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EVOLUTION OF HEAT PUMPS GEG-EMISSION USING DYNAMIC ELECTRICITY MIX, 2018-2025.

Summary

Heat pumps are recognized as a key technology for decarbonization. However, many studies assessing heat pump emissions rely on static emission factors or focus on only one or two years, which does not account for the variability in electricity sources. The objective of this study is to assess the evolution of heat pump emissions considering the German electricity mix of the past 8 years and the growing volatility driven by the deployment of wind and solar energy. Combining calculated hourly emission factors for the years 2018 to 2025 and results from simulations of a heat pump system and a gas system, emission using dynamic emission factors or yearly average will be compared to each other. Using these results and forecasted electricity mix for Germany, a trend for the future years will be extrapolated.

Keywords: heat pump, CO2eq-emission, electricity mix

Field of application for the findings: Sustainable Heating and Cooling Systems for Buildings: Heat Pump Systems for Buildings

1. Introduction

The building sector in Germany caused over 100 million tons of CO2eq in 2022 and 2023, making it the sector with the fourth highest emissions (Umweltbundesamt, 2025). Heat pumps (HP) are seen as the crucial decarbonization technology within the building sector (IEA - International Energy Agency, 2022).

Although many studies evaluate emissions from HP operation in European countries (Litjens et al., 2018; Gajewski et al., 2019; Buday and Buday-Bódi, 2023) using a static, annual electricity emission factor (EF), this approach does not capture the temporal variability in emissions driven by fluctuations in the electricity mix, particularly those due to renewable generation (Burger).

In a more recent German study for the year 2024 (Chaigneau et al., 2024), the authors reported that heat pump emissions calculated using dynamic hourly emission factors were 14–18% higher than those derived from a static method, yet still 58–65% lower than emissions from gas boiler variants. However, this study covered only a single year, which may not reflect the reality of actual climate, electricity demand and availability.

In the present article, hourly EFs for the years 2018 to 2025 in Germany will be calculated and combined with the results of heating systems simulations to quantify how heat pump emissions evolved under time-varying electricity mix. Using these results, possible results in the future will be discussed based on projections for the expansion of renewable electricity production.

2. Methodology

First the EFs for years 2018 to 2025 are calculated according to the methodology described in (Chaigneau et al., 2024), combining historical, quarter-hourly energy production data from energy-charts (Burger) and source-specific emission factors made available by the German Environment Agency (Umweltbundesamt - UBA) (Lauf et al., 2025). The EFs are then corrected to take into account imports and exports (based on a static country-specific EF), hydro pumped storage and network losses. An example of the resulting EF can be seen as heatmaps for the years 2023 and 2024 in Figure 1. The average EF in 2024 is with 326 $gCO2_{eq}/kWh_{el}$ 9% lower as the 362 $gCO2_{eq}/kWh_{el}$ from 2023. The green area in the summer months gives a clear view of the effect of PV power. The influence of wind power is more volatile, but the graphic shows that also during winter low EF can occur for extended periods, e.g. in December 2023 or January/February 2024.

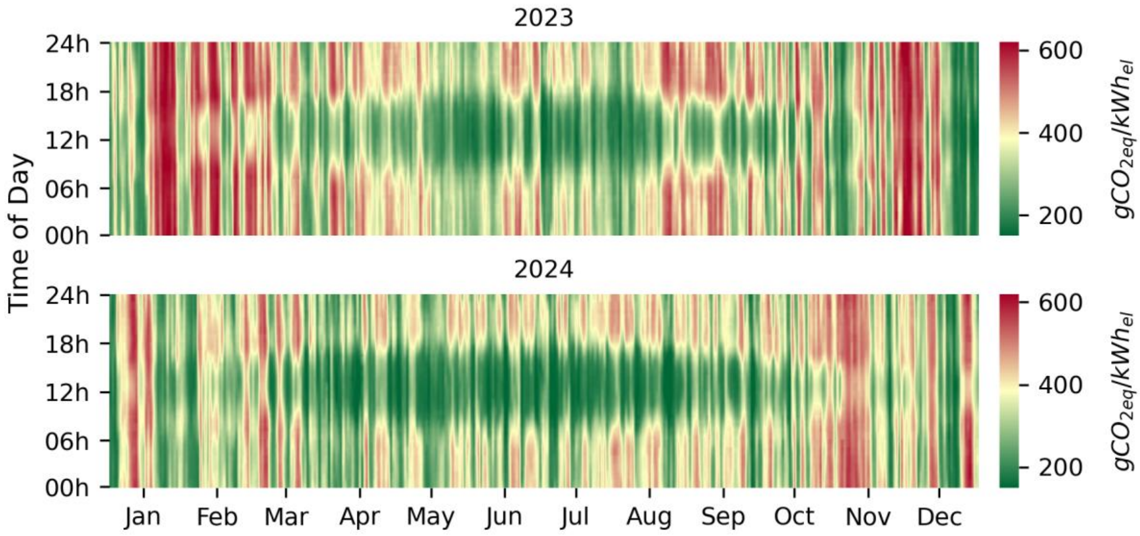

Figure 1: Emission Factors of the German electricity mix in 2023 and 2024 as Heatmaps.

Secondly, a heating system consisting of an air/water heat pump and another consisting of a gas boiler (for reference) is simulated for a reference building using the software Polysun. The building considered in this study is an Existing Single Family House (SFH), described in (Chaigneau, 2025). It has a habitable surface of 140m², a heat load of 71.4 W/m² and a yearly heat demand of 158 kWh/m². Previous studies (Chaigneau et al., 2024, 2025) showed very little difference in specific emission when comparing SFH with Multiple Families House. Simplified block diagrams of the two heating systems are shown in Figure 2.

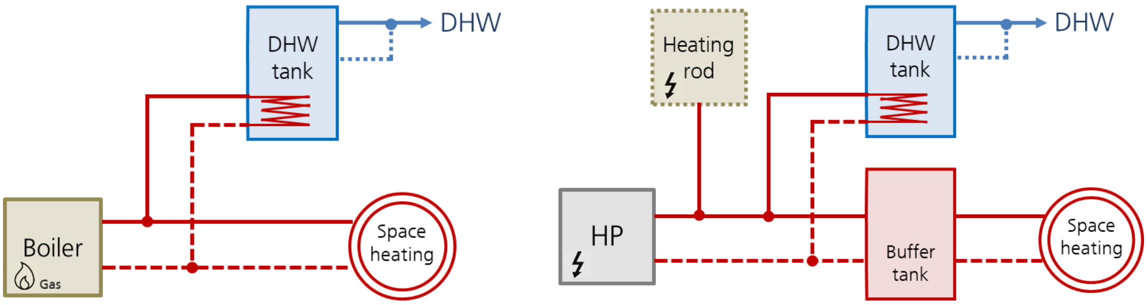

Figure 2: Simplified Block diagram of the gas boiler system (left) and the heat pump system (right)

3. Results and Conclusion

By combining dynamic EF and simulation results, it is possible to compare the emission for both systems for each of the considered years. As example, the specific emissions of the air-water-heat pump against the emission factor of the German electricity mix in 2024 are shown in Figure 3. The average specific emission of each system are represented with horizontal lines: 276 $gCO2_{eq}/kWh_{el}$ for the gas system and 115 $gCO2_{eq}/kWh_{el}$ for the heat pump, only 14% higher than when using an average EF. The graphic shows that, in 2024, the heat pump had higher emission than the gas during only 24 hours. Using the same methodology, those key metrics will be calculated for years 2018 to 2025. After establishing a correlation between the amount of renewable energy sources in the German electricity mix and the deviation between static and dynamic HP emission, a forcast for the future using forecasted electricity mix from (Brandes et al., 2021) will be made and discussed.

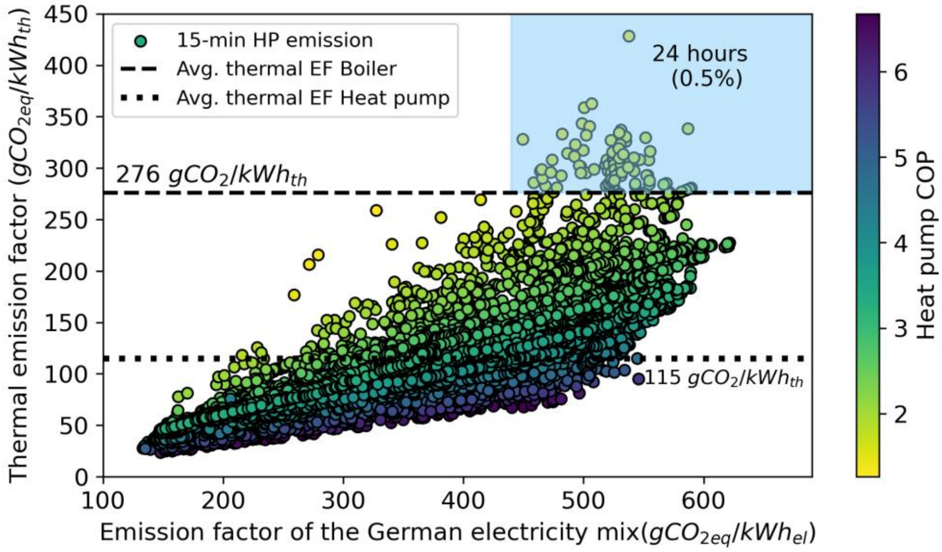

Figure 3: Specific emissions of the air-water-heat pump against the emission factor of the german electricity mix in 2024

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