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Self-consumption through power-to-heat and storage for enhanced PV integration in decentralised energy systems

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ABSTRACT

Many countries have adopted schemes to promote investments into renewable energy sources resulting, among others, in a high penetration of solar PV energy. The system integration of the increasing amount of variable electricity generation is therefore a highly important task. This paper focuses on a residential quarter with PV systems and explores how heat pumps and thermal and electrical storages can help to integrate the PV generation through self-consumption. However, self-consumption and PV integration are not only affected by technologies but also by pricing mechanisms. This paper therefore analyses the impact of different tariffs on the investment and operation decisions in a residential quarter and its interaction with the external grid. The considered tariffs include a standard fixed per-kilowatt-hour price, a dynamic pricing scheme and a capacity pricing scheme. To account for the interdependent uncertainties of energy supply, demand and electricity prices, we use a module-based framework including a Markov process and a two-stage stochastic mixed-integer program. Analysing a residential quarter in Southern Germany as a case study, we find that the integration of a PV system is economically advantageous for all considered tariffs. The self-consumption rate varies between 58 and 75%. The largest PV system is built when dynamic prices are applied. However, the peak load from the external grid increases by a factor of two under this tariff without any incentive for reduction. In contrast, capacity pricing results in a reduction of the peak load by up to 35%.

1. Introduction

On 30 November 2016, the European Commission published its "Winter Package", consisting of more than 40 planned measures, aimed at accomplishing climate targets on energy efficiency, greenhouse gases, and renewable energies (RE). One of the key objectives is to promote a better integration of electricity produced from renewable sources through market-based mechanisms. "The regulatory changes introduced by the current package and the shift from centralised conventional generation to decentralised, smart and interconnected markets will also make it easier for consumers to generate their own energy, store it, share it, consume it or sell it back to the market – directly or as energy cooperatives […] these changes will make it easier for households and businesses to become more involved in the energy system and respond to price signals." (European Commission, 2016).

With regards to Germany, the transition towards a more decentralised energy system (DES) with emphasis on RE is pre-eminently driven by the regulatory framework. It defines the target of covering 80% of German gross electricity consumption by RE in 2050 (BRD (Bundesrepublik Deutschland) [Federal Republic of Germany], 2012). In line with this target, Germany has been the world's top photovoltaic (PV) installer for several years (Rodrigues et al., 2016), outperformed only by China since 2015 (IEA, 2016). Particularly, the German Renewable Energy Sources Act (EEG) catalyses the expansion of decentralised renewable energy sources such as PV by guaranteeing a fixed feed-in tariff for the energy that is fed into the local grid. Since its introduction in 2000, electricity retail prices have risen about 5% per year on average until today. At the same time, the average costs of PV systems have decreased by an average of 9% per year (BSW (Bundesverband Solarwirtschaft) [German Solar Association], 2015). This cost decrease was accompanied by a continuous reduction of the PV feed-in tariff, which makes the self-consumption of electricity produced by PV more profitable and flexibilities to shift load (e.g., storages) more attractive. Fig. 1 shows the development of the household electricity price in comparison to the electricity production costs of PV systems for Germany, showing that the so-called grid parity has been achieved recently.

In the light of these developments and the statements by the EU

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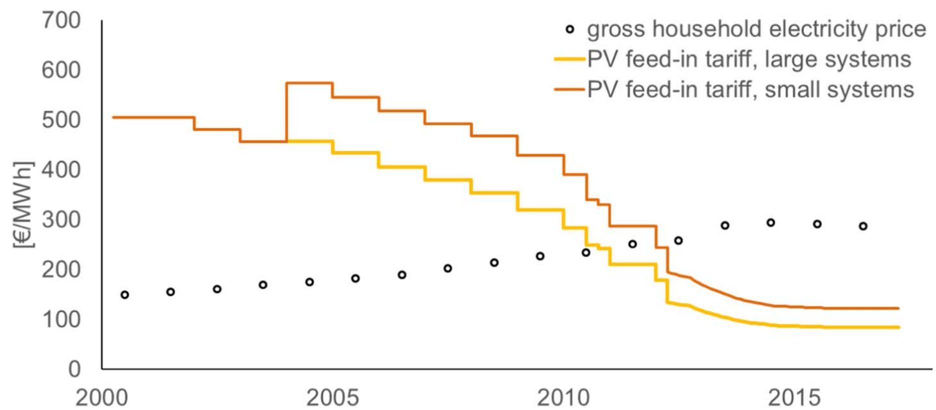

Fig. 1. Historical development of PV feed-in tariffs and end-user electricity price for households in Germany (Wirth, 2017).

promoting self-consumption as a means to support RE integration, the question arises (from a consumer perspective) what flexibilities to shift load and increase self-consumption are most profitable and how to optimally combine different sources of flexibility in the presence of uncertainty. Some researchers, however, also hold critical views on self-consumption (Khalilpour and Vassallo, 2015; Simshauser, 2016; Bertsch et al., 2017). Their criticism is not directed at self-consumption and PV expansion as such, but mainly raises distributional concerns. In systems where consumers pay for costs to build and maintain the energy system infrastructure on a per-unit basis (e.g., network charges), those consumers that can afford investments into technologies increasing self-consumption contribute less to maintaining the system while still benefiting from the security of supply from being connected to the grid. As a consequence, a decreasing amount of consumers who cannot invest into self-consumption bear the costs of the system. Several approaches to overcome these concerns are discussed, including the introduction of capacity-based price components, also called demand tariffs in the literature (Kaschub et al., 2016; Simshauser, 2016). This gives rise to the question how such different retail tariffs (pricing mechanisms) impact the profitability of different flexibility sources such as power-to-heat applications or energy storages and their optimal combination. Also, the question emerges what levels of self-consumption can be expected and how these are influenced by different tariffs under RE uncertainty.

This paper therefore presents a two-stage stochastic program to analyse different pricing mechanisms for a residential quarter with the option of a PV system and electrical as well as thermal storages. The stochastic program is embedded in an integrated, module-based framework. The required input data (e.g., load profiles on the demand and supply side) are generated on the basis of Markov processes under consideration of their mutual dependencies. Our analysis focusses on the optimal investment decisions under different tariffs and on essential energy values such as total energy costs, the PV self-consumption rate and grid load under uncertain weather-related conditions.

The structure of the paper is as follows. Section 2 provides a brief overview of related literature. In the subsequent Section 3, the modelling framework is described including the generation of input data as well as the stochastic program. Section 4 introduces the case study of a real-world residential quarter. The results are presented in Section 5, followed by a discussion and acknowledgement of limitations in Section 6. A conclusion and an outlook finalise the paper in Section 7.

2. Related literature and work

In general, DES are considered as systems that provide a portion of the energy required to satisfy their demand on-site, within the boundaries of, or located nearby and directly connected to, a building, community or development (Wolfe, 2008). The literature on optimisation of DES is large and growing. Due to the fluctuating properties of some system elements, the majority is based on a high temporal resolution of 15 min or 1 h, considering a time horizon of less than a day up to 25 years. Prevalently, electrical demand and supply is simulated or optimised (McHenry, 2012; Erdinc, 2014; Komiyama and Fujii, 2014; Dufo-López and Bernal-Agustín, 2015; ElNozahy et al., 2015; Kaschub et al., 2016; Zebarjadi and Askarzadeh, 2016). Other research focusses on the heat management (Zhang et al., 2007; Wei et al., 2015; Bahria et al., 2016; Fischer et al., 2017). Several cases analyse both electricity and heat:

- Evins et al. (2014) formulate a general 'energy hub concept' that can methodologically represent the interactions of many energy conversion and storage technologies for applications such as power plants, industrial facilities and urban areas. While their modelling approach to aggregate and optimise energetic resources on a relatively small scale and with relatively high detail exhibits some similarity to the representation in our study, they focus less on the economic implications of the various system designs. However, they find a strong potential of system components such as heat pumps to reduce carbon emissions by up to 22%.
- Kanngießer (2014) considers scheduling optimisation of energy storages by trading load shifting potential and operating reserve on the electricity market for an exemplary compressed air reservoir and pumped-storage power plant.
- Shang et al. (2017) schedule storages with a combined heat and power (CHP) application. They apply a non-dominated sorting genetic algorithm as metaheuristic to an illustrative building and evaluate the potential for the reduction of fuel consumption through including electrical and thermal energy storage in the system. Jochem et al. (2015) and, similarly, Kia et al. (2017) optimise the day ahead scheduling of CHP units with electrical and thermal storage. While Jochem et al. (2015) focus on decentralised micro-CHP at the household level and find significant potential to self-consume the CHP's electricity output to more than 50%, Kia et al. (2017) evaluate the CHP's added value to avoid costs imposed by security constraints in two alternative IEEE electricity networks. Vögelin et al. (2017) analyse gas engine CHP plants for building and industry heat demand under varying price structures. Núñez-Reyes et al. (2017) optimise the scheduling of grid-connected PV plants with energy storage for integration in the electricity market.
- Lorenzi and Silva (2016) optimise the dimension of PV systems and the self-consumption with energy storages as well as Beck et al. (2017) do with a power-to-heat application. Similarly, but at the scale of an entire city, Salpakari et al. (2016) analyse how different technologies, including power-to-heat, storage and load-shifting, can decrease surplus of variable renewable energy.
- Shirazi and Jadid (2017) have developed an energy management to optimise the household's energy operation cost by peak shaving through domestic load shifting and distributed energy resources