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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