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Heat pump and PV impact on residential low-voltage distribution grids as a function of building and district properties

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HIGHLIGHTS

- Comprehensive method includes variability in building and feeder characteristics.
- Detailed, 10-min, Modelica-based simulation of buildings, heat pumps and networks.
- Overloading and voltage issues appear from 30% heat pumps in rural Belgian feeders.
- Analysis of load profiles reveals great impact of heat pump back-up heaters.
- High correlation of building neighborhood properties with grid impact indicators.

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ABSTRACT

Heating electrification powered by distributed renewable energy generation is considered among potential solutions towards mitigation of greenhouse gas emissions. Roadmaps propose a wide deployment of heat pumps and photovoltaics in the residential sector. Since current distribution grids are not designed to accommodate these loads, potential benefits of such policies might be compromised. However, in large-scale analyses, often grid constraints are neglected. On the other hand, grid impact of heat pumps and photovoltaics has been investigated without considering the influence of building characteristics. This paper aims to assess and quantify in a probabilistic way the impact of these technologies on the low-voltage distribution grid, as a function of building and district properties. The Monte Carlo approach is used to simulate an assortment of Belgian residential feeders, with varying size, cable type, heat pump and PV penetration rates, and buildings of different geometry and insulation quality. Modelica-based models simulate the dynamic behavior of both buildings and heating systems, as well as three-phase unbalanced loading of the network. Additionally, stochastic occupant behavior is taken into account. Analysis of neighborhood load profiles puts into perspective the importance of demand diversity in terms of building characteristics and load simultaneity, highlighting the crucial role of back-up electrical loads. It is shown that air-source heat pumps have a greater impact on the studied feeders than PV, in terms of loading and voltage magnitude. Furthermore, rural feeders are more prone to overloading and undervoltage problems than urban ones. For large rural feeders, cable overloading can be expected already from 30% heat pump penetration, depending on the cable, while voltage problems start usually at slightly higher percentages. Additionally, building characteristics show high correlations with the examined grid performance indicators, revealing promising potential for statistical modeling of the studied indicators. Further work will be directed to the assessment of meta-modeling techniques for this purpose. The presented models and methodology can easily incorporate other technologies or scenarios and could be used in support of policy making or network design.

1. Introduction

Awareness of climate change has directed efforts towards CO_2 emission mitigation through improvement of energy efficiency and reduction of fossil fuel consumption. The residential sector was responsible for about 70% of CO_2 emissions in 2011, and

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optimistic scenarios suggest it could reduce its emission by up to 90% compared to 1990 levels by 2050 [1]. Such scenarios include more efficient buildings, heating electrification by means of highly efficient technologies such as heat pumps, and integration of distributed renewable energy generation, for instance rooftop photovoltaic systems (PV). In order to harvest the expected benefits from implementation of these technologies, several local technical barriers need to be overcome, which are in large-scale studies easily overlooked. For instance, often the transmission and distribution grid is assumed to deliver the required demand or accommodate renewable generation without any problems [2,3], which may result in misleading conclusions. Indeed, in the case of heat pumps, expected benefits from their widespread introduction will be restricted once taking into account the additional investment in grid infrastructure required for a smooth integration [4]. For example, the cost for CO_2 mitigation by means of residential heat pump implementation increases importantly when considering grid reinforcements [5]. Furthermore, PV generation may be curtailed if voltage becomes too high in the local grid, not yielding the anticipated production [6]. Demand Side Management (DSM) could offer benefits both for renewable electricity integration and grid stability maintenance, requiring, however, infrastructure for smart metering and control to be established, and all stakeholders to accept and promote a dynamic market [7].

Consequently, qualitative and quantitative consideration of these practical implications is necessary for a better evaluation of potential CO_2 mitigation solutions. To study the influence of local grid restrictions on such policies—and vice versa, the impact of certain technologies on the electrical grid—detailed and flexible models are needed, representing accurately building energy systems and the network, while encompassing a wide spectrum of scenarios related to demand diversity and network configurations. This paper, therefore, presents an approach to assess the impact of heat pumps and PV on residential low-voltage (LV) distribution feeders, and link it to building and district properties. For this purpose, the Monte Carlo method and detailed simulations of both buildings and the grid are used. In order to demonstrate the contributions of this paper, a review of the literature pertaining to the PV and heat pump impact on distribution grids is presented hereunder.

Recently research began to focus on distributed generation integration in LV distribution grids, in particular photovoltaic systems. Papers [8,9] reviewed potential effects of PV systems on the grid, such as voltage rise, reverse power flow, power factor changes and harmonics, among others, together with the available technical solutions. Obi and Bass [10] also addressed challenges from grid-connected PV, and reviewed related standards and methods to improve efficiency and mitigate problems. Few papers [11–14] have studied the impact of PVs, in terms of voltage levels and voltage unbalance, on a limited number of representative or example grids. Conclusions vary depending on the examined networks and assumptions, showing problems intensify with increasing installed capacity, highly depending on the load localization on the grid. In a similar approach, Tovilović and Rajaković [15] looked into the combined impact of PV and electric vehicles (EV), concluding that with appropriate penetration rates, load reduction and voltage improvement can be achieved in LV feeders. In these studies, grids are loaded only with present-day domestic electricity demand, which is represented as profiles resulting from either smart meter data [11–13,15], or stochastic models [14]. Such approaches are not flexible enough to assess changes in buildings their loads. Other papers focus on specific problems and solutions, examined only for test networks and demand conditions. For example, Moshövel et al. [16] studied the benefits of battery energy storage on reducing the grid impact. Mokhtari et al. [17] proposed a DC link to improve generation-load balancing and avoid curtailment in residential applications. In [18], a method for voltage regulation of distribution grids is presented, based on reactive power control and coordination through telecommunication of multiple PV inverters. Finally, Manito et al. [19] analyzed transformer aging related to increasing PV penetration rates.

Regarding heat pumps, research has been directed to load managing, rather than distribution grid technical constraints. Several studies focused on the heat pump potential for load shifting in order to improve self-consumption in buildings or balance renewable generation at the system level, for instance Refs. [20,21]. Even though load shifting often aims to relieve the grid, simulation of the actual network impact is not included in such studies. Müller et al. [22] discussed a concept of DSM at district level, accounting for grid current conditions, and proposed a platform to analyze control strategies in districts. Drawback of this approach remains the computational time, which requires simplified models and limits the range of cases to be investigated. Few impact studies have been carried out pertaining to heat pumps. In [23] the impact of heat pumps, PV and combined heat and power units (CHP) on a German grid was studied, using a rudimentary building model and assuming balanced grid. Akmal et al. [24] looked into the effect of heat pump start-up on transient voltages and Bottrell et al. [25] investigated the impact on harmonic power quality. In [26] the voltage profiles in a specific low-voltage grid are analyzed for various degrees of heat pump penetration, together with PV and CHP. Although these studies employ detailed network simulations, variation in energy consumption or network configuration is poorly represented, thus prohibiting a comprehensive impact examination. Navarro-Espinosa et al. [27] conducted an extensive analysis for air-source and ground-source heat pumps, including variability in load profiles and considering uncertainty in many parameters. In a recent paper [28], they extended the scope of their work to additionally cover other technologies, such as PV, EV and micro-CHP, and a wider variety of feeders. Despite the comprehensiveness and accurate power flow analysis, their method relies on measured consumption data, lacking flexibility and opportunities to investigate the influence of building properties.

In large-scale analyses, grid constraints for heat pump and PV deployment are commonly disregarded. The literature review also shows that studies looking into technical aspects either have narrow focus, for instance on particular technical solutions or specific networks, or rely on simplified representation of the building energy demand, often failing to account for variability therein. To bridge this gap in literature, this paper presents a methodology to enable accurate grid impact study, taking into account the influence of building and district properties in a probabilistic way. The aim is twofold: First, to analyze the impact of heat pump and PV systems on low-voltage feeders, concentrating on the importance of demand diversity in terms of building characteristics and load coincidence. Second, to encompass in this investigation a broader range of cases compared to literature, in order to assess the influence of variation in feeder scenarios on the heat pump and PV integration. The latter is achieved through a comprehensive Monte Carlo approach, which allows for a probabilistic impact assessment and facilitates identification of the most influential parameters. Modeling is based on the Modelica `OpenIDEAS` framework, which was developed in earlier work to enable integrated dynamic thermal and electric simulation of buildings and district energy systems [29]. This framework has been already used to assess strategies for EV integration in buildings [30] and to examine the influence of grid technical restrictions on self-consumption of a zero-energy designed neighborhood [6]. This paper expands the scope of previous work, where the grid impact of heat pump-equipped buildings was also studied [4,31], by including more feeder configurations and variation in building quality, while concentrating more on building properties and demand profiles. At the same time, the presented approach also provides a basis for further