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CO_2-abatement cost of residential heat pumps with Active Demand Response: demand- and supply-side effects

Dieter Patteeuw[a,c,*], Glenn Reynders[b,c,d], Kenneth Bruninx[a,c], Christina Protopapadaki[b,c], Erik Delarue[a,c], William D'haeseleer[a,c], Dirk Saelens[b,c], Lieve Helsen[a,c,*]

[a] *KU Leuven Energy Institute, Division Applied Mechanics and Energy Conversion, Department of Mechanical Engineering, KU Leuven, Celestijnenlaan 300 box 2420, B-3001 Leuven, Belgium*
[b] *Building Physics Section, Department of Civil Engineering, KU Leuven - University of Leuven, Belgium*
[c] *EnergyVille, Waterschei, Belgium*
[d] *Unit Energy Technology, VITO, Mol, Belgium*

Abstract

Heat pumps are widely recognized as a key technology to reduce CO_2 emissions in the residential building sector, especially when the electricity-generation system is to decarbonize by means of large-scale introduction of renewable electric power generation sources. If heat pumps would be installed in large numbers in the future, the question arises whether all building types show equal benefits and thus should be given the same priority for deployment. This paper aims at answering this question by determining the CO_2-abatement cost of installing a heat pump instead of a condensing gas boiler for residential space heating and domestic hot-water production. The electricity system, as well as the building types, are based on a possible future Belgian setting in 2030 with high RES penetration at the electricity-generation side. The added value of this work compared to the current scientific literature lies in the integrated approach, taking both the electricity-generation system and a bottom up building stock model into account. Furthermore, this paper analyzes the possible benefits of active demand response in this framework. The results show that the main drivers for determining the CO_2-abatement cost are the renovation level of the building and the type of heat pump installed. For thoroughly insulated buildings, an air-coupled heat pump combined with floor heating is the most economic heating system in terms of CO_2-abatement cost. Finally, performing active demand response shows clear benefits in reducing costs. Substantial peak shaving can be achieved, making peak capacity at the electricity generation side superfluous, hence lowering the overall CO_2-abatement cost.

Keywords: Building stock, Heat pump, Active Demand Response, Electricity generation, Integrated model, CO_2-abatement cost

Nomenclature

$\bar{\eta}_{EGS}$ Average electricity-generation system efficiency [-]

*Corresponding authors

Email addresses: dieter.patteeuw@kuleuven.be (Dieter Patteeuw), lieve.helsen@kuleuven.be (Lieve Helsen)

η	Efficiency [-]
a	Annuity [-]
AC_{CO_2}	CO_2-abatement cost [EUR/ton CO_2]
CO_2	CO_2 emission [$ton/year$]
d	Electric power demand [MW]
g	Electric power generation [MW]
hor	Optimization horizon [h]
I	Investment cost [EUR]
i	Discount rate [-]
n	Number of years [$year$]
nb	Number of buildings [-]
$OPEX$	Operational costs [$EUR/year$]
PEF	Primary energy factor [-]
Q_{demand}^{year}	Yearly building heat demand [kWh]
SPF	Seasonal performance factor [-]
T_j	Vector with temperature states [$^\circ C$]
ACHP	Air coupled heat pump
ADR	Active demand response
CCGT	Combined cycle gas turbine
CGB	Condensing gas boiler
DHW	Domestic hot water
Fh	Floor heating
fix	Fixed demand; without heat pumps
GCHP	Ground coupled heat pump
HP	Heat pump
IM	Integrated model
OCGT	Open cycle gas turbine
PP	Power plant

Rad	Radiators
RES	Renewable energy source
SH	Space heating

1. Introduction

Heat pumps are often suggested as a key technology for decreasing the CO_2 emissions associated with space heating in the residential building sector [1]. According to a study for the European Heat Pump Association [2], large-scale introduction of heat pumps could reduce CO_2 emissions by 34% to 46% in the building sector of certain European countries by 2030. Bayer et al. [3] report a CO_2-emissions saving in space heating for multiple European countries up to 80%, depending mainly on the heat pump efficiency, the replaced fuel type and the CO_2 intensity of the electricity-generation system. In these studies, the CO_2 emissions associated with the electricity consumption of the heat pumps is assessed by considering an average carbon intensity of the electricity-generation system. Such methodology can be questioned for multiple reasons. First, the heat pump electricity demand can be strongly correlated to high or low instantaneous CO_2 intensities of the electricity-generation system, that can significantly deviate from the average CO_2 intensity. For instance, Reynders et al. [4] found that due to passive solar gains the space heating demand is mostly lower at times when PV panels are generating electricity; hence, a carbon intensity strongly affected by PV might not be a good measure for the CO_2 emissions related to space heating. Second, the electricity demand associated with a massive heat pump introduction could correlate with peak electricity demand, increasing the need for peak power capacity [5]. Finally, these published methods for accounting CO_2 emissions are unable to predict the emission reduction and peak shaving potential when heat pumps participate in active demand response (ADR) programmes. Active Demand Response is a form of demand side management where consumers change their electricity consumption in response to certain signals [6].

This paper aims at a thorough assessment of the CO_2-emission savings potential of residential heat pumps with ADR. The emission savings are determined by applying an integrated modeling approach that combines detailed operational aspects of both the electricity-generation system and single-family residential buildings with heat pumps. According to Hewitt [7], buildings equipped with heat pumps can play a role in coping with the variability and limited predictability of renewable energy sources. Different studies illustrate how introducing heat pumps, possibly combined with ADR, may be used to increase the penetration of RES and avoid curtailment losses [8, 9, 10] Hedegaard [11] [12] evaluated the added value of using heat pumps with ADR in energy systems with 50% wind power penetration. However,in all of the above mentioned studies, the building types which are better suited for installing heat pumps were not evaluated. Thereby, the main challenge lays in the wide variation of building types all with their own characteristics. The building parameters may affect many important factors, such as the overall heat demand, the heat pump cost and heat pump efficiency as well as the load shifting potential and peak electric power demand.

In order to compare the suitability of different building types for installing heat pumps with ADR, the CO_2-abatement cost is calculated, which is a measure for the cost of reducing CO_2 emissions. Although CO_2-abatement costs are known to be sensitive to assumptions on economic parameters such as fuel prices [13] or discount rates [14], this quantity is employed in this study for relative comparison between building and heating system types. As such, the numerical results obtained from this study on CO_2-abatement costs can only be compared to other technologies if identical assumptions on technical and economic parameters are made. A few studies report a CO_2-abatement cost for installing a heat pump instead of another heating system, but with not-fully adequate results due to simplifying modeling assumptions. Joelsson [15] reports an abatement cost of 100 EUR/ton CO_2 for a heat pump compared to a condensing gas boiler, -120 EUR/ton CO_2 compared to an oil-fired boiler and -190 EUR/ton CO_2 compared to direct electric heating. These values are obtained by considering yearly average values for energy use, heat pump performance and efficiency of the electricity-generation system. No attention is paid to the impact the heat pumps may have on the electricity generation. Kesicki [16] employs a long-term energy planning model, UK MARKAL, which considers system-wide interactions, and finds that heat pumps would become widely implemented in the UK if the CO_2 price exceeds 137 $£/ton$ CO_2. However, Kesicki reports that his study lacks the inclusion of more than two building types, heat pump peak demand, demand side management and occupants behavior. Our current study goes beyond this work by thoroughly taking into account all important factors for determining the CO_2-abatement cost, specifically: the operational cost and CO_2 savings, the investment in heat pumps and the investment in extra peak electric power capacity needed to cover the additional peak electricity demand. We do so by applying the integrated modeling approach as presented by Patteeuw et al. [17], which includes models of both the electricity-generation system and residential buildings equipped with heat pumps. The analysis in this paper is carried out for an energy system inspired by the Belgian power system. A high RES future energy system is assumed with wind and PV providing respectively 30% and 10% of the electric energy on a yearly basis.

The paper is structured as follows. First the modeling approach is discussed in Section 2. Section 3 shows the CO_2-abatement cost for the various building types, as well as the intermediate steps in determining this cost. The discussion section (Section 4) elaborates on some peculiar aspects of the results, in order to formulate the main conclusions in Section 5.

2. Methodology

The methodology section describes how the CO_2-abatement cost is determined in Section 2.1. To quantify both costs and benefits which make up the CO_2-abatement cost, an integrated model (IM) is needed, which is presented in Section 2.2.

2.1. CO_2*-abatement cost*

In many Northern European countries, like Belgium, a commonly installed heating system is the condensing gas boiler (CGB) [18], which is assumed to be the baseline heating system in this study. Installing a heat pump (HP) instead of a CGB requires a higher investment cost, but may lower CO_2 emissions and operational costs. This can be expressed in a CO_2-abatement cost (AC_{CO_2}) which is the sum of the difference in annual operational costs of the system and the annuity, a_i^n, of the additional investment, divided by the annual CO_2-emission savings [1].

[1]During the life cycle of the heat pump, there are also greenhouse-gas emissions associated with leakage of the refrigerant. As shown by Bettgenhäuser et al. [19], these greenhouse-gas emissions can cancel out up to a quarter of the greenhouse-gas emissions savings of installing a heat pump. There is a large debate on whether the use of these refrigerants should be phased out in favor of refrigerants with a lower greenhouse-gas potential. In the interest of transparency, greenhouse-gas emissions due to refrigerant leakage are not considered in this study. Hence, the reported CO_2-emission savings are only energy-related.

$$AC_{CO_2} = \frac{a^{20}_{0.035}(I_{HP} - I_{CGB} + I_{OCGT,IM}) - (OPEX_{CGB} - OPEX_{HP,IM})}{(CO_{2,CGB} - CO_{2,HP,IM})} \quad (1)$$

$$a^n_i = \frac{1-(1+i)^{-n}}{i} \quad (2)$$

In this expression, I_{HP} and I_{CGB} represent the investment cost of the heat pump and condensing gas boiler, respectively. It is assumed that the investment in a heat pump is performed at the end of life of the previous heat production system. Hence, the difference in investment cost is considered. $I_{OCGT,IM}$ stands for the investment cost of extra peak electricity generation capacity under the form of open cycle gas turbines, determined from the integrated model (IM). $OPEX$ are operational costs as explained below while CO_2 stands for the CO_2 emissions. These annual operational costs are to be compared with the annuity of the investment cost, in which the number of years, n, is considered to be the life time of the heat pump. This life time is 20 years as also assumed by Blarke [20]. For the discount rate, i, two values are assumed, one choice leaning more towards a societal perspective, 3.5% [21], and one reflecting a more private viewpoint, 7%[22].

The cost of generating the additional electricity demand of the heat pumps, $OPEX_{HP,IM}$, is determined through the application of an integrated model (IM) approach presented in Section 2.2. This integrated model is a centralized optimization towards minimal cost of generating the total electricity demand which includes the additional electricity demand of the heat pumps. In the baseline case, the operational costs stems from the purchasing of natural gas for the CGB from the wholesale market, $OPEX_{CGB}$. The wholesale-market price of natural gas is assumed to be constant at 25 $EUR/MWh_{thermal}$ [23], based on the higher heating value of natural gas. For both electricity and natural gas, the costs such as costs for transmission, distribution, taxes and RES levies are ignored. The reported operational cost savings are hence system wide costs, as CO_2 abatement costs are more commonly reported from a societal perspective [16, 21, 24].

Assuming a CO_2 intensity of 205 $kg\ CO_2/MWh_{thermal}$ [25], based on the higher heating value, for natural gas, both for CGB and gas fired power plants, and zero CO_2 intensity for PV and wind, the CO_2-abatement cost can be determined as the difference in emissions for the case of heating the building with a CGB, $CO_{2,CGB}$, and with a heat pump, $CO_{2,HP,IM}$. In the former case, the CGB burns natural gas directly but does not cause an increase in the electricity demand[2]. Hence, in the baseline case, the CO_2 emissions of the electricity-generation system remain unaltered. In the latter case, the emissions due to the heat pump arises from a rise in electricity consumption. The CO_2 emissions associated with this increased consumption are determined by the integrated model.

The investment costs include both the investment in the heat pump, I_{HP}, the avoided investment in a condensing gas boiler, I_{CGB}, and the investment in extra electric peak power capacity, assumed to be open cycle gas turbines (OCGT), $I_{OCGT,IM}$. The investment in peak-power units is assumed to be 750 EUR/kW [26]. This extra investment in peak capacity is determined by the integrated model, as it not only depends on the installed heat pump capacity but also on the simultaneity and stochastic aspects of both the electricity demand and RES-based generation. Additionally, ADR can further decrease the need for additional investment in peak capacity. The

[2]Both CGB and heat pump consume electricity for the controller and the circulation pump, but this is not considered as this will be the same for both cases.

cost for ADR infrastructure is not taken into account in this study.
The cost of a CGB is assumed to be $3,200\ EUR$ and independent of the size. The heat pump investment cost is based on Van der Veken et al. [27], although care should be taken with these data as this investment cost of a heat pump can vary significantly depending on the manufacturer and the installer. Depending on the nominal heating capacity, $\dot{Q}_{nom}$ in kW, of the heat pump, Van der Veken et al. pose a cost for a ground-coupled heat pump of $(1,000 \cdot \dot{Q}_{nom} + 10,000)\ EUR$. The cost of a low-temperature air-coupled heat pump depends on whether it is connected to radiators $(675 \cdot \dot{Q}_{nom} + 7,150)\ EUR$ or to floor heating $(410 \cdot \dot{Q}_{nom} + 7,650)\ EUR$. For a high temperature air-coupled heat pump, a cost of $(385 \cdot \dot{Q}_{nom} + 9,450)\ EUR$ is assumed, based on Heylen et al. [28].

2.2. Integrated model description

As it is the aim of this paper to identify whether specific building types are better suited for installing heat pumps with ADR, multiple building types (36 cases) and heating system types (3 cases) are considered. For every combination of building and heating system type, the CO_2-emission reduction, operational cost savings and increase in peak electricity demand are determined. In order to have a significant impact on the electricity-generation side, it is assumed that for each case (combination of a building case and heating system case) the electricity demand is scaled up to 250,000 buildings [3]. According to the study for the European heat pump association [2], this is the total number of heat pumps that is expected to be installed in Belgium by 2030.

As shown in Fig. 1, the integrated model is an optimization problem that considers all buildings, heating systems and electricity generation simultaneously. When ADR is applied, a centralized control is assumed in which the control of the heating systems interacts with the electricity-generation system. Hence, arrow (2) in Fig. 1 works bidirectionally. A simplified representation of the optimization problem is given by Eq. (3) to Eq. (7):

$$\underset{g^{PP},d^{HP},T}{\text{minimize}} \quad \sum_{j}^{hor} cost(g_j^{PP}) \tag{3}$$

$$\text{subject to} \quad \forall j : g_j^{PP} + g_j^{RES} = d_j^{fix} + nb \cdot d_j^{HP} \tag{4}$$

$$\forall j : f(g_j^{PP}) = 0 \tag{5}$$

$$\forall j : d_j^{HP} = h(T_j) \tag{6}$$

$$\forall j : T_j^{min} \leq T_j \leq T_j^{max}. \tag{7}$$

with g_j^{PP} and g_j^{RES} the electricity generated by conventional power plants and renewable energy sources (RES), respectively. The objective is to minimize the overall operational cost, $cost(g_j^{PP})$, of generating electricity with the conventional plants limited by their operational constraints, $f(g_j^{PP})$. The electricity demand, excluding the demand of the heat pumps, is assumed not to vary in this

[3]The number of buildings is taken to be identical for all combinations of building types and heating system types, in order to make the relative comparison between these types independent of the number of buildings. Each case is calculated separately, meaning that the 250,000 buildings are always of one single building type with one single heating system type. Hence, the number of buildings for each case does not directly correspond to the distribution in the Belgian building stock as presented in [29].

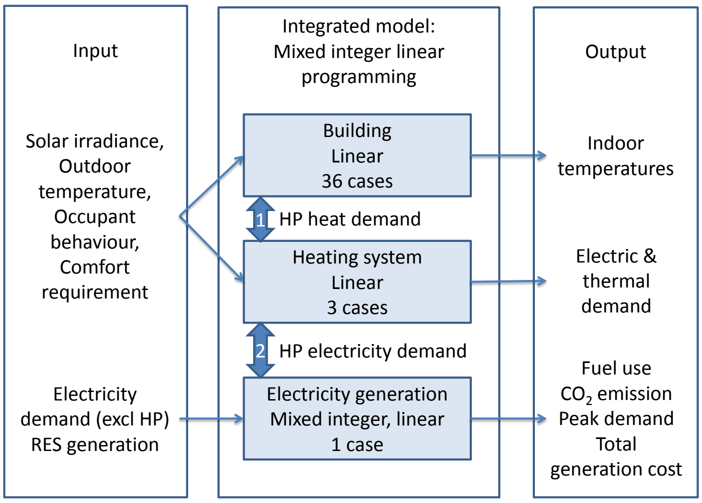

Figure 1: Schematic representation of the integrated model, which simultaneously dispatches electricity-generation units and activates heat pumps in order to deliver the total electricity demand and maintain thermal comfort in the buildings.

study and is denoted as the fixed electricity demand, d_j^{fix}. When heat pumps are considered, these cause an extra demand for electricity, d_j^{HP}. This demand is scaled up by a factor nb in order to represent a larger number of buildings. in the baseline case, where all buildings are equipped with a CGB, d_j^{HP} is zero. The temperatures in the buildings and the domestic hot-water tank, denoted by the vector T_j, are restricted state by state by a lower bound vector, T_j^{min}, and upper bound vector, T_j^{max}, in order to assure thermal comfort. The margin between these two bounds, and the dynamics of both building and heating system $h(T_j)$, determine the ADR potential of the heat pumps. Thereby, the building structure and domestic hot-water tank are used as thermal energy storage.

In the case of no ADR, the consumers minimize their own electricity consumption (Eq. (6) to Eq. (7)) regardless of the implications for the electricity generation side. The electricity-generation system then minimizes the cost for supplying the resulting electricity demand profile (Eq. (3) to Eq. (5)).

The time step j is assumed to be one hour, and the prediction horizon (hor) is one week. The results reported in this study are for one year, obtained by solving the optimization problem for each week of the year. A receding horizon is employed, in which the states of the system at the end of a week are passed on to the next week. In this study, perfect prediction of disturbances in the system is assumed and hence the presented results serve as an upper bound of the practically attainable operational and CO_2-emission savings. The potential for peak shaving is determined through an a-priori optimization of the critical week with the highest residual electricity demand[4], in which the installed capacity of the power plants is minimized. This installed capacity is then applied as an upper bound for g_j^{PP} throughout the considered year. A more detailed description

[4]The residual electricity demand is the electricity demand from which the generation from renewable energy sources is subtracted. This is hence the demand which the traditional power plants need to deliver.

of the modeling framework is given by Patteeuw et al. [17].

The electricity system, as well as the building types, are based on a possible future Belgian setting with high RES penetration at the electricity-generation side (Section 2.2.1) and increased insulation of the buildings (Section 2.2.2). For the sake of consistency, all input profiles to the model, such as weather data, RES-based electricity generation and electricity demand, are taken for the same year (2013) and for the same country (Belgium). The RES-based electricity generation is scaled up in order to represent a high-RES system.

2.2.1. Electricity generation

Regarding the electricity-generation side, profiles on fixed electricity demand and electricity generation from RES are taken from the Belgian transmission-system operator Elia [30] for the year 2013. We consider a high-RES system with 30% and 10% of the electric energy consumption covered by wind and PV respectively. This is largely in line with the European Commission's overall ambition of 45% RES in the power sector by 2030 [31]. This corresponds to an installed capacity of $8,274$ MW of wind onshore, $2,000$ MW wind offshore and $8,217$ MW of PV. The peak electric power demand, in the absence of heat pumps, amounts to $13,119$ MW. With this assumed RES capacity and taking the meteorological conditions of 2013, the peak in residual electricity demand, without heat pumps, is found to be $12,392$ MW. The latter peak demand is the most critical since it depicts the need for traditional power plants, which causes the high costs associated with covering peak demand. The remainder of the electricity-generation system is assumed to consist solely of combined-cycle gas turbines (CCGT) and open-cycle gas turbines (OCGT) with different efficiencies. We consider 28 CCGTs with a total installed capacity of $11,200$ MW, with a nominal net efficiency between 60% and 48%. The remainder of the electricity-generation system comprises of OCGTs, for which the installed capacity depends on the a priori optimization of the critical week with the highest residual demand. These plants have a nominal net efficiency between 40% and 30%. For both power-plant types, natural gas has a cost of 25 $EUR/MWh_{thermal}$. For RES-based electricity generation, it is assumed that the marginal cost is zero. Curtailment costs are zero. The electricity-generation system is modeled via a merit order, which considers efficiencies, minimal and maximal power output of power plants and neglects all other technical constraints. As shown by Patteeuw et al. [17], this approach can approximate the cost savings determined via a state-of-the-art unit commitment and economic dispatch model. Taking into account the system efficiencies and gas consumption, the overall CO_2 emissions for electricity generation and the resulting average system efficiency (in this paper defined as $\bar{\eta}_{EGS}$, as used in Eq. (8)) can be calculated.

2.2.2. Buildings

In this paper, only single-family residential buildings are considered. The building descriptions for the dynamic models originate from a bottom-up stock model based on the TABULA [29] building stock, as presented by Protopapadaki et al. [32], to which additions for new and renovated buildings are made. As illustrated in figure 2, a total of 36 different building types is considered, representing the Belgian residential building stock. The latter is divided in three typologies, six age classes and two renovation levels. The three different building typologies are typical for single-family buildings (i.e., detached, semi-detached and terraced houses). Each of these typologies is subdivided in six age classes (i.e., before 1945, 1945-1970, 1971-1990, 1991-2005, 2006-2012, after 2012), of which the most recent class is represented by low-energy houses with an overall heat loss coefficient of 30 W/K, corresponding to the economic optimum for Belgium found by Verbeeck [33].

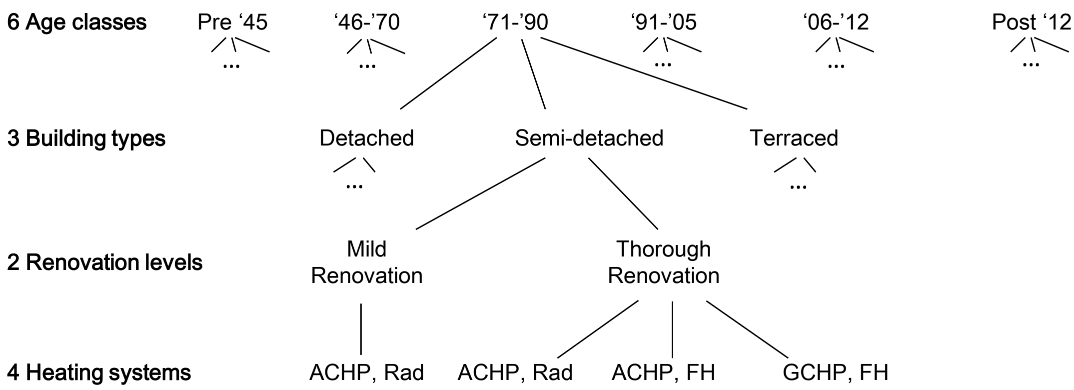

Figure 2: Overview of the different building types based on the Belgian residential building stock [32]. Given the 6 age classes, 3 building types and 2 renovation levels, there are in total 36 building cases.

Only in the buildings after 2005 a ventilation system is installed for which two cases, with and without heat recovery, are considered according to the TABULA description. A thermal efficiency of 84% is assumed for the heat recovery unit. For each age class before 2005, two renovation scenarios are considered. First, a "mild" renovation scenario includes roof insulation, replacement of the windows and an improvement of the air tightness. In the second, "thorough", renovation scenario the outer walls and floor are also insulated [32]. The original buildings without renovation are not considered in this paper since the supply water temperature for these buildings is too high to be supplied by a heat pump. Additionally, all poorly insulated Belgian buildings are assumed to have undergone at least a light renovation by 2030, in accordance with the proposed evolution of the Belgian building stock by Gendebien et al. [34]. The thermal behavior and heat demand of the dwellings are modeled using a two-zone reduced-order building model consisting of a 9 states lumped capacity model [35]. This thermal network model is translated to a linear state space model and included in Eq. (6). The assessment of the accuracy of this representation is described by Reynders et al. [35].

In order to represent the user behavior regarding temperature set points and domestic hot water demand, 52 user stochastic behavior profiles were generated using the method of Baetens and Saelens [36]. In order to reduce calculation time, this user behavior is aggregated by averaging the predetermined, effective lower temperature bounds [37]. The upper bound for the indoor temperature setpoint is $22\,°C$ and $20\,°C$ for the day zone and night zone respectively [38]. For the weather data, measurements in Uccle (Brussels, Belgium) for 2013 are used, which is the same year as the RES generation and fixed electricity demand as mentioned before. In this data set, the average temperature is $10.2\,°C$, the minimal temperature $-9.3\,°C$ and the number of heating degree days is $2,474$ with respect to a reference indoor temperature of $16\,°C$.

2.2.3. Heating systems

When considering the application of a heat pump, there are three main cases for the heating system: (1) an air-coupled heat pump (ACHP) with radiators, (2) an ACHP combined with floor heating and (3) a ground-coupled heat pump (GCHP) with floor heating[5]. Floor heating is only

[5] The radiators in the "thoroughly" renovated buildings are assumed to have a nominal supply water temperature of $45\,°C$. GCHPs are generally not combined with this kind of radiators, as the high supply water temperature of

considered in the buildings built after 1990, for which the nominal heating power allows applying a low temperature heat emission systems, such as floor heating [39]. In each case, the heat pump also supplies the domestic hot water demand (DHW), which is stored either in a 200 l or 300 l tank at 50 $°C$, depending on the maximum daily demand. For each renovation case with radiators, it was chosen to keep the original heat-emission system for low-temperature heating after renovation. For the "mildly" renovated building, depending on the age category, this leads to a nominal supply water temperature for zone heating that can be higher than 60 $°C$. This is too high to be supplied by a standard heat pump, in which case a double-compression, high-temperature air-coupled heat pump is considered [28]. The heat pump's efficiency is typically expressed by the coefficient of performance (COP) which is the ratio of the instantaneous heating power delivered divided by the electric power of the heat pump. The seasonal performance factor (SPF) is defined as the ratio of the thermal energy delivered throughout the year to the yearly electric energy consumption of the heat pump. In this study, the COP is determined according to Bettgenhäuser et al. [2], which results in an SPF as shown in Table 1. The newer buildings (built after 2005) show very similar SPF values to the "thoroughly" renovated buildings and are not shown separately. Based on Verhelst et al. [40], the COP is assumed to be constant during the course of each week.

Table 1: Range of heat pump seasonal performance factor for the different building cases.

Renovation Heat pump source Heat emission	Mild Air Radiator	Thorough Air Radiator	Thorough Air Floor	Thorough Ground Floor
Min SPF	1.8	2.3	2.5	3.3
Max SPF	2.1	2.6	3.0	4.0

For the ground-coupled heat pump, a borehole heat exchanger is assumed with average thermal properties for the ground in the north of Belgium, namely a thermal conductivity of 1.8 $\frac{W}{mK}$ and a volumetric heat capacity of 2.2 $\frac{MJ}{m^3K}$ [41]. The heat pump is sized to 80% of the nominal heat demand in accordance with the code of good practice in Belgium [42], with the peak heat demand delivered by a back-up electric heater. The model of the heating system comprises a set of linear equations, and is described in detail and verified with respect to a detailed simulation model by Patteeuw and Helsen [37]. This model consists of power limits for the heat pump and linear state space models for the heat emission system and the storage tank for DHW. This tank is assumed perfectly mixed and needs to be at a higher temperature than 50 $°C$ at times when DHW is demanded. It can be heated by the heat pump up to 60 $°C$, but also by the back-up electrical heater up to 90 $°C$. An exception to this is the high-temperature heat pump, which can heat up the storage tank for DHW up to 80 $°C$.

2.2.4. Illustration of IM output

Fig. 3 illustrates the output of the model for the case of newly built detached dwellings with heat recovery on the ventilation, an ACHP and radiators. The left figure shows the demand of the heat pumps, d_j^{HP}, on top of the fixed electricity demand, d_j^{fix}. When no ADR is applied, the heating systems do not interact with the electricity-generation system and only present a specific demand profile without feedback. In this case the mean temperature of the buildings (right figure)

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the radiators spoils the efficiency gain of the ground coupling.

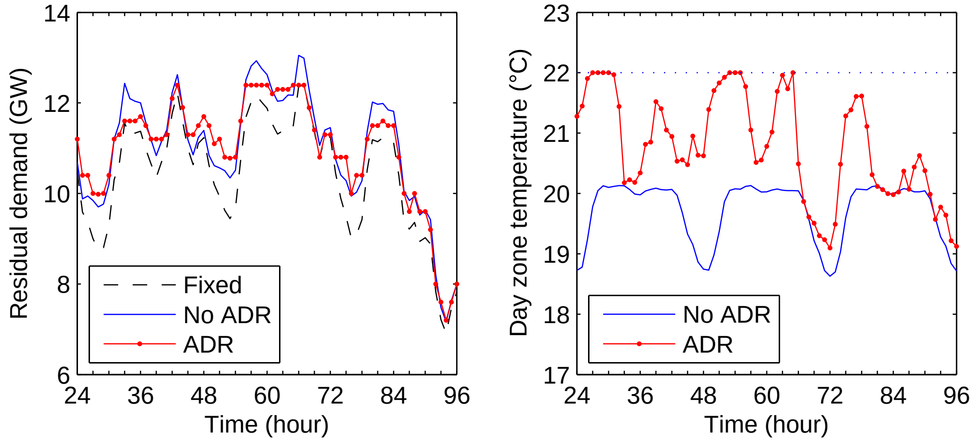

Figure 3: Electricity demand minus RES generation (left) and average day zone temperature (right) for three days of a typical week. The heat pumps cause an extra demand on top of the fixed electricity demand.

stays as low as possible while maintaining thermal comfort. Note that when assuming no ADR, optimal control is applied which results in an indoor temperature close to the minimum comfort temperature. When ADR is applied, the building is preheated up to higher temperatures in order to avoid electric demand at times of expensive electricity generation. Load shifting occurs during hours 26 to 31, avoiding demand when the fixed demand is already high and hence the least efficient power plants are running. From hour 56 to 67, the electricity demand is also shifted in time in order to reduce heat pump demand at peak demand (peak shaving). Although ADR has a direct impact on the indoor temperature, the temperature stays between the comfort bounds at all times and the rate of change of the indoor air temperature does not exceed $1\,°C$ per hour.

In practice, the temperature range that is available for ADR is expected to vary significantly depending on occupant preference. Moreover, it should also not be constant in time. Nevertheless, the comfort band of $2\,°C$ is assumed to be an acceptable range, taking into account the indoor temperature fluctuations observed for current state-of-the-art control strategies [43]. Traditional control systems apply a feedback control on the indoor air temperature with a typical spread of $1\,°C$ to $2\,°C$ [43] which will result in a similar average and similar fluctuations of the indoor air temperature.

3. Results

The first part of this section shows the CO_2-abatement cost for different building and heat pump cases, which allows a comparison between these cases. The sensitivity of this CO_2-abatement cost towards economical parameters is illustrated by the different discount rate cases. Next, the different drivers of this abatement cost are described in detail, namely the CO_2 emission (Section 3.2), the operational costs (Section 3.3) and finally the need for peak electrical capacity (Section 3.4).

3.1. CO_2*-abatement cost*

In Eq. (1), the CO_2-abatement cost includes operational cost savings, the additional investment in a heat pump and the extra investment in OCGT needed to cover the increase in peak electricity demand. In this abatement cost, the heat pump investment plays an important role. As shown in

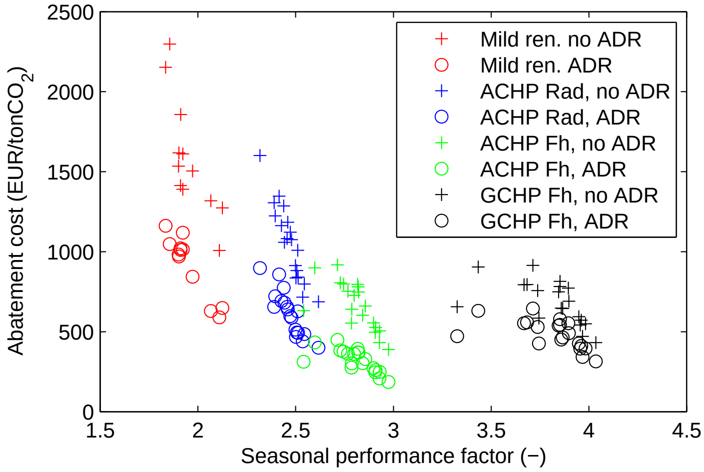

Figure 4: Overview of the CO_2-abatement cost as a function of the heat pump's seasonal performance factor (SPF) for a discount rate of 7%.

Fig. 4, the CO_2-abatement cost depends strongly on the heat pumps' SPF. In Fig. 4 there is a clear "clustering" of the results based on the four heat pump cases shown in Table 1. The "mildly" renovated buildings (SPF 1.8 to 2.1) are the least attractive buildings in which to install a heat pump, as these have the highest abatement costs. Applying ADR for these buildings does bring the abatement cost closer to that of the "thoroughly" renovated buildings.

For these "thoroughly" renovated buildings, coupling the heat pump to the radiators leads to somewhat higher seasonal performance factors (SPF 2.3 to 2.6) and also to lower abatement costs. However, the lowest abatement costs are obtained with the air-coupled heat pumps coupled with floor heating (SPF 2.5 to 3). For the best case, an abatement cost of 185 EUR/ton CO_2 is obtained. Ground-coupled heat pumps (SPF 3.3 to 4) lead to the highest CO_2-emission savings, as shown in the next section, but this is not enough to counteract the higher investment cost; hence the abatement cost is on average 100 $EUR/ton\ CO_2$ higher than for the air-coupled heat pump with floor heating. Furthermore, it must be noted that all buildings have been at least "mildly" renovated and the original heat-emission system was kept for low-temperature heating after renovation. As such, the main differences in abatement cost are induced by the heat pump investment cost and the influence of the supply-water temperature which is directly affecting the SPF of the heat pumps. These factors cause a large spread on the abatement cost as shown in Fig. 4. What also follows from the strong clustering of the results based on the SPF, is that there are little differences between the considered building types. As soon as the buildings possess are well insulated, i.e. the "thoroughly" renovated buildings and buildings built after 2005, their CO_2-abatement cost depends mainly on the type and SPF of the heating system. In those cases, it is observed that the age class and building type are of lesser importance. In order not to overload the figures this is not illustrated. Throughout all cases, the application of ADR is beneficial and lowers the abatement cost with 300 $EUR/ton\ CO_2$ on average.

The results in Fig. 4 are determined with a discount rate of 7%, reflecting a more private perspective. In order to illustrate the sensitivity of this abatement cost, the results are shown for the more societally-oriented discount rate of 3.5% in Fig. 5. This lower discount rate lowers the weight of the investment in the determination of the CO_2-abatement cost (Eq.1). This causes the

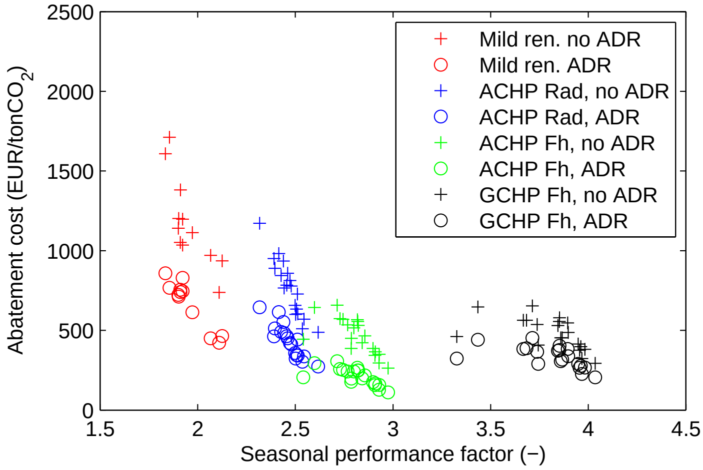

Figure 5: Overview of the CO_2-abatement cost as a function of the heat pump's seasonal performance factor (SPF) for a discount rate of 3.5%.

CO_2-abatement cost, on average, to reduce by 250 $EUR/ton\ CO_2$ and 150 $EUR/ton\ CO_2$ for the cases without and with ADR, respectively. In the best case, the abatement cost becomes 115 EUR/ton CO_2. The relative differences and trends between the different building and heating system cases appear to be similar to Fig. 4.

3.2. CO_2 *emissions*

Fig. 6 shows the relative change in CO_2 emissions associated with replacing a condensing gas boiler with a heat pump. The relative CO_2-emission savings are highly dependant of the SPF of the heat pump, for which four groups can be distinguished based on Table 1. The first group consists of the mildly renovated buildings which are all equipped with a high temperature ACHP (SPF 1.8 to 2.1) for which the CO_2 emissions are lowered by 15% to 25%. For the second group, consisting of the thoroughly renovated buildings with an ACHP and radiators (SPF 2.3 to 2.6), the CO_2-emission reduction is higher: 25% to 35%. The third and fourth groups represent the buildings with floor heating combined with an ACHP (SPF 2.5 to 3) or a GCHP (SPF 3.3 to 4) respectively. For these groups the decrease in CO_2 emission is 30% to 40% and 40% to 55%, respectively. Applying ADR leads to an additional reduction in emission of approximately 15% on average. For the cases with floor heating, applying ADR seems to cancel out the differences between the building types, leading to a general 45% or 60% emission reduction for an ACHP or GCHP, respectively. Note that these are all relative reductions in CO_2 emission. As buildings get better insulated and the annual heat demand lowers, the absolute CO_2 emission for the heat pump cases will converge.

One could also make a simplified estimation of the results in Fig. 6. If one would assume that all electric demand of the heat pump is covered by an electricity-generation system with a yearly average system efficiency, $\bar{\eta}_{EGS}$, and the heat pump has a seasonal performance factor, SPF, the estimation of the relative CO_2-emission reduction would be:

$$\frac{\sum^{year} CO_2(HP)}{\sum^{year} CO_2(CGB)} = \frac{\frac{CO_{2,gas} \cdot Q^{year}_{demand}}{\bar{\eta}_{EGS} \cdot SPF}}{\frac{CO_{2,gas} \cdot Q^{year}_{demand}}{\eta_{CGB}}} = \frac{1/(\bar{\eta}_{EGS} \cdot SPF)}{1/\eta_{CGB}} \tag{8}$$

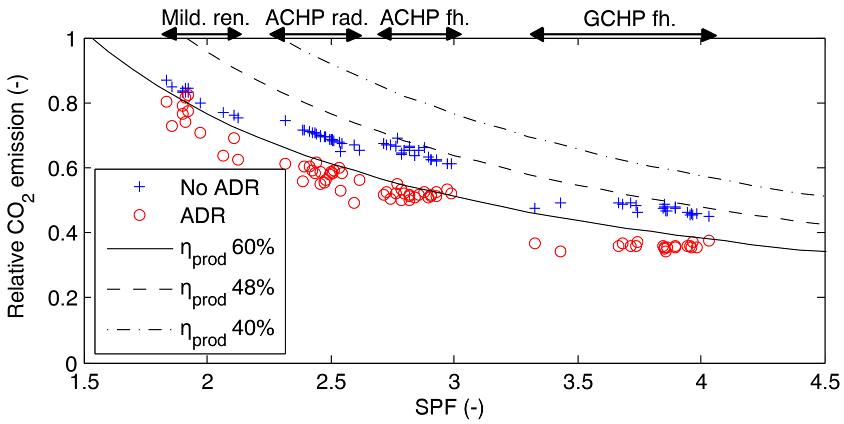

Figure 6: Relative CO_2 emission when replacing the reference condensing gas boiler with a heat pump which does not (no ADR) or does participate in ADR (ADR). The results are shown as a function of the seasonal performance factor (SPF) of the heat pump. Additionally, the simplified estimation based on three typical values of the yearly average electricity-generation-system efficiency $\bar{\eta}_{EGS}$ (Eq. 8) is shown.

with $CO_{2,gas}$ the CO_2 intensity of burning natural gas and Q^{year}_{demand} the yearly thermal energy demand of a building. This estimation is plotted in Fig. 6 if $\bar{\eta}_{EGS}$ would correspond to the minimal (48%) and maximal (60%) efficiency of a CCGT as well as the maximal efficiency of an OCGT (40%). As can be seen from Fig. 6, this equation is good in estimating the relative CO_2 savings when no ADR is applied. This is because, when no ADR is applied, most of the electricity demand of the heat pumps is covered by gas-fired power plants, as discussed in Section 3.3. If one assumes an η_{CGB} of 0.92, the fitted equivalent electricity-generation-system efficiency would be 51.8% with a coefficient of determination R^2 of 0.94. A similar fit can be found for the cases with ADR, attaining an equivalent electricity-generation-system efficiency of 65.1% with a coefficient of determination R^2 of 0.95. This equivalent efficiency is higher than what the power plants can attain, as applying ADR allows for a higher uptake of RES. Of course, the presented values will change if the boundary conditions of this study change.

Table 2: Equivalent electricity-generation-system efficiency, $\bar{\eta}_{EGS}$, which can also be interpreted as the inverse of the primary-energy factor (PEF).

Case	Literature	no ADR	ADR
$\bar{\eta}_{EGS}$	40%	52%	65%
PEF	2.5	1.9	1.5

The equivalent electricity-generation-system efficiency, $\bar{\eta}_{EGS}$, can also be interpreted as the inverse of the primary-energy factor (PEF) of electricity (Table 2). For example for the boundary conditions of this study, a heat pump with ADR has a PEF of 1.4 which means that for 1 kWh of electricity, on average 1.4 kWh of fuel is needed. In the literature, the PEF is typically around 2.5 [44] [45] [46] or varying between 2 and 3.5 [47]. The PEF is highly dependent on the mix of generation systems in the electricity-generation system. In this study, the mix consists mainly of efficient CCGTs and RES, causing the PEF to be lower than the typical value in the literature. The integrated model is able to determine this PEF accurately and determine the change in PEF due to the application of ADR.

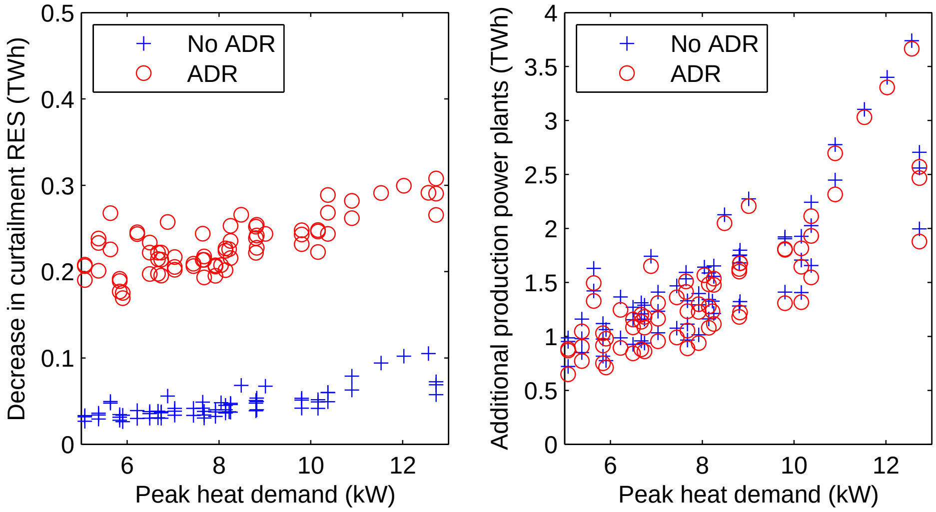

Figure 7: The electricity demand of the heat pumps is covered by reduction in RES curtailment (Left) and by additional generation from the gas-fired power plants (Right). Mind the difference in y-axis.

3.3. Operational aspects

Regarding the operational cost savings, the trends of relative cost savings with respect to the heat pump SPF are identical to those of the CO_2-emission reduction. Indeed, as natural gas is the only fuel considered in the study and the cost of RES is considered to be zero, the only driver in this study that reduces CO_2 emissions and fuel cost is a reduction in natural-gas demand. However, 250,000 heat pumps will have a significant impact on the electricity-generation system, which is discussed in this section.

The increase in electricity demand due to the 250,000 heat pumps is covered either by a reduction in RES curtailment (left in Fig. 7) or by an increase in generation by gas-fired power plants (right in Fig. 7). As Fig. 7 shows, this demand is mainly covered by a higher generation from the gas-fired power plants. When no ADR is applied, a minor fraction of the heat pump demand is covered by RES. In this case, the CO_2-emission reduction of installing a heat pump instead of a condensing gas boiler is dominated by the difference in overall efficiency.

When ADR is applied, CO_2 emissions do not only decrease due to a higher overall efficiency, but also due to load shifting. This load shifting improves the average efficiency of the power plants and, through a higher uptake of RES, decreases the generation by these power plants, as shown later in Fig. 9. On average, ADR causes these plants to produce 0.1 TWh less by increasing the use of RES by 0.15 TWh on average. In relative terms, the better insulated buildings will have a higher share (15% to 25%) of the heat pump electricity demand covered by RES compared to the less insulated buildings (5% to 15%).

Load shifting in heating systems typically leads to higher average temperatures (e.g. Fig. 3) and hence higher thermal losses and higher energy use. Fig. 8 shows this increase in energy use associated with load shifting. For all building cases, the domestic hot-water tank is used almost identically: around 3% more thermal energy is added to this storage tank, causing the yearly average temperature of the storage tank for DHW to be 4 $^{\circ}C$ higher. Regarding space heating with radiators (SH Rad), when ADR is applied, a clear trend can be observed: as the peak heat demand decreases, relatively more heat is emitted to the building. On average, the energy consumption

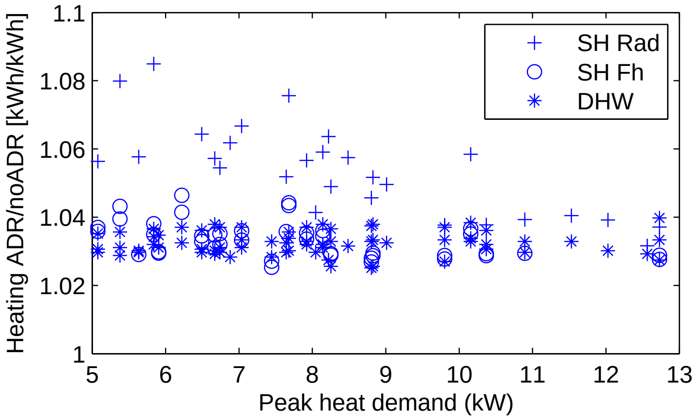

Figure 8: Rise in heat demand for space heating (SH) and domestic hot-water demand (DHW) when ADR is applied.

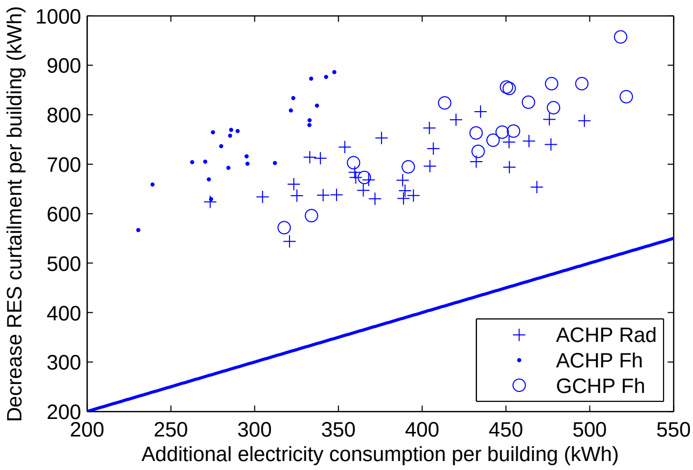

Figure 9: Decrease in curtailing RES per building with respect to extra electricity consumption per building when applying ADR. The thick contour line depicts the situation in which, on a net basis, no net reduction is achieved.

increases by 5.5% and the indoor operative temperature by $0.5\,°C$. If the buildings are equipped with floor heating (SH Fh), the trend is less pronounced, leading to an average increase in energy consumption by 3.5% and an average increase in indoor operative temperature by $0.2\,°C$.

One may perhaps argue that the extra energy use is just wasted in higher thermal losses. To see whether this is the case, the decrease in RES curtailment per building is plotted against the increase in electricity use per building in Fig. 9. For example, applying ADR causes a building to consume 200 kWh_e of electricity more but reduces 600 kWh_e of RES curtailment, then on a net basis, the gas-fired power plants produce 400 kWh_e less. From this figure it is clear that the decrease in curtailment is always higher than the increase in electricity consumption due to ADR. Hence on a net basis, less electricity from gas-fired power plants is used. For an ACHP with floor heating, this difference is the highest, reducing 400 kWh_e to 550 kWh_e electricity consumption from gas-fired power plants per building. Note that, due to the high RES assumption, the curtailment in the case with no ADR is rather high to begin with, namely around 2000 kWh_e per building. Hence, the relative reduction in curtailment is between 30% and 45% and is similar to values found in the

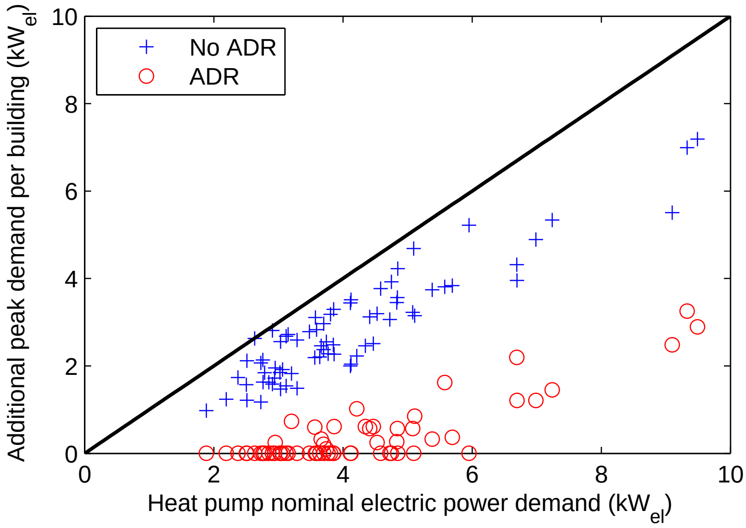

Figure 10: Performance of ADR in peakshaving. The electric power that each building is contributing to the demand at peak time is shown with respect to the nominal electric power demand of the heat pump.

literature [12, 48].

3.4. Peak capacity

In the calculation of the CO_2-abatement cost, the investment in additional peak power plant capacity is taken into account (Eq. 1). At an investment cost of 750 EUR/kW (Section 2.1), this additional capacity can be an important term in the CO_2-abatement cost, which is typically not included in heat pump CO_2-abatement cost in the literature. The need for additional peak power plant capacity depends highly on the simultaneity of the heat pumps' demand and the other electricity demand, assumed to be fixed, at peak periods. Fig. 10 shows how the heat pumps contribute to the electricity demand at peak periods, as also shown by Hawkes [49]. For the considered climate and demand profile, i.e. Belgium, the highest demand of the heat pumps will occur at cold and dark days which typically coincides with the peak electricity demand. As shown in Fig. 10, when no ADR is applied, the additional peak demand per building is strongly correlated with the nominal electric power demand of the heat pump. Regarding buildings with the same heat demand, a ground-coupled heat pump would hence perform best in this case, as this system has the highest COP and therefore the lowest peak electricity demand.

Installing heat pumps with ADR can cause the need for additional peak power plants to decline, as peak shaving can be applied. Below a certain capacity of the heat pump, the buildings are able to shift almost all demand away from the hour with the highest electricity consumption (Fig. 10). The buildings with floor heating generally perform better than the same building with radiators. Fig. 10 shows that peak shaving becomes less effective at higher design electricity demand. The reason for this is twofold. First, the buildings with a higher electricity demand at design conditions are also the less insulated buildings for which preheating is less efficient. Second, the load can only be shifted a limited number of hours. If a significant number of heat pumps perform this shift, the hours before the peak might become "saturated", e.g. in hour 56 in Fig. 3. When this occurs, there is no other option than to increase the consumption in these hours, and therefore the installation of additional peak power is required. Note that in this study, for each case, the heat pump demand

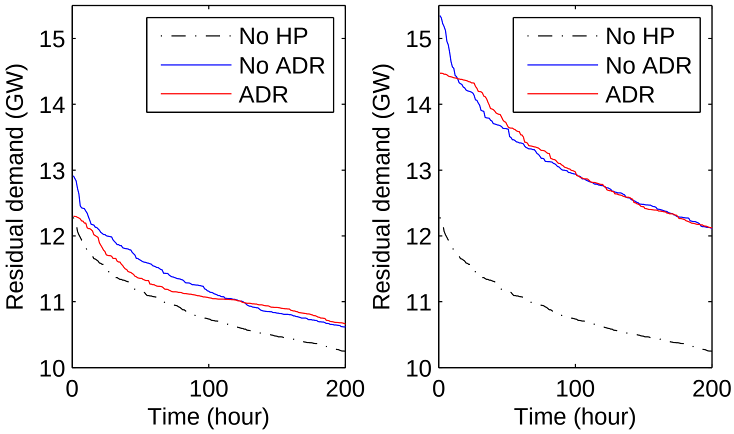

Figure 11: Part of the residual load duration curve for the cases of installing 250,000 air-coupled heat pumps with radiators in the best (left) and worst (right) insulated detached buildings. ADR decreases the need for extra peak power. For the best insulated buildings, the electricity generation covered by the peak power plants is also reduced.

was scaled up to represent 250,000 buildings. Altering this number of buildings can alter this "saturation" and hence also alter the results shown in Fig. 10.

Additionally to peak shaving, heat pumps with ADR also demand less power when the peak-power plants are running (Fig. 11). Since these are typically less efficient OCGT, compared to CCGT, this also leads to lower CO_2 emissions for this case. This effect is predominantly observed for the better insulated buildings (left in Fig. 11) where more load shifting is performed.

4. Discussion

The lower values of the CO_2-abatement cost found in this study are in the same order of magnitude as in the work of Joellson [15] and Kesicki [16]. However, those studies lack to highlight the large spread in abatement cost associated with the building renovation level, the type of heat pump installed and the application of ADR. As shown in Fig. 4, these factors cause the abatement cost to vary between 185 and $2,300$ $EUR/ton\ CO_2$. Furthermore, the abatement costs obtained here are not comparable to the other studies, as this study takes into account operational and investment costs at both demand and generation side.

What might also cause a large spread in the CO_2-abatement cost are the characteristics of the studied electricity-generation system. Van den Bergh et al. [50] and Delarue et al. [13] illustrate that the abatement cost is highly dependant on RES deployment and RES cost as well as the fuel mix and fuel cost of conventional power plants in the electricity-generation system. In order to limit the scope of this paper, only gas as a fuel was considered.

Applying ADR on heat pumps causes a reduction in peak electricity demand and RES curtailment. However, other technologies may be more cost-effective in attaining these reductions. For example, Dupont et al. [48] studied the application of ADR with battery electric vehicles and white good appliances. For a future scenario with 18% of electricity generation stemming from PV and wind and 8% of the cars being electric, this reduces RES curtailment with 41%. Hence, the potential for ADR on heat pumps also lowers. Another possible source of ADR competition stems from stationary batteries, which are a favourable option to combine with rooftop PV [51].

A number of factors influencing the CO_2-abatement cost could change by 2030. A limited sensitivity analysis towards these factors is shown in Table 3. A large-scale introduction of heat pumps can increase the electricity demand up to the point that extra investments in the distribution and transmission network is needed. It is hard to estimate the associated costs since these are very area-dependant [52]. For an arbitrary value of 3000 EUR of grid enforcement per household based on [52], Table 3 shows that the CO_2-abatement cost rises. This rise is however limited for most cases and does not alter the difference among the demand side technologies. One can also argue whether the additional investment in network infrastructure should be solely attributed to heat pumps, since a higher uptake of distributed PV needs similar investments [53]. Additionally, the investment cost of heat pumps could be lower in 2030, due to the learning curve effect associated with higher production volumes [54]. If one assumes a similar cost reduction as in Switzerland [54], the CO_2-abatement cost significantly lowers as shown in Table 3. Thus, the heat pump investment cost represents a substantial part of the CO_2-abatement cost, and lowering this cost can make a heat pump a more attractive option in lowering CO_2 emissions. Finally, according to the World Energy Outlook [55] the price of natural gas could rise 25% compared to 2014 levels. The CO_2-abatement cost appears to be less sensitive to this price as Table 3 shows.

Table 3: Sensitivity of the CO_2-abatement cost (in $EUR/ton\ CO_2$). The results are only shown for the cases with ADR for the detached buildings build between 1971 and 1990.

Renovation Heat pump source Heat emission	Mild Air Radiator	Thorough Air Radiator	Thorough Air Floor	Thorough Ground Floor
Reference case ($i = 7\%$)	981	493	249	395
3000 EUR network investment [52]	1128	624	347	470
40% cheaper heat pumps [54]	555	193	60	150
25% higher natural gas price [55]	986	476	227	370

In this paper, a large-scale deployment of heat pumps is considered to cause an additional electricity demand on top of the fixed electricity demand, and the extent to which this additional demand can be covered by RES is quantified. Thus, in this paper, we employ the incremental emission factor as defined by Bettle et al. [56]. Bettle et al. advise the application of this incremental emission factor for assessing a change in electricity demand and hence for the application in this paper, the replacement of condensing gas boilers with heat pumps. According to Bettle et al., the incremental emission factor can lead to 50% higher CO_2 emissions than employing the average emission factor, in which the CO_2 emission of a particular electricity demand profile is assessed in each time step with the average CO_2 emission of the electricity generation in that time step.

Table 4: Yearly CO_2 emissions in ton for certain scenarios for the cases with a condensing gas boiler (no HP), heat pump without ADR (no ADR) and heat pump with ADR (ADR).

Renovation level	Mild			Thorough		
Ton CO_2/year	no HP	no ADR	ADR	no HP	no ADR	ADR
Detached pre 1945	12.9	10.9	10.4	3.8	2.6	2.2
Terraced 1971-1990	3.2	2.7	2.3	2.1	1.5	1.2

This study does not include investment costs for building renovation, but assumes that the renovated buildings are already present. Of course, one could argue whether the investment in a heat pump is justifiable in a mildly renovated building, and whether this money should not better be spent on a more thorough renovation of the building. Judging from the results, this appears to be very case dependent, as shown in Table 4. For example, for the worst building case (detached building pre 1945) renovating the building envelope is more effective in reducing CO_2 emissions. In case of a better insulated building (terraced building from 1971-1990), installing a heat pump and performing ADR leads to almost the same emission reduction as renovating the building shell. For these cases, installing a heat pump and performing ADR is hence a viable alternative for newer and more compact buildings, where a thorough renovation of walls and floor might not be a feasible option.

For the ground-coupled heat pumps, the CO_2-abatement cost is on average higher than the air-coupled heat pumps with floor heating (Fig. 4). Ground-coupled heat pumps are known to have high global efficiencies in applications where both heating and cooling are needed, such as office buildings, thanks to the high efficiency of direct cooling [57]. This benefit is not exploited in residential buildings in a climate similar to that of Belgium, leading to longer pay-back periods.

It is important to note that from a consumer point of view, the increase in electricity consumption can demotivate the consumer of participating in ADR. A consumer will only participate in ADR schemes when facing a lower overall energy cost. This cost for the end-consumer typically consists of energy-related costs (the cost of electricity generation) and non-energy related costs (taxes, transmission and distribution tariffs), which are currently transferred as a proportional tariff (per kWh) to the end-consumer. A time-dependent price signal through the energy component of this tariff may be insufficient to motivate the end-consumer to participate in an ADR scheme: the decrease in energy-related costs, via a time dependent tariff, may be fully offset by an increase in the non-energy related costs. The latter increase can result from the increased energy use and hence, the time-invariant non-energy related component of the tariff.

5. Conclusion

This paper makes an assessment of the suitability of heat pumps for reducing CO_2 emissions in the residential building sector. A large-scale deployment of heat pumps with active demand response (ADR), instead of the commonly installed condensing gas boilers, is investigated by taking into account the effects on the electricity-generation system. To this aim, a detailed integrated model of buildings, heating systems and the electricity-generation system is employed. This allows a thorough assessment of the CO_2 emissions, fuel usage and peak-capacity investment. From the results, it appears that the reduction in CO_2 emission is dominated by the seasonal performance factor of the heat pump and the application of ADR. This ADR allows a higher uptake of RES-based electricity generation that would have otherwise been curtailed. The heat pumps appear to contribute significantly to the peak electricity demand. The application of ADR partially alleviates this problem, especially for the buildings with floor heating.

To allow comparison between heating systems and buildings, the above results are summarized in a CO_2-abatement cost. This CO_2-abatement cost is sensitive to assumptions on economical parameters, as illustrated by the difference in results due to a different discount rate. The numerical values on CO_2-abatement cost are hence only valid within identical assumptions on boundary conditions as in this study. Furthermore, the sensitivity on the assumptions on the characteristics of the electricity-generation system was not considered in this study. Rather, the focus is on demand side, where it appeared that the CO_2-abatement cost is already strongly influenced by multiple factors at the building level. The result is a large spread on the CO_2-abatement cost as a function of the heating system and building characteristics. The first factor is the renovation level of the considered dwellings, which causes large differences in CO_2-abatement costs. Installing a heat pump in "mildly" renovated buildings causes a low relative reduction in CO_2 emissions and hence a high CO_2-abatement cost. Buildings which have undergone a "thorough" renovation, as well as new buildings, show a substantially lower CO_2-abatement cost and CO_2 emissions when installing a heat pump. The second factor is the heating system. For the new buildings and the "thoroughly" renovated buildings, an air-coupled heat pump combined with floor heating is the most competitive heating system in terms of CO_2-abatement cost. The ground-coupled heat pump leads to higher CO_2-emission savings, but results in a higher abatement cost due to the difference in investment cost and the absence of cooling demand in residential buildings in a Belgian climate. The third factor is the application of ADR. This lowers the CO_2-abatement cost because of a lower investment in peak-power-plant capacity, operational cost savings and lower CO_2 emissions. These savings are reached by load shifting which causes, on average, the heat demand for domestic hot water to grow by 3% and the space heating demand by 5.5% for radiators and 3.5% for floor heating.

The proposed methodology can support policy makers in prioritizing investments in the building sector that reduce CO_2 emissions. It is shown that, within the boundary conditions of this study, particular buildings and heating system configurations are more cost-effective than others in reducing CO_2 emissions by installing a heat pump. Additionally, the effects of a large-scale deployment of heat pumps with ADR on the electricity-generation system are illustrated.

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