CO_2 Emission Savings Resulting from Smart Control of Photovoltaics and Heat Pumps in Residential Dwellings and Office Spaces in Belgium

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***Abstract*—This paper quantifies the CO_2 emission savings from photovoltaics and heat pumps in residential dwellings and office spaces in Belgium. The focus lies on the operational part of the lifecycle, using the CO_2 intensity of the conventional generation mix and a condensing gas boiler as a reference. Emission savings are calculated under normal operating conditions and under smart control of a flexible heat pump, which includes three strategies: minimal emissions, minimal electricity purchasing cost, and minimal grid interaction. The results illustrate that CO_2 savings by photovoltaics depend heavily on the technologies that are substituted. By default, heat pumps are found to create high emission savings, reaching up to 79% in residential houses. In addition, the results suggest strong potential for smart control of heat pumps towards minimal electricity costs and grid interaction, but less potential for control towards additional emission reductions.**

Keywords: CO_2,, Emission, PV system, Heat pump

I. INTRODUCTION

In light of the European Union objectives concerning energy-efficiency and sustainability, several Member States are advocating for the integration of renewable and distributed generation technologies, as well as alternatives to conventional space heating. With the aim of creating carbon emission reductions, consumer investment in photovoltaic (PV) generation systems and heat pumps (HPs) is often encouraged through tax benefits or direct subsidies. However, the marginal benefit of these technologies depends on the existing alternatives.

This paper aims to quantify the current ability of PV and HPs to obtain CO_2 emission savings in Belgian residential homes and office spaces , using condensing gas boiler heating and the country's underlying generation mix as a reference. Furthermore, the potential for additional benefits through smart control of a flexible HP in conjunction with a local PV system is analyzed. Four control strategies are compared: minimal energy consumption (i.e. normal control), minimal emissions, minimal annual cost, and minimal grid interaction of a PV-HP system. The focus of this work lies on the operational part of the lifecycle. Hence, emissions resulting from manufacturing or waste disposal are not accounted for.

The structure of this paper is as follows. Section II describes the input data, the methods used, and the different cases that are examined. Section III describes the results for photovoltaics. Section IV then describes the results for heat pumps, both under normal and under smart control. Finally, Section V concludes.

II. DATA AND METHODOLOGY

A. *CO_2 intensity of electricity generation in Belgium*

Because the year 2014 was rather atypical in terms of electricity generation, largely due to long outages of nuclear power plants, the Belgian generation mix during the year 2013 is considered for the purposes of this paper. Technology-specific generation data for every 15-minute interval are publicly available on the website of the national transmission system operator (TSO), Elia.

For most of the year 2013, the total installed capacity of the Belgian generation portfolio amounted to 16.6GW, including facilities based on nuclear (36%), natural gas (40%), water (8%), wind (4%), coal (4%), liquid fuel (2%), and various other sources (6%) [1]. Note that the latter includes units based on biomass, waste, and solar. Fig. 1 illustrates the composition of the Belgian mix in terms of electricity generated. Because the exact composition of the category 'other' is unknown, it is omitted from this analysis. Instead, solar generation is added based on dedicated solar data [2]. Similarly, electricity import and transport losses are not accounted for.

Table 1 summarizes technology-specific CO_2 intensities. They result from the CO_2 intensity of fuel combustion [3] and the efficiency of electric energy conversion [4]. The intensity of coal is assumed to be the average between brown coal and lignite, whereas the average of gasoline, diesel and LPG is denoted by 'fuel'. The intensity of nuclear, water, wind and solar generation is assumed to be zero. Combining the technology-specific CO_2 intensity from Table 1 with generation data allows to compute the weighted average CO_2 intensity (WAI_t) of the Belgian power system for every 15-minute interval t of the year 2013, by simply dividing total emissions by total corresponding electricity generation.

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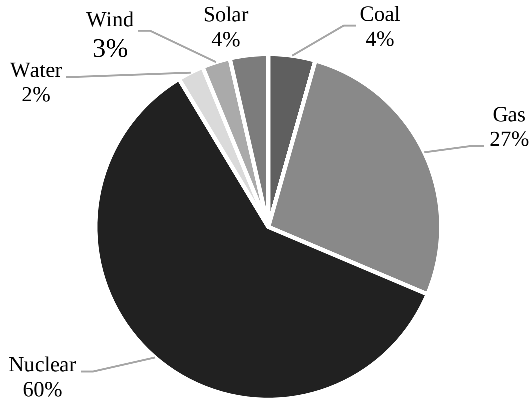

Figure 1. Belgian generation mix in 2013 [1].

TABLE I. TECHNOLOGY-SPECIFIC CO_2 INTENSITY [3] [4].

Energy source	CO_2 intensity of fuel combustion (kg/kWh)	Energy conversion efficiency (%)	CO_2 intensity (kg/kWh)
Coal	0.37	38.00	0.96
Fuel	0.25	35.00	0.71
Gas	0.23	55.00	0.42

B. *Calculating solar emission savings*

Because the CO_2 emission savings of additional solar generation depend on the CO_2 intensity of the electricity generation that is being substituted, two scenarios are considered:

- Scenario 1 assumes that solar generation substitutes every other generation technology in accordance with its weight in the contemporary generation mix. In other words, annual emission savings are calculated as $\sum_t \mathrm{Gen}_t^{PV}.\mathrm{WAI}_t$, with Gen_t^{PV} the quarter-hourly PV generation profile.
- Scenario 2 assumes that solar generation substitutes the most expensive generation technology in the merit order. Here, this is assumed to be gas-fired generation. This assumption is reasonable, given that gas (and liquid fuel) based generation is typically more expensive and more flexible than nuclear or renewables [5]. Furthermore, Fig. 1 shows that gas makes up a large portion of electricity generation. The corresponding CO_2 intensity thus equals 0.42kg/kWh (cf. Table 1).

In order to assess the sensitivity of the results to differences in location and orientation of the PV panel, two generation profiles are constructed, according to different approaches:

- Approach 1 computes the profile of an average PV panel in Belgium, based on country-wide generation data published by the TSO. The average output (%) of a PV system is calculated by dividing actual generation measurements by the total monitored solar capacity, and subsequently multiplying the result with the peak power of the PV system.
- Approach 2 simulates the profile of a specific PV panel, with a given location, orientation, and weather conditions, and using the PV model described in [6]. A Southern orientation with a 35 degree inclination is assumed.

The main advantage of the former, is that it represents the average behavior of solar generation in Belgium, whereas the latter allows to specify the characteristics of a specific PV panel, which is compatible with the way in which HP profiles are simulated.

C. *Calculating heat hump emission savings*

HP profiles are generated in Dymola and Matlab, using the model described in [7]. Annual CO_2 emission savings are computed relative to emissions from condensing gas boilers. The reference emission is obtained by multiplying annual heating demand with the CO_2 intensity of gas combustion, which is 0.23 kg/kWh (cf. Table 1).Note that in the case of offices, it is assumed that the HP is also used for cooling. This is reasonable, given their large demand for cooling, which creates potential for active demand shifting in combination with local PV. Therefore, the reference case for offices also includes cooling based on an air-coupled HP.

Because emission savings may depend on factors such as the type, size and age of the building, as well as user behavior, heat emission system and meteorological circumstances, several test cases are considered. In particular, a distinction is made according to building type (2), HP type (2), and control strategy (4), each of which is further clarified below.

<u>Building type</u>

Two types of environments are considered: a recently built residential house, and a typical office space of an SME. Although each type has its own characteristics, the following are shared:

- Detached and located in Brussels
- Low-energy, with a U-value of 0.1 W/m²K for the roof, 0.3 W/m²K for the façade, 0.15 W/m²K for the floor an0.1 W/m²K for the windows. The n50 value is 1 per hour.
- Floor heating for heat emission, with a design supply and return temperature of 35°C and 30°C respectively.

In the residential building, the floor area for the day zone is 132m², with 137m² for the night zone. In the day zone, occupants desire an indoor temperature of 21.5 °C when present and 15.5°C otherwise. The minimal temperature for the night zone is 12°C. During the heating season, temperatures are not allowed to exceed 24°C in the day zone and 22°C in the night zone. The occupants demand on average 100 liter of hot water at 38°C per day. To this aim, a hot water storage tank of 200 liter is installed with a standby loss of 1.7 kWh per day in case of a 45°C temperature difference. This tank can be heated up by the heat pump up to 60°C, but even higher with the use of the back-up electrical resistant heater to 90°C. HPs installed have a thermal peak power of 10kW.

In the office, the floor area is 2000m². The HP is here also used for cooling, using radiant cooling panels with an energy efficiency ratio (EER) of 4.5 and 5 for an air- and ground-coupled HP respectively. The building has two floors, with one person per 15m². In order to attain thermal comfort (ISO7730) during office hours, the temperature should stay between 20 and 24°C in winter and 23 and 26°C in summer. Internal heat gains of appliances and lighting account for 17 W/m². There is no hot water demand considered in this building. The HPs installed have a thermal peak power of 30kW. Fig. 2 illustrates the difference in shape of the profile compared to residential usage on a typical day, under normal operating conditions.

Heat pump type

A heat pump provides warmth by absorbing heat from a cold source, and transferring it to a warmer heat sink. Because heat is moving in the opposite direction of its spontaneous flow, external power, in the form of electricity, is needed to accomplish this work. Although various types of HPs exist [8], air- and ground coupled compression HPs are considered in this paper. Their characteristics are described below.

An air-coupled HP extracts heat from the ambient air surrounding the building. On average in Belgium, an air-coupled HP typically reaches an average coefficient of performance (COP) of 3 [9], meaning that this HP can deliver 3 kWh of heat using 1kWh of electricity. The COP is modelled in accordance with [10]:

$$\mathrm{COP} = A \cdot \frac{T_{supply}}{T_{supply} - T_{source} + B} \quad (1)$$

with T_{supply} the temperature of the water flowing towards the heat sink (i.e. the living space) and T_{source} the temperature of the water of the heat source, in this case an air heat exchanger. According to [10], the parameters A and B are 0.38 and 10 respectively. In addition, the COP decreases linearly below the bivalence temperature of -3°C to a level of 1 at -15°C.

A ground-coupled HP works similarly, except that the ground is used as a heat source through the use of a ground heat exchanger. Typically, an average yearly COP of 4 is reached in Belgium [9]. The parameters A and B are 0.5 and 10 respectively. The ground heat exchanger is assumed to be a borehole in the soil with a thermal conductivity of 1.8 W/mK and a volumetric heat capacity of 2.2 MJ/m³K. The configuration of the borehole itself is assumed to have a radius of 0.1m and a thermal resistance of 0.13 mK/W.

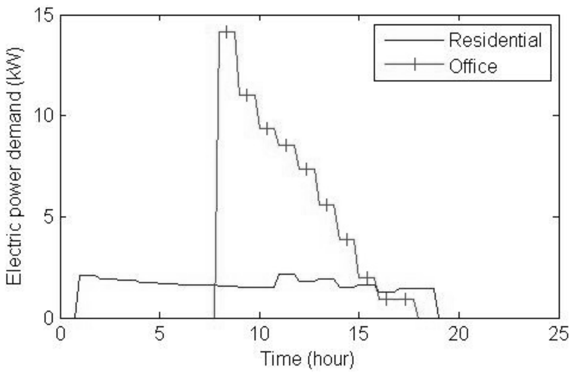

Figure 2. Residential and office HP profile shape.

Control strategy

This paper features four types of control strategies for operation of a flexible HP. These are described in more detail below. Note that the latter three are referred to as 'smart control'.

- Normal control (C1): here, the HP minimizes its annual electricity consumption, within predefined boundaries such as technical and comfort limits.
- Minimal CO_2 emissions (C2): the HP minimizes the annual CO_2 emission from consuming electricity. The WAI of the Belgian generation mix in each 15-minute interval of 2013 is used for this purpose. Emission savings are obtained through shifting of consumption towards less CO_2 intensive times.
- Minimal cost (C3): the HP minimizes annual electricity purchasing costs. Consumption is shifted towards cheaper moments in time. Because electricity retail prices are usually static, it is assumed here that electricity can be purchased directly from the wholesale market. Prices are based on the BELPEX day-ahead market in Belgium during the year 2013.
- Minimal grid (C4): the HP aims to minimize the annual net interaction with the distribution grid, in terms of electricity withdrawal and injection, by synchronizing consumption and generation from a local PV system. PV generation profiles are used in accordance with approach 2 (cf. subsection A). Furthermore, the PV system is dimensioned in such a way that the HP-PV combination becomes energy-neutral, meaning that annual generation equals annual consumption. As a result, the number of PV panels installed depends on the building type and on the type of HP.

An important caveat for interpretation of the results in Section IV is that -with the exception of grid interaction- all results correspond to HPs separately. For instance, the calculated annual cost assumes that all electricity was purchased on the wholesale market, instead of being partly sourced from local PV. Simply adding emission reductions of both technologies, in order to calculate the emission savings of a PV-HP system, would be incorrect. This is because part of the HP electricity consumption is then sourced from local PV, and therefore its emission reduction estimate is no longer accurate.

III. Results: Photovoltaics

Applying the two approaches for simulation of PV generation, according to two scenarios for generation substitution, allows to compute annual emission savings in four different combinations. Table 2 summarizes these results. Note that results are described in terms of kg CO_2 emission saving per kW installed generation capacity.

From Table 2, it can be seen that the results are heavily affected by the scenarios considered. On the other hand, the effect of using a different PV modeling approach is found to be relatively small. In practice, scenario 2 is arguably more realistic, as solar generation usually substitutes the most expensive and flexible technologies in the market, instead of for instance nuclear power plants. According to these results, an average-sized PV installation in Belgium of 4 kW_p can

TABLE II. ANNUAL EMISSION SAVINGS BY SOLAR (kg/kW)

	Scenario I	Scenario II
Approach I	132.8	409.5
Approach II	146.1	448.8

create up to 1795kg in annual CO_2 emission savings. In the worst-case scenario, an installation of the same size would create approximately 531kg in annual emission savings.

IV. Results: heat pumps

All the major results related to heat pumps are summarized in Table 3. The four parts of the table each represent a unique combination of building and HP type. Each column corresponds to a control strategy, as described in section II. The results considered are respectively:

- Absolute emission saving per unit of maximum thermal power. Recall that residential HPs are assumed to have a thermal power of 10kW, while office HPs are assumed to have a thermal power of 30kW. An important caveat is that, as opposed to PV, the results for HPs are not linearly related to the thermal power of the system and, as such, they cannot be used for upscaling.
- Relative emission savings compared to condensing gas boilers. Note that annual CO_2 emissions in the reference case are calculated at 5.322kg and 9.449kg in residential houses and office spaces respectively. Recall that in offices, the reference case includes cooling by means of an air-coupled HP.
- Annual electricity demand for heating. This also includes cooling in the case of office spaces.
- Annual electricity purchasing cost, assuming that it is purchased on the BELPEX day-ahead wholesale market.
- Annual grid interaction as the sum of injection and withdrawal, when a PV system is present large enough to make the PV-HP system energy neutral.

First, these results are compared between HP type and building type under normal control (C1). Second, normal control is compared with smart control (C2-C4).

A. Normal control

Consider the results in the first column (C1) of Table 3. It can be seen that using HPs all cases leads to high emission savings compared to heating based on condensing gas boilers. A ground-coupled HP with a capacity of 10kW in a residential house and 30kW in an office space is shown to bring 4225kg and 6900kg respectively in annual emission savings. The relative emission savings range from 61.3% in office spaces with air-coupled HPs to 79.4% in residential dwellings with ground-coupled HPs.

Another general observation is that ground-coupled HPs bring substantially higher emission savings than their air-coupled counterparts. For instance, a ground-coupled HP in a residential building leads to approximately 10.5% higher emission savings than using an air-coupled HP. This can be explained by their greater inherent efficiency (COP). For the same reason, the annual electricity demand, grid interaction and costs of ground-coupled HPs are typically lower. For example, electricity costs are 31% lower in offices using ground-coupled, instead of air-coupled HPs. Note that, the smaller electricity demand, the smaller the size requirement for a PV system to become energy-neutral.

When comparing the relative performance of HPs in residential and office spaces, it is found that, per unit of unit of peak thermal power, higher emission savings are obtained in residential environments. This may seem counter-intuitive, as offices demand most heat during the day, when electricity generation is typically less CO_2 intensive than during the evening peaks. However, office spaces are characterized by high internal gains (e.g. through heat released by people and appliances), making them relatively less dependent on dedicated heating infrastructure. As a result, heating demand of offices is more concentrated around colder periods, whereas heating demand for households is more evenly spread throughout the year. This is reinforced by the fact that the COP decreases with the temperature of the heat source.

TABLE III. RESULTS OVERVIEW FOR HEAT PUMPS

Residential/AIR	C1	C2	C3	C4
Saving (kg/kW)	382.4	384.6	377.7	355.0
Saving (%)	71.9	72.3	71.0	66.7
El. demand (kWh)	8061	8243	8727	10135
El. cost (€)	422.4	411.5	379.0	532.0
Grid interaction (kWh)	11647	11877	13704	7941

Residential/GROUND	C1	C2	C3	C4
Saving (kg/kW)	422.5	424.3	419.4	403.0
Saving (%)	79.4	79.7	78.8	75.7
El. demand (kWh)	6035	6130	6508	7532
El. cost (€)	312.0	304.2	284.1	391.2
Grid interaction (kWh)	8294	8437	9736	5456

Office/AIR	C1	C2	C3	C4
Saving (kg/kW)	193.0	199.0	184.7	171.1
Saving (%)	61.3	63.2	58.7	54.3
El. demand (kWh)	19951	20663	24611	25457
El. cost (€)	1149	1061	828.9	1380
Grid interaction (kWh)	27310	30491	40660	16109

Office/GROUND	C1	C2	C3	C4
Saving (kg/kW)	230.0	233.9	224.3	211.1
Saving (%)	73.0	74.3	71.2	67.0
El. demand (kWh)	14687	15101	17677	19238
El. cost (€)	793.0	737.1	621.7	989.9
Grid interaction (kWh)	20324	21862	28683	11643

B. Smart control

Consider the results in the second column (C2). It can be seen that switching from normal control to minimal emissions has little effect. For instance, in the case of residential houses with air-coupled HPs, the absolute emission saving increases by 0.6%. Simultaneously, annual electricity demand and grid interaction always increase in a slightly more pronounced way. In the example above, electricity demand goes up by 2.3%, while grid interaction increases by 2%. This is a recurring effect, regardless of building or HP type.

Now consider the third column (C3), corresponding to the minimal cost control algorithm. Compared to normal control, it can be seen that this strategy leads to significant cost reductions. Although relative cost reductions are slightly higher for air-coupled than for ground-coupled HPs, there is a much more noticeable difference between building types. While an air-coupled HP in a residential premise can create 10.3% cost reduction using this algorithm, the same type of HP can create a 27.6% cost reduction in an office environment. In addition, it can be seen that controlling for minimal costs also leads to slightly lower emission savings than under normal control. However, the impact on electricity consumption and grid interaction is much more pronounced, especially in offices. In particular, electricity consumption increases by approx.. 8% in residential buildings, whereas it increases by more than 20% in offices. This is because offices have room for consumption shifting throughout the whole year, whereas residential users are more restricted to shifting during the winter period.

Lastly, consider column C4, where the HP is controlled towards minimal grid interaction, in conjunction with a local PV system. It can be observed that large reductions in grid interaction are possible compared to what is achieved under normal control of a PV-HP system. Using this algorithm, residential consumers can reduce their interaction with the grid by approximately 32%, while offices can achieve reductions of up to 43%. The type of HP has little effect on this result. Offices have higher potential for reduction in grid interaction because they can also use local generation for cooling purposes, and the need for cooling typically coincides with moments of high PV generation. In addition, it can be seen that controlling for minimal grid interaction always leads to slightly lower emission savings, but significantly higher electricity consumption (25-31% increase).

V. CONCLUSION

From this study, it can be concluded that photovoltaics and heat pumps in Belgium create substantial emission savings, making them effective tools in the pursuit of emission reductions from electricity generation and space heating.

Second, it can be concluded that heat pumps are sufficiently flexible to be controlled towards other objectives than energy efficiency. Although smart control towards minimal emissions is shown to have little added value, it is found that control towards minimal electricity purchasing costs can have a substantial impact, especially in offices which also use a heat pump for cooling. The downside of this approach is the more profound increase in electricity consumption, although the effect on emissions is small. This algorithm allows to couple the positive environmental externalities of heat pumps (in terms of emission reductions) to economic benefits for the users. Therefore, the existence of alternative and dynamic pricing schemes in retail markets can be beneficial towards heat pump investment. Smart control towards minimal grid interaction, in conjunction with a local PV system, is also shown to have large potential, although the current design of electricity prices and network tariffs does not typically encourage such behavior.

Finally, the results confirm the hypothesis that ground-coupled heat pumps are more energy-efficient than their air-coupled counterparts which, under normal control, is shown to result in lower electricity demand, grid interaction, and electricity purchasing costs. On the other hand, when comparing the performance of heat pumps in residential and office spaces, it is found that the former provide more room for emission reduction, per unit of installed thermal power. This can be attributed to the fact that residential heating demand is less concentrated around colder, more CO_2 intensive periods of the year, as opposed to offices which benefit from larger and permanent internal heat gains.

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