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Smart Grid Ready Controls' Effect of Heat Pumps on Operational Carbon Emissions

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Abstract

This study investigates the impact of Smart Grid Ready (SGR) control strategies on reducing the operational carbon emissions of air-to-water heat pumps in residential buildings across Germany, Denmark, and France. Using dynamic energy simulations that incorporate both real-time and predictive grid carbon intensity data, the research compares perfect and data-informed demand response approaches for heat pump operation. Results demonstrate that SGR controls, especially with perfect day-ahead forecasting, can shift heat pump operation to periods of lower grid carbon intensity, leading to reductions in the carbon intensity of electricity consumed by HVAC systems of up to 3%, with the most substantial gains observed in Germany (a decrease of 14 gCO_2/kWh in 2022). However, absolute reductions in operational carbon emissions remain less than 2.6%, partly due to slight increases in electricity demand caused by higher storage temperatures during load shifting. Furthermore, the study highlights that optimizing PV system sizing, based on self-production and grid liability metrics, is crucial for effective renewable energy integration, which yields a lower PV capacity than traditional Net Zero Energy Building (NZEB) methodologies suggest. These findings highlight the importance of advanced, context-sensitive control algorithms and integrated design for achieving meaningful carbon mitigation in grid-interactive, renewable-powered residential buildings.

Keywords

Smart Grid Ready control, heat pumps, PV systems, operational carbon emissions, load matching, renewable energy integration, Net Zero Energy Buildings

1 Introduction

The ongoing energy transition focuses on reducing consumption and increasing the integration of renewable energy sources, positioning the building sector at the forefront of climate action. Within the European Union, major legislative initiatives such as the "Fit for 55" package [1], the Energy Efficiency Directive [2], and the Renewable Energy Directive [3] collectively aim to achieve, by 2030, a 55% reduction in greenhouse gas emissions compared to 1990 levels and to raise the renewable energy share in the building sector to 49%. The Energy Performance of Buildings Directive (EPBD) [4] further advances these ambitions, targeting the development of zero-emission buildings and promoting nearly Zero Energy Buildings (nZEBs) and Net Zero Energy Building (NZEB) concepts that combine improved thermal envelopes with high-efficiency, renewable-powered technical building systems [5, 6].

A common approach for achieving these ambitious performance goals involves integrating efficient building structures with advanced renewable energy technologies: primarily heat pumps for space heating, cooling, and domestic hot water (DHW), alongside on-site photovoltaic (PV) systems for clean electricity generation. Such configurations enable residential buildings to reach NZEB targets on an annual basis in a cost-effective manner [5–7]. However, this annual net-zero framework introduces a core challenge: load matching, the temporal coincidence of intermittent PV generation with dynamic building energy demand [6, 8].

Load mismatches occur when PV production and building demand do not align in real-time, resulting in surplus electricity exports or periods where the grid must supply supplemental power. This mismatch can impose strain on the electric grid, heighten congestion and voltage management issues, and, at times, necessitate balancing energy

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that may originate from fossil-fuel-based generation [9–11]. Therefore, improving the simultaneity of on-site renewable production and consumption is viewed as an essential factor in maximizing the decarbonization benefits of renewable integration and supporting power system stability [8, 12, 13].

To address these challenges, both passive and active measures have been proposed. Passive strategies, such as enhanced building design and better envelope performance, help to lower overall energy demand. In addition, novel performance indicators such as self-production and grid liability have been introduced to guide technically optimal PV sizing, typically recommending lower installed capacities than the conventional NZEB sizing approach [8]. On the active side, dynamic management of building energy systems, such as Smart Grid Ready (SGR) heat pump controls, offers significant flexibility. These SGR features allow heat pumps to respond to grid signals and optimize operations based on electricity prices, grid needs, and the carbon intensity of the electricity mix, thus enhancing renewable self-consumption, reducing grid dependency, and potentially lowering operational carbon emissions [9, 10, 13].

This paper aims to expand the understanding of SGR controls' effectiveness in residential buildings for reducing operational carbon emissions. It systematically reviews active and passive load matching measures and, drawing on dynamic building simulation and empirical data, evaluates the impact of SGR strategies for air-to-water heat pumps across three European countries with different electricity mixes: Germany, Denmark, and France. The analysis compares control strategies based on both perfect and data-informed (day-ahead) prediction of grid carbon intensity, quantifying effects on electricity demand and CO_2 emissions. The findings intend to inform decision-makers and building professionals seeking to optimize the emission performance of smart, grid-interactive residential buildings.

2 Methods and data

2.1 Simulation model

In our research we used dynamic simulation to determine the electricity demand. This is done with DesignBuilder version 7.3.0.038, which uses EnergyPlus 9.4.0.002 as the computing engine.

The internal heat gains were set to an average of 5 W/m^2, which is the value according to the Hungarian ÉKM decree [14]. The user profiles were defined in accordance with to MSZ EN 16798-1:2019 [15].

The model was run with a resolution of 15 minutes.

2.1.1 Building and HVAC model

For the simulation, we used the type 9 building from the Hungarian building typology [16]. It is a single-story single-family house with a heated floor area of 100 m^2. The building was modelled in a renovated condition, which resulted in an average U-value of 0.461 W/m^{2}K for the building envelope. Fig. 1 shows the model built in DesignBuilder.

The heating and cooling energy is provided by an air-to-water heat pump system with surface heat radiators and water heat exchangers, as illustrated in Fig. 2.

2.2 Control specifications

2.2.1 Smart Grid ready control

Air-to-water heat pumps have recently come with Smart Grid Ready control functions, which serve the improved utilization of such appliances for the various control objectives, in a somewhat standardized and simplified way. Heat pumps have dedicated relay contacts that are able to differentiate the following operation modes:

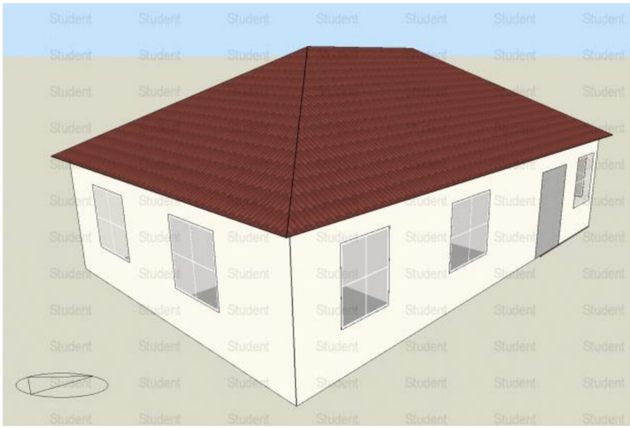


Fig. 1 Type 9 building model

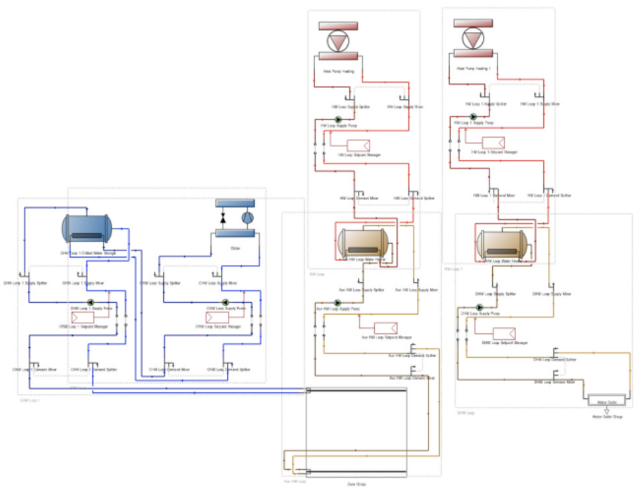


Fig. 2 The modelled HVAC system

- Normal
- Recommended On
- Forced On
- Off.

Control algorithms can be written to activate these signals in different periods, to achieve better prices, support the electricity grid or to optimize renewable energy consumption / on-site PV consumption.

In the present paper the specific setpoints for the different operation modes are summed in Table 1 and Table 2.

2.2.2 Control signal for demand response

For demand response purposes, three control approaches are analyzed.

- Standard: The heat pump operated the way that it maintains the required setpoints for domestic hot water, heating and cooling.
- D0 data: Heat pump operation was modified based on electricity mix intensity of the present day. This leads to "perfect prediction" at the very beginning of the day, so that the HP operates in Forced On mode for the hour of the lowest carbon intensity, in Recommended On or the second and third lowest carbon intensity values and Forced Off operation for the hour of highest carbon intensity. Due to the perfect prediction, Forced On and Off operations are triggered exactly for 1–1 hours while Recommended On is operated for 2 (not necessarily consecutive) hours a day.
- D-1 data: In case of D-1 control, the difference is that instead of a perfect prediction for the day, the triggering threshold of the previous days are used. In this manner, there is no restriction in the number of triggers for the specific day. If the carbon intensity of the electricity mix is greater for the whole day than the previous day's maximum, Forced Off operation is activated. (This necessitates the fall-back temperature limit for Forced Off operation.)

Table 1 Zone and tapping setpoint temperatures of smart grid control

Zone and tapping temperatures	Heating setpoint	Cooling setpoint	DHW setpoint
Normal	20 °C	26 °C	40 °C
Recommended On	20 °C	26 °C	40 °C
Forced On	22 °C	24 °C	40 °C
Forced Off	20 °C	26 °C	40 °C

Table 2 Storage setpoint temperatures of smart grid control

Storage temperatures	Heating setpoint	Cooling setpoint	DHW setpoint
Normal	40 °C	16 °C	50 °C
Recommended On	45 °C	14 °C	55 °C
Forced On	50 °C	14 °C	60 °C
Forced Off	30 °C	18 °C	40 °C

2.3 Weather data and regions

The present study concentrates on three different European Capitals, namely Berlin, Copenhagen and Paris, with similar climates (Temperate, no dry season, warm summer (Cfb)), based on the Köppen-Geiger climate classification [17].

From the perspective of electricity mix, the specific countries are much more different. France has major sources of nuclear power, that is a low-carbon base load power plant source. Additionally, significant wind, solar and hydro sources are present. The other two countries observed have no nuclear power plant generation in their portfolio (as for the present, yet the simulation periods still cover the nuclear phase out period for Germany). Denmark has major sources from wind generated electricity and also notable source from solar installations. While Germany is leading Europe in renewable capacities of wind and solar power. Detailed capacities of the portfolios mentioned can be seen in Fig. 3 [18].

The evaluation period covers the years 2021 and 2022, for which both meteorological and carbon intensity data are available. Weather conditions were obtained from the database of the System Advisor Model (SAM) program [19]. Carbon intensity data was accessed from electrictymaps.com datasets, in the form of hourly resolution carbon intensity [20].

3 Results

In the results section, three subpoints are evaluated. At first, the control schedules of the different countries and approaches are contrasted to clarify how the specific approaches trigger the HVAC system for demand side response. Then the energy consumption of the specific cases is compared, resulting from the various schedules. Finally, carbon emissions of the base case and the steered versions are contrasted to evaluate the efficiency of such approaches.

3.1 Control signal scheduling

3.1.1 Electricity mix intensity

Fig. 4 reveals, despite major renewable capacities in wind and solar, Germany still exploits significantly higher carbon intensity mix than Denmark or France. Obviously, this is once due to the intermittent production manner of RES, but more importantly, to the significant use of carbon

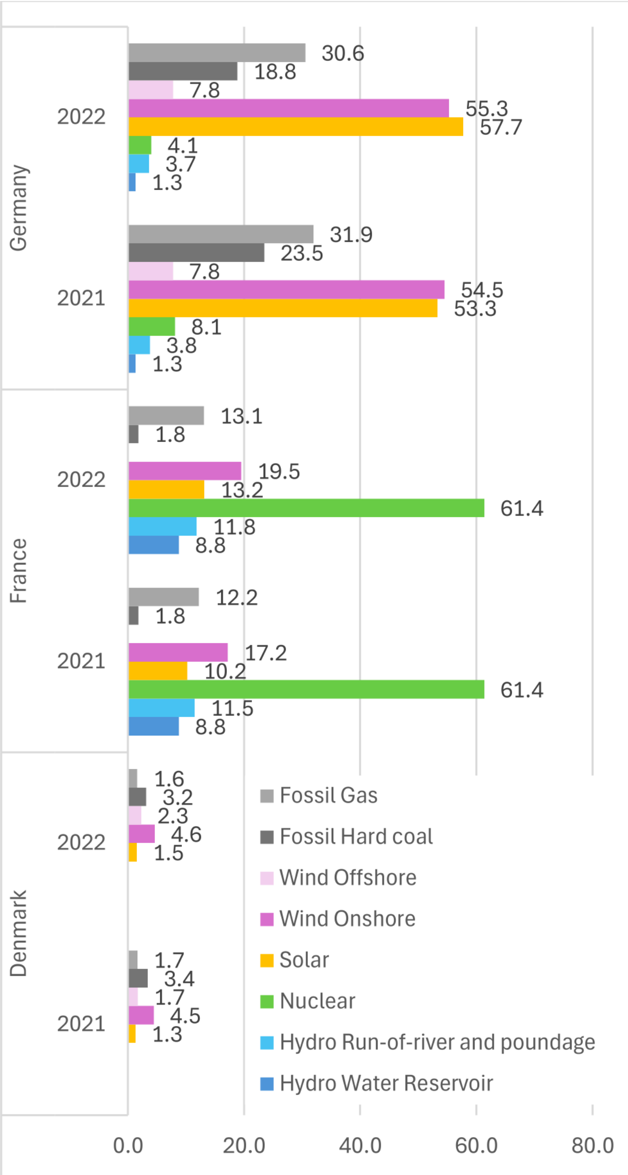


Fig. 3 Power plant capacities of nuclear solar and wind in Denmark, France and Germany in 2021 and 2022 [18]

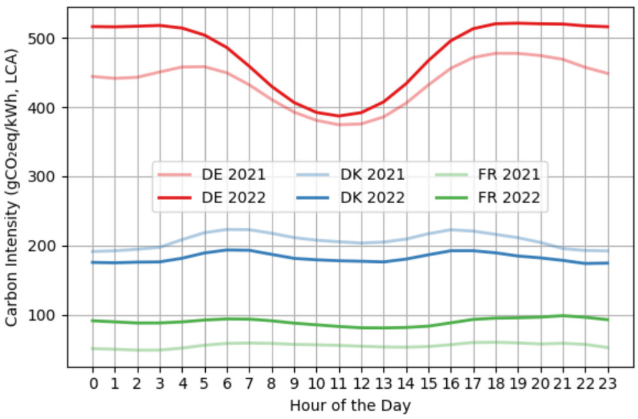


Fig. 4 Hourly average carbon intensity of the electricity mix (gCO_2/ kWh) per country and year

capacities. Moreover, significance of installed PV capacity can be observed on electricity intensity patterns. During the period of 6 a.m. to 4 p.m. there is a notable drop in carbon intensity due to PV generation.

On the other hand, Denmark and France exhibit much lower and balanced carbon intensity patterns as wind and nuclear power generation are more pronounced in these cases. Accordingly, patterns of wind can be traced in the case of Denmark's electricity intensity, and France appears to have the most balanced and lowest intensity.

3.1.2 Control signal activation

From the perspective of control signal activation (Table 3), the first major difference between D0 and D-1 prediction is the number of activations. While in the case of perfect prediction (D0) the number of activations is 365-365 and 730 in a year for Forced Off, Forced On and Recommended On for all the countries in both years, D-1 prediction shows much less activation.

From the perspective of triggering hours, the impact of solar power generation is clear in the case of Germany in Fig. 5, displaying the number of activations in the case of D-1 scheduling in 2022. Forced On and Recommended On activations are the most intense for this country. In the case of the French example, electricity mix triggers much less ramping activations, however, effects of high PV share can be still read from the number of activations. Somewhat expectedly, the Danish electricity mix completely misses this trend, activations are more evenly distributed through the day. However, in all cases, there is a major number of activations in the early hours. In the case of Germany, this mostly comes in a form of Forced Off schedule, due to the higher carbon intensity, while in the cases of Denmark and France ramp ups are dominant due to the effects of wind generation lowering carbon intensity of the mix.

Table 3 Summary of number of control activations per year, country and control type

Country and year	Forced On	Off	Recommended On
2021	589	586	1347
DE	190	179	392
DK	200	217	481
FR	199	190	474
2022	601	605	1362
DE	183	190	409
DK	208	208	482
FR	210	207	471

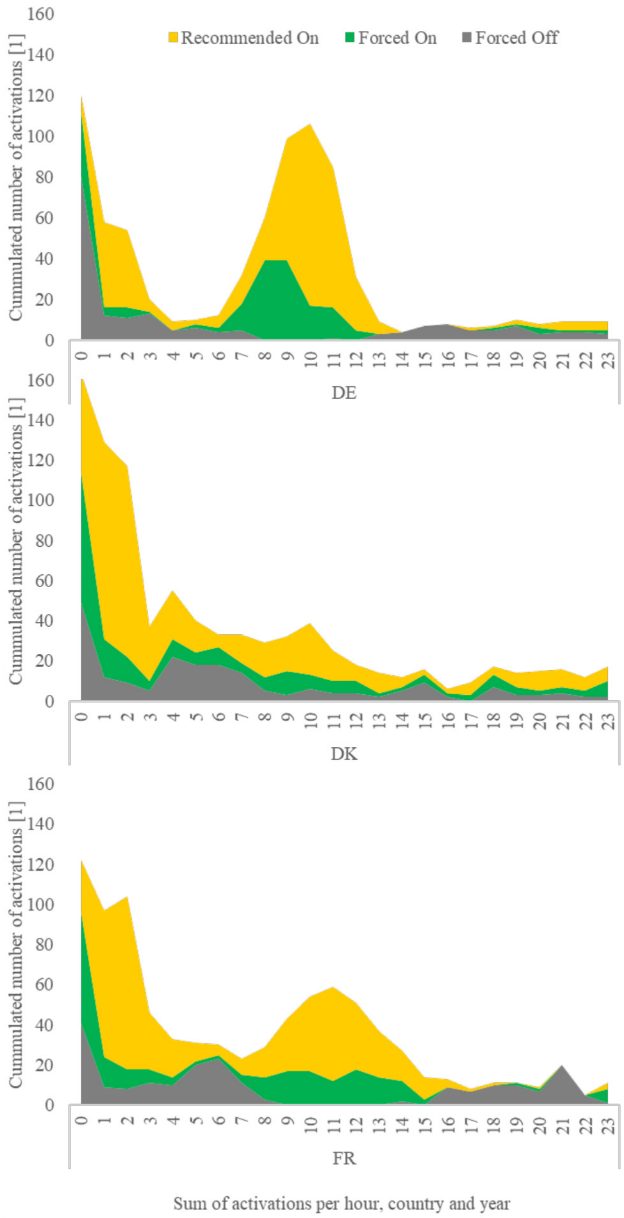


Fig. 5 Smart grid ready activation signals' distribution across the hours of the days for the different countries with the D-1 prediction approach for the different countries in the year 2022

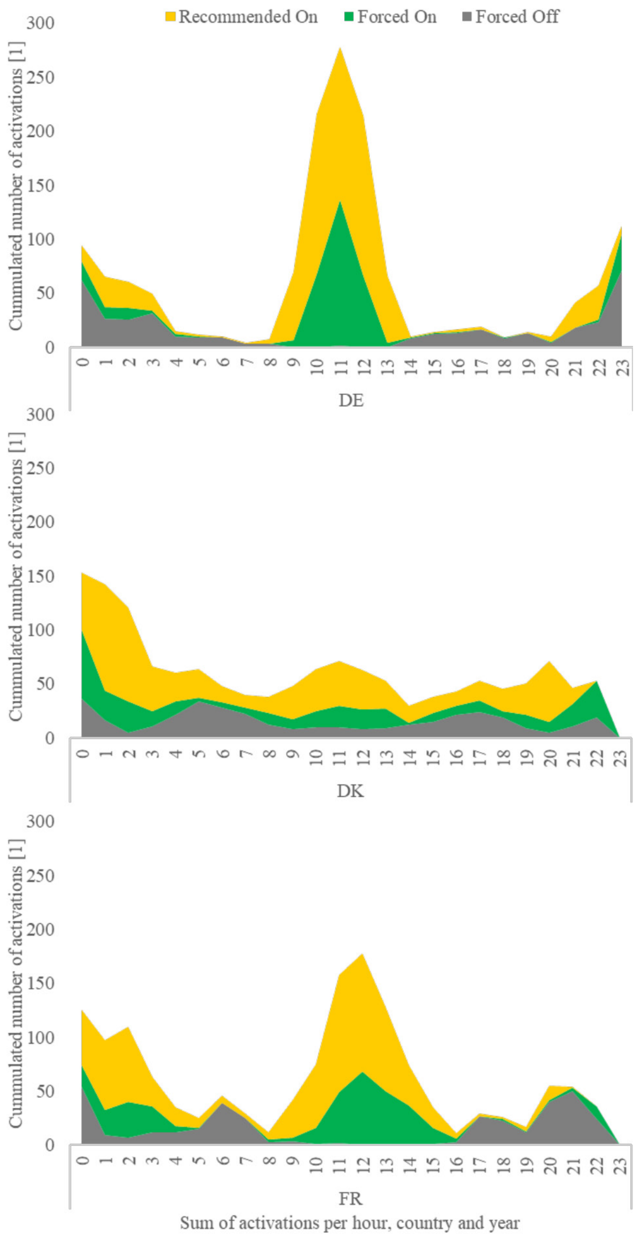


Fig. 6 Smart grid ready activation signals' distribution across the hours of the day for the different countries with the D0 prediction approach for the different countries in the year 2022

In case of perfect prediction (Fig. 6), hourly electricity mix effects are further emphasized. In the case of Germany, for example, 77% of the ramping up signals are activated in the period of 9 a.m. to 1 p.m. period, while Off signals are scattered around midnight.

France exploits a similar trend, but with much more moderate values. Furthermore, minor Off signal peaks can be observed in the morning and the afternoon as well. This is most probably due to the balanced base load of nuclear power generation with low emissions but increased consumption that requires starting of plants with higher carbon emissions. Finally, in the case of Denmark, control signals are the best distributed across the day. Besides the relatively balanced imports, ramp up signals are distributed to intensive wind generation periods (early morning and afternoon) and solar generation periods (midday) as well.

3.2 Electricity consumption

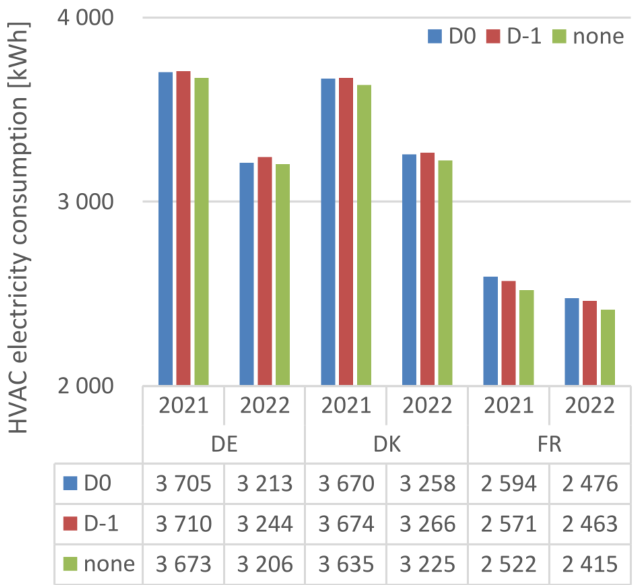
Intervening in the operation of the heat pump clearly influences energy and electricity consumption of the HVAC system as well. Net energy demand increases, as net demand does not reduce (DHW is supplied at the required 40 °C tapping temperature and room setpoints are not reduced). While storage temperatures mostly increase (with the activation of Recommended On and Forced On operations), leading to increased storage losses.

The case of electricity consumption is more complex. The coefficient of performance (COP) of inverter-driven heat pumps is greatly affected by the supply and the heat source temperature, as well as the part load ratio of the heat pump. Hence, in all cases the HP is steered by a control signal, these factors are to be contrasted to the original operation and can result both in increase and decrease of the COP. Overall, in all cases, electricity consumption of the different cases shows negligible increase (below 3%) compared to the base case (Fig. 7).

From the perspective of electricity consumption, the German and the Dannish example comparable consumptions, while in the French cases there is roughly 1,000 kWh reduced electricity demand.

3.3 Carbon emissions

Possible CO_2 savings result from the combination of previous two factors. Theoretically, this could end in both increase and decrease from the perspective of carbon emissions. However, due to the planned manner of activations, a reduction is expected. Efficacy of the mitigation of carbon intensity per unit of electricity used is verified by Fig. 8. In all cases, relative carbon intensity of the mixes reduced compared to the normal operation. As expected, the reduction is greater in the case of the D0 activation approach. However, the order of magnitude of mitigation is



	DE 2021	DE 2022	DK 2021	DK 2022	FR 2021	FR 2022
D0	3 705	3 213	3 670	3 258	2 594	2 476
D-1	3 710	3 244	3 674	3 266	2 571	2 463
none	3 673	3 206	3 635	3 225	2 522	2 415

Fig. 7 Annual electricity consumption of HVAC systems under the different control strategies (D-1, D0, and the base case) per country and year observed

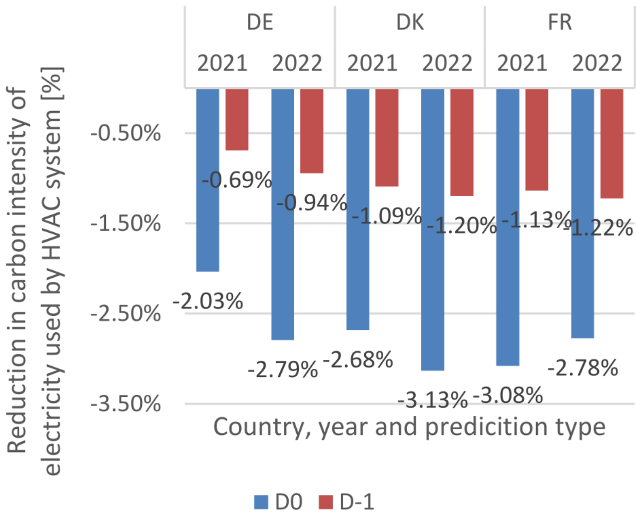
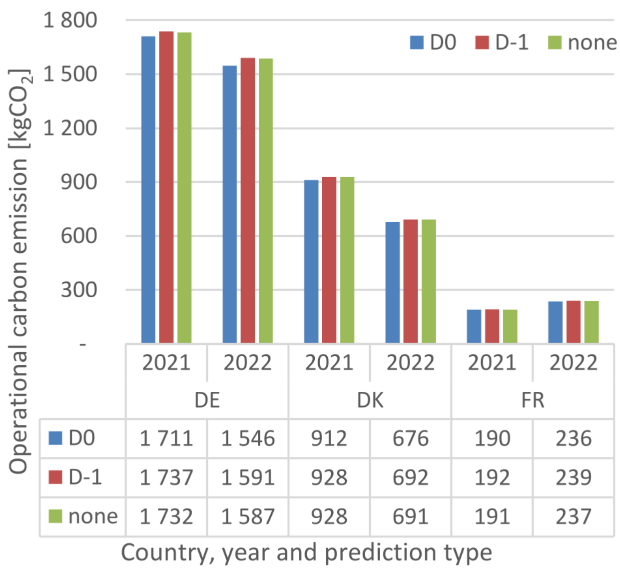


Fig. 8 Reduction of carbon intensity consumed by the HVAC system by the specific prediction type, country and year

quite limited. Even with D0 approach, the relative reduction is maximized around 3%. The greatest reduction in electricity intensity consumed by the HVAC system can be achieved in Germany, D0, 2022, by 14 gCO_2/kWh_e (from 495 to 481 gCO_2/kWh_e).

Despite the mitigated electricity mix intensity in all the cases, orders of magnitude suggest that this does not necessarily lead to overall increase in operational carbon emissions, due to the increased consumption rates presented earlier. Fig. 9 reveals that in fact, in all the cases when D-1 approach is used, there is even marginal increase in the overall operational carbon emission of the HVAC system. While D0 can achieve reduction in all cases, the effect remains quite limited. Largest decrease can be achieved in Germany, 2022, with 31 $kgCO_2$ (−2.57%).



	DE 2021	DE 2022	DK 2021	DK 2022	FR 2021	FR 2022
D0	1 711	1 546	912	676	190	236
D-1	1 737	1 591	928	692	192	239
none	1 732	1 587	928	691	191	237

Fig. 9 Operational carbon emission of HVAC system by country, year and control strategy

4 Discussion

Study results emphasize that application of simplified control approaches, even with perfect prediction have marginal effects on operational carbon emissions. Resolving limitations on activation times and Smart Grid Ready controls' limitations on the specific setpoints, model-predictive controls could possibly offer greater savings in operational carbon emission [11].

Nevertheless, Smart Grid Ready control functions themselves can be relevant for other objectives, such as demand side response methods for electricity network issues [13]. Especially as the configuration has been required by the German Heat Pump Association with the collaboration of manufacturers and is available in majority of the residential applications (especially new installations) in Europe. Leading to possible integration of several Home Energy Management System producers' products [21].

On the other hand, if carbon emissions are in the limelight, a reasonable consideration to mitigate carbon emissions is better insulation of the building stock. However, this opens up the conflict of embodied and operational carbon emission and should be handled carefully in a whole life-cycle approach to actually reach overall global warming impact [22, 23].

A further possibility is the evaluation of building operation services, that offer observable energy savings, hence probably lead to carbon reduction as well [24].

5 Conclusions and implications

Carbon emission mitigation is one of the main focus of the EU. Contributing major emissions, the building sector is often in limelight of reducing emissions. One possible means of mitigation is the use of Smart Grid Ready contact in the case of heat pump systems, that are somewhat standardized control methods. The current study analyzed the efficacy of applying those functions in three different countries, Denmark, France and Germany, with different greatly different electricity mixes. Study compared two different methods for the activation of SG controls. One is a perfect prediction of the present day in terms of electricity mix intensity, and activating Forced On and Recommended On operation in three hours with the lowest emission, heating surplus heat in storages, while turning off the heat pump in the hour with the highest carbon intensity. The other activation approach takes the previous days' threshold values in terms of electricity intensity and activates signals similarly. Results showed that activation periods are heavily dependent on the mix. In the case of Germany, major share of ramping ups come midday. France exploits similar trend with less extreme number of activations, due to the relatively high PV share as well. While in the case of Denmark, activations are divided across the day, wind source intensive production periods can be traced based on activation numbers.

While relative carbon intensity (gCO_2/kWh_e) can be reduced in case of both activation approaches, operational carbon emission is only achieved in case of perfect prediction. Despite the reduced relative carbon intensity, there is an increase in the electricity demand that is more significant. However, overall, both the achieved decreases and increases in the case of HVAC related carbon emissions are marginal. This implicates that oversimplified approaches in HP controls have a marginal effect on carbon emission reduction and that advanced control approaches should be sought.

Acknowledgement

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