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Optimal operation, configuration and sizing of generation and storage technologies for residential heat pump systems in the spotlight of self-consumption of photovoltaic electricity

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HIGHLIGHTS

- MILP optimization model for operation and investment of residential energy systems.
- Influence of heat pump systems on photovoltaic self-consumption and self-sufficiency.
- Assessment of economical efficiency of flexibility options for heat pump systems.
- PV as a robust measure to decrease TCO of heat pumps under scenarios assumptions.

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ABSTRACT

A rapid growth in interest in self-consumption of electricity generated by rooftop photovoltaic (PV) systems has been observed in recent years. This is fueled by decreasing levelized cost of electricity and feed-in tariffs for PV-systems as well as by increasing electricity prices, especially in the residential sector. Besides PV-battery systems, electrical heat pumps are a promising measure to increase self-consumption of electricity generated by distributed generation technologies in residential dwellings. However, little scientific research on the ability of heat pump systems to increase self-consumption of PV-electricity has been carried out so far. Therefore in this paper a mixed integer linear programing model for the optimal operation, system configuration and sizing for heat pump based house energy systems is developed and applied under different scenario conditions. The results show that the dimensioning of the heat pump is hardly influenced by the scenario assumptions, whereas the optimal sizing of PV is strongly dependent on the scenarios and in particular on the electrical load profiles. Over all scenario variations, the sizing of electrical and thermal storages is demand-driven and hardly any interdependencies with respect to optimal sizing can be observed between the different storage technologies. The availability of feed-in-tariffs generally yields large PV systems with high levels of self-sufficiency but low levels of self-consumption. Stricter feed-in-limitations lead to a reduction of the optimal PV systems size, but not to an increase in the optimal size of storage technologies. Over a wide range of base scenarios and scenario variations PV systems as well as additional flexibility options are part of the optimal system configuration, rendering it a promising and robust measure to decrease the operating cost of heat pump systems in the future. The results obtained in this study can provide valuable guidelines for manufacturers, installers and end-customers for the design of cost-effective self-consumption driven heat pump systems in the future.
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1. Introduction

1.1. Motivation

Rapidly increasing interest in self-consumption of electricity generated by rooftop photovoltaic (PV) systems in the residential sector has been observed in recent years [1]. The economic

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attractiveness of self-consumption of electricity generated by distributed electricity generation technologies benefits from decreasing levelized costs of electricity (LCOE) of these technologies and feed-in tariffs (FIT) as well as from increasing end customer electricity prices especially in the residential sector [2–4].

The increasing economic attractiveness of photovoltaic self-consumption has fostered research in grid-connected battery storage systems [5–7] with the target of increasing self-consumption. Whereas the potential of general demand-side management measures to increase self-consumption is regarded as rather low [8], heat pump systems are often amongst the electrical consumers with the largest power in residential applications and also make up for a large amount of the annual electrical energy consumption. Heat pumps are therefore a promising measure to increase the self-consumption rates of PV systems. For the remainder of this paper, the rate of self-consumption (which represents the amount of self-generated electricity that is consumed locally) and the rate of self-sufficiency (which is defined as the ratio of the locally consumed electricity and the entire electricity consumption) are employed. A detailed mathematical formulation of these characteristic numbers is given in Section 3.5.

Future residential house energy systems will exhibit an increased complexity with respect to the operation and system configurations. The economic efficiency of these systems does not only depend strongly on the future development of energy prices and feed-in-tariffs, but also on future regulatory boundary conditions and on user behavior. This demands a holistic approach for the optimal system operation, configuration and sizing of residential dwellings under consideration of interdependencies between the end-use domains of electricity, hot water and space heating demands. This paper therefore assesses the cost optimal heat pump systems and the role of additional flexibility options such as thermal and battery storage with respect to self-consumption of PV electricity. A mixed integer linear programming model for the optimal operation, configuration and sizing of residential house energy systems is therefore developed and employed under different scenarios. Today, no guidelines for the sizing of heat pump based house energy systems exist under the impact of PV self-consumption for practical applications.

The results of this paper can yield valuable information with respect to the optimal configuration and sizing of the employed PV systems as well as electrical and thermal storage options for future heat pump systems. Furthermore, the analysis of different economic and regulatory boundary conditions (such as FIT and grid feed-in limits) can be used by political decision makers to develop suitable electricity market regulations and support mechanisms for the integration of renewable energies and flexibility options in residential dwellings.

1.2. Literature review

1.2.1. Review

Several papers address the applicability of optimized control and operating strategies for residential heat pumps in load shifting applications. Patteeuw et al. [9] investigate the load shifting potential of heat pumps applying a central optimizing approach under different incentive schemes. Verhelst et al. [10] show that the optimal control problem can be accurately modeled with simplified convex heat pump models, by applying a modified cost function that penalizes power peaks. Ikegami et al. [11] apply a mixed integer linear programming model to optimize the operation schedule of a hot water heat pump system. The authors highlight the importance of variable electricity prices to provide incentives for flexible operation of heat pumps.

Due to the increasing attractiveness of self-consumption of electricity generated by roof-top PV systems, research on operation strategies has recently shifted towards increasing local self-consumption rates. Operating strategies to increase self-consumption while simultaneously reducing the stress on the distribution grids are proposed in [12]. Tjaden et al. [13] study self-sufficiency rates for different building standards equipped with heat pumps, PV and battery systems. The applicability of rule-based and optimization-based strategies to heat pump systems, equipped with both thermal and battery storage systems, to achieve an increase in self-consumption and a reduction of the operating costs without violating the required comfort levels is proven in [14,15]. The activation of the thermal mass of buildings to allow for a more flexible operation of heat pump systems is investigated by Reynders et al. [16]. The authors apply a detailed building simulation and prove the potential to shift electricity demand to off-peak hours and increase PV self-consumption. They are able to achieve an increase in self-consumption, which however doesn't yield a significant increase in self-sufficiency due to the overall increase in electricity consumption.

Thus far, no approaches for combined optimal operation and sizing for heat pump systems with a focus on residential dwellings are known to the authors. In practical applications, heat pump systems are sized by the installers solely based on the heat load of a building. This simplified approach frequently leads to oversized systems [17]. For residential applications, different mathematical optimization techniques have been employed to identify the optimal configuration and sizing of PV-battery systems [18–20] or combined heat and power systems [21–23].

For larger scale energy systems, the integrated system configuration, sizing and operation has been more popular in the research community. An exhaustive review on the role of optimization methods for energy management in microgrid research can be obtained from [24]. Mixed integer linear programming approaches have been successfully applied to the integrated configuration, sizing and operation of microgrids [25–28], larger commercial buildings or multi family homes [29,30] and the planing of residential neighborhoods with district heating networks [31,32]. Besides the linear and mixed integer linear programming approaches, heuristic based multi-objective optimization models have been applied to load shifting in smart grids [33] or electrical energy storage in islanded networks [34]. A generic methodology for optimization of operation of large scale hybrid energy systems with focus on prediction of renewable generation and economic market information is presented in [35,36].

1.2.2. Discussion

An overview on the articles presented in the previous section is provided in Table 1. The different articles are categorized with respect to the employed optimization method and variables, the scale of the energy systems and the employed end-use domain.

The literature review highlights the efforts of various researchers to demonstrate the applicability of advanced control strategies for load shifting applications such as demand response, peak shaving or adaption to dynamic pricing signals [9–11]. Additional measures to increase self-consumption such as battery storage, thermal storage or the activation of the thermal building mass have been subject to research in combination with heat pump systems [12–16]. In contrast to the larger research interest in large hybrid energy systems and microgrids [33–36,25–32], no works are known to the author that provide a holistic view on integrated optimization of optimal operating, configuration and dimensioning of residential energy systems with special attention to the role of self-consumption and storage technologies. So far this problem for single dwellings has been mainly targeted for subsystems (electrical, thermal) and specific technologies (PV, CHP) [18–23,34].

A variety of different optimization approaches is reported in the articles. A categorization of the different articles with respect to the

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