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Combined design and control optimization of residential heating systems in a smart-grid context

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ABSTRACT

Electricity generation from intermittent renewable energy sources is expected to rise drastically, which may have profound implications for building design and operation. The authors propose a combined design and control optimization that takes intermittent renewable energy sources into account and adds two steps to the literature. First is the use of multiple temperature levels, which allows a more realistic representation of energy storage and conversion efficiencies. Second is the explicit inclusion of a simplified representation of the electricity generation side, which allows quantifying the value of flexible electricity demand. The proposed modeling framework is applied to nine scenarios for the electricity generation mix in Belgium. The results indicate that a hot water storage tank is not an attractive technology in the presented scenarios, altering the CO_2 emissions less than 0.05 ton per building per year. This lowers the added value of modeling the temperature levels. The combination with the electricity generation system allows for a thorough assessment of the CO_2 emissions. Within the boundary conditions of the case study, combining an air coupled heat pump, floor heating and PV panels reduces yearly CO_2 emission up to 2 ton per building for an increase in annual cost below 350 EUR.

1. Introduction

Thermal energy storage (TES) at the residential building level can facilitate the integration of intermittent renewable energy sources (RES), such as from PV-panels and wind turbines, in the electricity generation system [1,2]. As shown in previous work by the authors [3], employing the passive and active TES potential of the building structure and of the domestic hot water (DHW) tank respectively, can decrease curtailment of RES in order to avoid electricity generation from power plants later on. This can lower the CO_2 emission associated with heat pumps. Hedegaard et al. [4,5] showed that installing heat pumps can already reduce curtailment and passive thermal storage decreases curtailment even further. In both studies, Hedegaard et al. find that a thermal storage tank is not cost-effective in this context. In previous work of the authors [6,3], the flexible operation of heat pumps is shown to reduce the curtailment of RES roughly by half. As found by Hedegaard et al. [5], this reduction in curtailment significantly ameliorates the conditions for offshore wind, leading to an increased investment in this technology. Waite and Modi [7] show how this reduction in RES curtailment varies for different wind and heat pump penetration levels, albeit without considering the flexible operation of heat pumps.

In contrast to the aforementioned work, this paper inverses the question of the impact of installing heat pumps on curtailment of RES: does a large-scale integration of RES has significant impact on the design of heating systems on a residential building level? In other words, will other residential heating systems or hybrid systems become more cost-efficient due to a large increase in electricity generation from RES? Examples could be the selection of a larger DHW tank or a storage tank coupled to floor heating in order to use more electricity during times of curtailment. Another option could be the installation of a heat pump with a supplementary gas-fired boiler to avoid electricity demand during times of low electricity generation by RES.

To this aim, an investment model for residential heating systems is needed which takes the dynamics of the heating systems and building structure into account. Furthermore, the electricity generation by RES should be explicitly included in the decision process.

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In this paper, *an optimization problem is proposed which simultaneously selects, sizes and operates the residential heating systems, in combination with an approximate modeling of the electricity generation system*. On a residential level, heating system investment costs typically have an important fixed cost component which is independent of the heating system size [8]. In order to take this into account in the sizing optimization, an integer decision variable is needed. Hence, the optimization problem for selecting, sizing and operating heating systems is modeled as a mixed integer linear program (MILP).

The use of MILP for heating system optimization differs from the more widely used genetic algorithms. According to Attia et al. [9], these genetic algorithms combined with building simulation tools are the most common optimization methodologies applied in the field of building energy performance research. The main advantages of this method, according to Attia et al., are the suitability for multi-objective optimization such as in [10,11], the ease of use and the robustness as it explores many points in the solution space simultaneously. The disadvantage lies in the large number of simulations needed and hence, the long calculation times.

Using the genetic algorithms, typically only controller setting parameters are included in design optimization [9,12]. In contrast to this method, this paper features a MILP optimization approach, where no building simulation tool is needed. The dynamics of the building envelope and heating system are explicitly modeled, in a simplified way within the optimization problem. This offers the advantage of faster simulation times, at the cost of lower accuracy. Another advantage is the aforementioned possibility of simultaneously optimizing design and control during each time step, which is necessary to accurately include the interaction with the electricity generation system [13]. This combined optimization approach has a long history in large scale energy system investment planning, using tools such as TIMES [14] and Balmorel [15], which are both based on linear programming (LP).

The MILP approach has been applied before to multiple scales to study the effect of the integration of RES on investment decisions in the build environment. On a single building level, these studies were performed using MILP [16] or a combination of genetic algorithms and MILP [17]. On an urban scale, Allegrini et al. [18] provided a literature review focusing on multiple energy networks and urban micro climate. The integration of RES on this scale was studied using a wide variety of approaches, from detailed multi-physics simulation models [19] to multi-objective operational approaches [20,21]. In contrast to the literature, the current paper studies the interaction of building energy demand with renewable energy on a national scale, which features a set of buildings in the order of magnitude of a million.

For this large scale, Hedegaard and Balyk [22] developed an investment model for buildings with heat pumps, which acts as an extension to the Balmorel model [15]. Investment in two technologies was considered, namely in a controller to activate the passive storage potential of the building structure and in a hot water storage tank for space heating. Given the combination with Balmorel, investment in these technologies is performed as a response to opportunities in the electric system. In this paper, a more detailed representation of building structure and storage tanks is employed as well as a consideration of other technologies such as back-up fuel-fired heating, PV panels and solar thermal collectors.

Some of the heating system models presented in this paper are similar to the framework of Ashouri et al. [16]. Ashouri et al. simultaneously optimized the selection, sizing and operation of both electrical and heating related system components in a single commercial building. These components are modeled as first-order linear differential equations. The main differences with the presented work and the work of Ashouri et al. lies in two points. First, different temperature levels are considered, which allows applying different efficiencies when a heating system is supplying heat to radiators, floor heating or a domestic hot water tank. This difference is crucial for heat pumps as these supply temperatures strongly influence system efficiency. A second difference lies in the explicit modeling of the electricity generation side. As shown by Patteeuw et al. [3], a massive uptake of heat pumps can have a large impact on the electricity generation system and hence alter any price or CO_2 emission profile stemming from this electricity generation system.

Table 1
Thermal energy content of a 1000 l hot water storage tank heated up by an air coupled heat pump or in the last row, by an electrical resistance heater (ERH). The numbers are for the case where the tank is coupled to floor heating and where the outdoor temperature is 5 °C.

Mean tank temp. (°C)	Heat pump COP (–)	Thermal energy stored (kWh)
30	3.3	0
35	2.9	6
45	2.4	17
60	1.9	35
90	(ERH) 1.0	70

A specific reason to combine these two additions, is the possibility to investigate the full energy storage potential of a thermal energy storage tank for space heating (TESsh), as illustrated in Table 1. For example, a residential heating system consisting of an air coupled heat pump (ACHP) and floor heating can be complemented with a 1000 l hot water storage tank. Suppose the floor heating has a supply temperature of 35 °C and a return temperature of 30 °C, at an outdoor temperature of 5 °C. The air coupled heat pump could load the TESsh in a stratified manner to contain 6 kWh_{th} at a COP of 2.9. However, at a time of abundant electricity generation from RES which is being curtailed, it could be beneficial to load the tank even further. The ACHP could heat up the tank further to 45 °C in order to contain 17 kWh_{th} at a COP of 2.4 and further to 60 °C to contain 35 kWh_{th} at a COP of 1.9. After this, an electrical resistance heater (ERH) could heat up the TESsh even further to 90 °C to contain 70 kWh_{th} at a COP of 1. Hence, *the different temperature levels are needed to model the TESsh in such a detailed manner while the explicit modeling of the electricity generation side provides the correct incentives to use this energy storage.*

The aim of this paper is twofold. The first aim is to assess whether the addition of the different temperature levels and the explicit modeling of the electricity generation side is crucial in the selecting and sizing of heating systems in residential buildings. Given the large variety in electricity generation mixes, heating system investment costs and climates in different countries, it is hard to perform this assessment in a general way. Therefore, a general methodology is developed and this methodology is applied to the case study of Belgium. The value of the two modeling additions will be tested for nine different electricity generation scenarios. This will provide insight in the impact of intermittent RES in Belgium on the residential heating system design including optimal control, which is the second aim of this paper.

This paper is structured as follows. First, the MILP optimization problem for selecting, sizing and operating heating systems combined with the approximate modeling of the electricity generation system is presented in Section 2. This modeling framework is applied to a case study of Belgium, for which the parameters and assumptions are provided in Section 3. The results presented in Section 4 show two aspects, namely the added value of the modeling framework and the implications for the case study. This is discussed further in Section 5 and finally the results are summarized in Section 6.