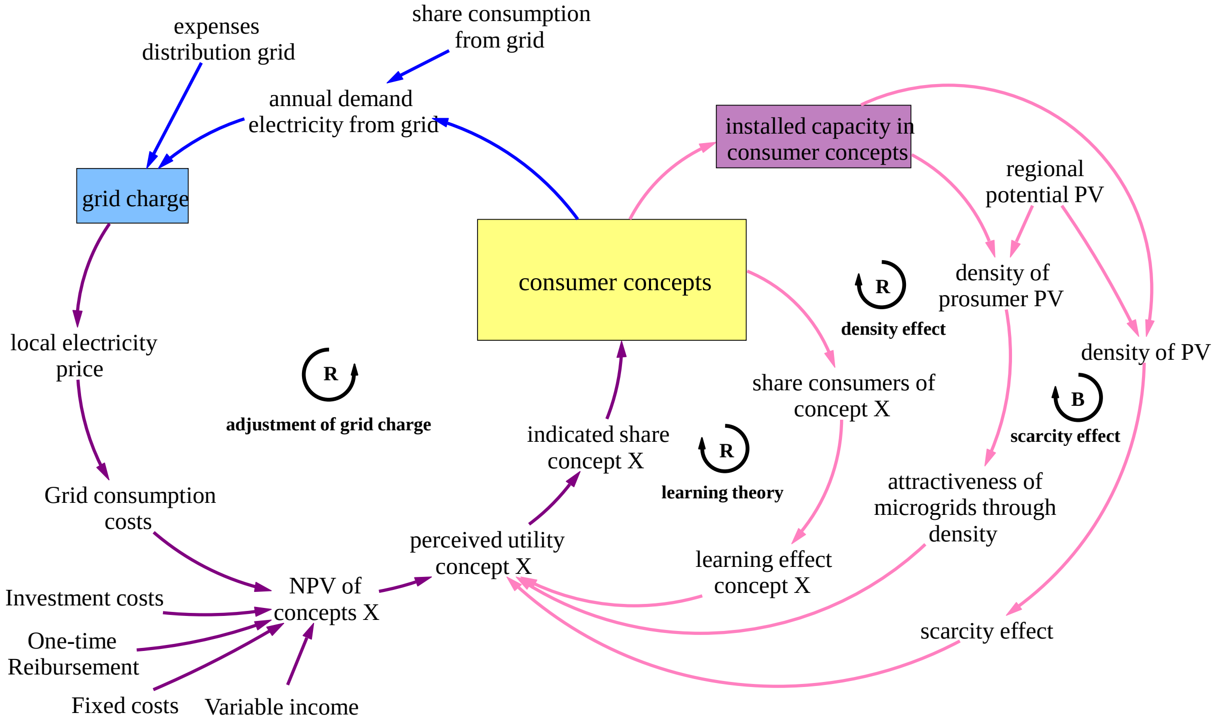

Figure 1: Overview of the feedback loops represented in the model. Underlined variables represent structure elements that are modelled with subscripts.

Feedback loop R1 “adjustment of grid charge” addresses the effect of reduced demand from the main grid, on the grid charge, caused by increased captive power generation, and the feedback to the investment decision. In particular, the number of prosumers is crucial for 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 still strongly use 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. Grid parity, equal generation costs of captive power systems compared to the total energy costs paid for the electricity consumed from the grid, is considered as the crucial point for the diffusion of prosumer systems [8] and consequently is sensitive for the attractiveness of all other distributed generation systems. In network theory, scholars frequently speak about positive externalities of increased 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 grid charge adjustment (R1). 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 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.

Feedback loop R2 “learning theory” is built based on the insights gained in network theory. The adjustment of perceived utility due to higher awareness and improved information is in network theory called the learning theory [15]. In this model it is assumed that a higher information level leads to more positive evaluation of the concepts. This theory is supported by Basu et al. [10] for the case of microgrids, which mentions a lack of experience and information as a barrier for the deployment of microgrids. In System Dynamics the concept of the word-of-mouth effect [7] is more common. In contrast to the learning theory, the main argument for the word-of-mouth effect is the exposure to advertising, which more referring to awareness rather than the actual information level.

In network theory literature, a set of fad theories are discussed. Fad theories become important in innovation diffusion with ambiguous profitability of the innovation and unclear or no information flows. Therefore, social processes and information on the adopters become more important and affect the diffusion. Abrahamson et al. [15] distinguish between four types of fad theories. They address the motivation for adoption through the assumption of better knowledge of others, an evaluation bias due to 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 competitive advantage. These types of network effects are not represented in the 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, which would result in redundancies. The analysis of the relevance of fad theories and their impact are still to be explored in future research.

Feedback loop R3 “density effect” is chosen to address the aspect of geographical closeness as a crucial factor for microgrid deployment. If microgrids are formed through the connection of existing prosumer systems, this requires the physical closeness to build a reasonable microgrid. This interconnection is also a network effect. The relation of this effect to existing network-theories needs to be discussed in more detail. 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. 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, and do not just increase their own utility through the addition of another product.

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, since this would require a larger model boundary than desired for our purpose. 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 our model a photovoltaic 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 alter the attractiveness of this concept. An indirect network effect of a similar manner arises through the combination of several technologies in the microgrid concept. Here, the photovoltaic plants, the CHP plant and the other supporting plants all need to be attractive for an investment. Systems with complementary goods frequently have coordination problems for marketing the products due to the two-way contingency for demand [18]. From a transition perspective, this also raises questions of timing. Here, we hope to make a contribution with the System Dynamics approach by analysing different transition patterns and their interactions. 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.

Feedback loop B1 “scarcity effect” is a typical process emerging from a diffusion reaching its carrying capacity. The rate of growth is reduced through the limitations appearing. 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.

RESULTS

We here present some preliminary simulation results of the base run. An extended analysis of the effect of the network effects in the transition patterns is submitted to the journal Energy Research & Social Sciences and will therefore not be presented at the place [19]. The analysis focuses on the generic patterns arising in the transition on regional energy systems and not exact numerous outcomes. The simulation analysis is conducted for an imaginary region with 50,000 households. Initially, all households are assumed to consume their electricity from the main grid and are therefore “grid consumers”. The potential for PV plants in this imaginary region is set to 150 MW. The simulation period starts in the year 2010 and ends in 2040.

In Figure 2 the simulation results for the different consumption concepts are presented. The first graph shows the transition of all concepts, while the graph on the right focusses on the distributed generation consumption concepts.

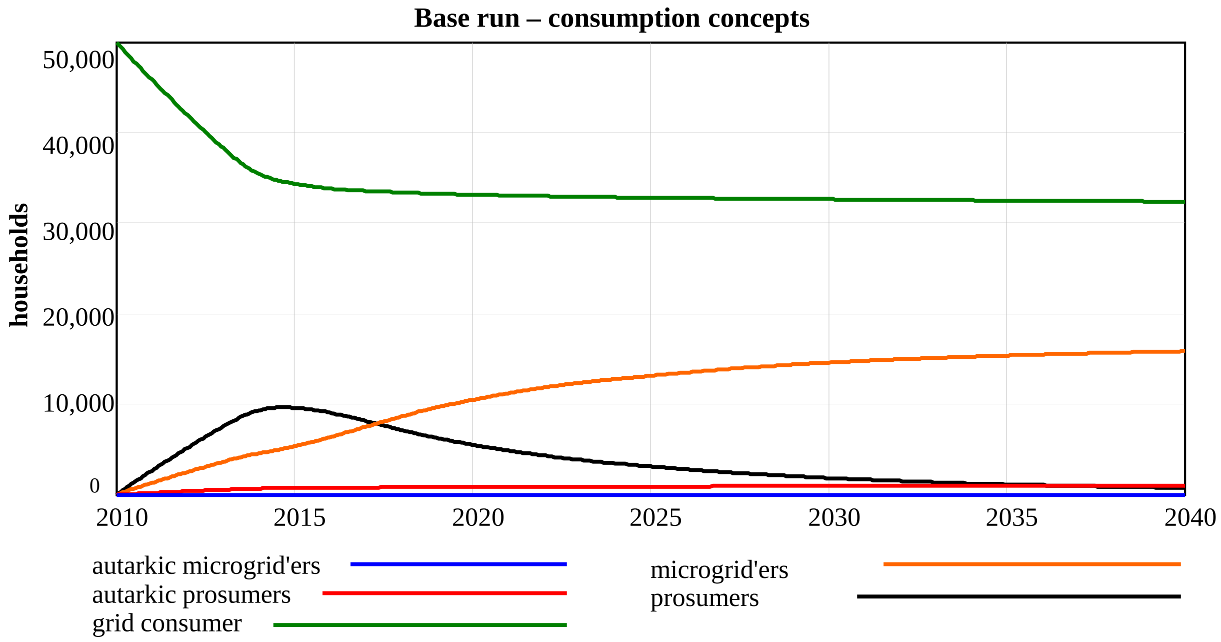

Figure 2: Base run – Simulation results for the number of households in the different consumption concept

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 “adjustment of grid charge”. The increasing number of prosumer causes the grid charge to increase and makes prosumer systems even more attractive. This development reaches its peak in the year 2015. 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 – deployment of microgrids from a previous prosumer system and the direct installation of a microgrid. The autarkic concepts – autarkic prosumers and autarkic microgrids – are low in their perceived utility. The concept autarkic prosumer finds some applicants, while the autarkic microgrid seems totally unattractive. The transition towards the autarkic prosumer system shows a similar pattern, with the shift between the two deployment pathways, as observed in the transition to microgrids.

It is important to understand that these dynamic patterns are driven by the network effect and do not emerge from changes in technology prices. These dynamics are all driven by the structure of the system and the network effects gaining on weight and influencing the investment decision by the consumers.

CONCLUSION

Distributed energy generation systems are becoming increasingly attractive and are adopted more frequently. These decentralisation dynamics cause a major transition in regional energy systems. Although increasing shares of prosumer systems and microgrids do have 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 attention in research so far.

A System Dynamics simulation model was built to address the question of likely transition patterns of consumption concepts related to distributed generation. Major drivers for this transition are arising network effects between the installed base of the consumption concepts and the development of complementary technologies. We model the direct network effects: adjustment of grid charge, learning theory and density effect. Indirect network effects between complementary concepts and technologies are addressed between photovoltaics, storage technologies, CHP plant and a 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 the high impact of network effects on the decentralisation dynamics of a regional energy system in general and on the different consumption concepts related to distributed generation in particular.

Our paper makes the following contributions. By shedding light on the decentralisation dynamics in regional energy systems, new perspectives and options for strategy development are highlighted. The application of the network effect concept on energy systems research in combination with dynamics simulation is novel. 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 the research in the field of energy transitions.

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