# The Potential of Combined PV and Air Source Heat Pump Systems in German Residential Buildings

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**Abstract**

Heat pumps are considered a cornerstone of the process of decarbonizing building stock. Especially in combination with electricity provided by rooftop photovoltaic (PV) systems, a large-scale roll-out of heat pumps will constitute a valuable element in the EU's endeavor to increase both energy efficiency and the share of renewable power utilized in buildings. However, the installation of both PV systems and heat pumps is subject to various constraints, e.g., roof shapes for the former and available space for the latter. Therefore, we are investigating the feasibility of extensively implementing air source heat pumps combined with PV. This paper introduces a detailed spatial analysis of the available space around buildings that could be available for heat pumps, and couples it with an overview of the rooftop PV potential of these buildings. The analysis is carried out for two example regions in North Rhine-Westphalia, Germany. The results for the city of Cologne show that the combination of an outdoor air source heat pump with rooftop PV is feasible for 47% of residential buildings. In rural Winterberg, the share of suitable buildings is 74%. This illustrates both the potential for a large-scale roll-out of heat pumps in combination with PV in some regions, as well as the relevance of limiting factors such as available space in others. Furthermore, the results underline the importance of detailed spatial analyses for assessing the potential of the large-scale roll-out of heat pump–PV systems in Germany.

*Keywords: Heat pumps, air source heat pumps, feasibility analysis, outdoor space, spatial analysis, Germany, decarbonization, residential, PV*

## 1. Introduction

Buildings account for 40% of the total energy consumption in the EU and 36% of greenhouse gas emissions. Therefore, they will play a central role in the EU's goal of reaching climate neutrality by 2050, as defined in the European Green Deal (European Commission, 2020a). The electrification of the heat supply and increasing the share of renewable energy used are two measures that can contribute to the decarbonization of the building sector (European Commission, 2020b; Thomas et al., 2022). Heat pumps are one of the main technical solutions available for this, carrying many potential economic and environmental advantages (Wang et al., 2020). Operating heat pumps in residential buildings using electricity from rooftop photovoltaic (PV) installations will lead to an efficient and decentralized zero-emission heat supply, which is necessary for achieving the emissions reduction goals.

However, even the installation of the most popular and easiest-to-install type of heat pumps, namely the air-sourced model, is subject to a range of constraints. These include indoor and outdoor space availability, acceptable noise levels, roof load, and heat supply temperatures. The feasibility of rooftop PV, on the other hand, depends largely on roof shape. Whether an existing building is suitable for the installation of an air source heat pump combined with PV therefore depends on its individual characteristics.

On the one hand, the political agenda and conceptual decarbonization pathways clearly aim to increase the number of heat pumps and PV systems in buildings (Bundesministerium für Wirtschaft und Klimaschutz and Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen, 2022; Bundesverband Wärmepumpe (BWP) e. V, 2021; Prognos et al., 2020; Stolten et al., 2022). On the other, studies analyzing the feasibility of


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combined heat pump and PV installations primarily focus on individual buildings or building types. Rieck et al. (2020), Bee et al. (2019), and Pena-Bello (2021), though with slightly differing emphases and approaches, all investigate the feasibility of PV-powered heat pump systems for individual buildings using house and grid simulations. Solar generation potential for Germany has been evaluated using spatial analyses and simulations by, e.g., Risch et al. (2022). Spatial analyses addressing heat pumps, such as Volkova et al. (2021), focus on using them for district heating and not for individual buildings or assessing the potential of ground source heat pumps (Konetschny et al., 2018). The link between the two levels, i.e., the techno-economic modeling of individual building heating systems on the one side and the political goal of the large-scale decarbonization of the heating sector via air source heat pumps and renewable energy on the other is, to our knowledge, not clearly understood.

In order to contribute to quantifying the potential of combined PV and air source heat pump systems, this study conducts a detailed, building-level spatial analysis using the example of two regions in the federal state of North Rhine–Westphalia in Germany. In order to account for characteristic regional differences, we analyze one region each from the two ends of the spectrum defined by the RegioStaR classification (Bundesministerium für Digitales und Verkehr, 2018), with Winterberg serving as a representative example of a rural/village area and Cologne being representative of a metropolis. The goal is to determine the percentage of residential buildings with sufficient outdoor space for setting up an easy-to-install air source heat pump, as well as sufficient rooftop PV potential.

## 2. Methodology

In our study, we employ a two-step approach. First, we analyze the space availability of buildings (sub-sections 2.1.–2.2.). Then, we calculate and evaluate the ratio between yearly solar generation potential and yearly heat demand for those buildings (subsections 2.3.–2.5.). Based on the results of these two analyses, we can draw conclusions regarding the share of buildings in our example areas that fulfill both the space requirement and meet the targeted ratio threshold (subsection 2.6.).

### 2.1. Outdoor space requirements of air source heat pumps

As a first step, a thorough analysis of the outdoor space requirements for air source heat pumps of different capacities and by various producers is carried out. This is performed by drawing on the information provided in the product sheets published on producers' websites.

### 2.2. Spatial analysis of outdoor space availability

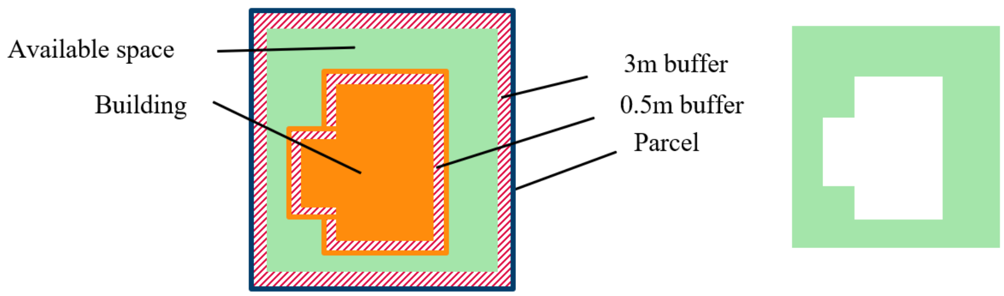


**Fig. 1: Illustration of available space around a building. On the left: parcel with a 3m buffer inside the polygon and buildings with a buffer of 0.5m on the outside; on the right: the remaining available space after removing the buffer and building areas.**

The basis for a detailed spatial analysis is data on individual building footprints and associated plot areas for the building stock. For North Rhine–Westphalia, open governmental 3D data of buildings in level of detail 2 (LoD2) is available (Bundesamt für Kartographie und Geodäsie, 2021). All ground surface areas present in the data are extracted and considered as building footprints in the subsequent analysis.

Buildings are then divided into residential, non-residential, and irrelevant instances. All buildings below a footprint area threshold of 30 m² are considered irrelevant, thus excluding structures such as garages and garden sheds from the analysis. Residential and non-residential buildings are then differentiated by spatially joining the European settlement map "ESM 2015 – R2019" (Corbane and Sabo, 2019). This raster dataset labels every 10m x 10m grid cell in Europe as residential or non-residential. Buildings are classified by calculating the zonal statistics of their footprint polygon with the rasterstats package (Perry, 2022). Each building is thereby assigned the most frequently-occurring raster cell value from the European Settlement Map that its footprint polygon touches.

Based on the assumption that the available outdoor space of a building is best estimated by the size of the parcel on which it is located, cadastral parcels are the second dataset required for the space availability analysis. For North Rhine–Westphalia, this data is openly available (Geobasis NRW, 2022). Parcels are assigned to buildings by spatially-joining both datasets. All buildings, the centroid of which intersect a parcel polygon, are assigned such a parcel. For the space availability analysis, the total parcel area is reduced (1) by a buffer of 3m within the parcel polygon based on the German standard border margin for buildings as defined by federal building regulations; and (2) by the area of all buildings located on the parcel plus a buffer outside of them of 0.5m. The remaining space is then deemed potentially available for a heat pump (see Figure 1).

Finally, we analyze whether a heat pump of size 1m x 1.5m as derived from the product research described in 2.1 fits into the available space. For this, we first rasterize the remaining parcel area in 0.1m x 0.1m raster cells, resulting in a matrix in which free and occupied space are represented by zeroes and ones. Then, we rasterize the heat pump at the same resolution, i.e., a heat pump with the aforementioned dimensions is described by a matrix with the dimensions 10 x 15 filled with ones. This heat pump matrix is rotated by 45°, 90°, and 320° to account for different possible orientations of the heat pump on the parcel, and for each of these we test whether the heat pump matrix can be found in the matrix describing the parcel. As a result, it can be determined whether each residential building has sufficient outdoor space for an air source heat pump or if space could be a critical factor.

### 2.3. Heat demand assignment

The basis for an estimation of the buildings' yearly heat demand is the EU project Hotmaps (Hotmaps Consortium, 2022), which calculated residential heating demand for each hectare based on statistical values. For our analysis, each residential building's yearly heat demand was determined by spatially-joining the building centroids with the Hotmaps raster data for residential buildings (*Hotmaps Project, D2.3 WP2 Report – Open Data Set for the EU28*, 2018). A raster grid cell value as given by Hotmaps was divided amongst the residential buildings that lie within that raster cell proportionally to the buildings' footprint areas.

### 2.4. Rooftop PV potential analysis

Another input dataset for our analysis was rooftop PV potential. Specifically, we employed the data generated by Risch et al. (2022). The underlying data were: (1) LoD2 building models for Germany (Bundesamt für Kartographie und Geodäsie, 2021), providing information about roof area, tilt, and orientation; and (2) the surface solar radiation dataset by EUMETSAT (EUMETSAT, 2019). Based on this data, the potential for every roof surface was simulated using RESKit (Ryberg et al., 2022).

The time series generated during the simulation were aggregated into a single yearly generation value per roof. We then assigned these values to the buildings based on roof positions. All roof centroids that lie within the building footprint polygons were then summed up and assigned to the respective building.

### 2.5. Ratio threshold approximation

We define a target of 50% of heat demand supplied from PV. This means that the local PV generation can account for 50% of the electricity supply that is needed by the heat pump over the course of the year. Because of the inverse yearly profiles of heating demand and solar generation, the temporal fluctuation over the course of a year must be considered, which is why we calculate a monthly profile from the aggregated yearly value for both heat demand and PV generation potential. The yearly heat demand was distributed to all months of a year proportionally to the heating degree method with data provided by the Institut Wohnen und Umwelt (IWU) (2022), whereas the yearly solar generation was distributed to all months based on the monthly horizontal irradiation with data from the same source. To give an indication of the variability of data based on the geographical location under consideration, especially with the aim of extending our analysis to a larger geographical scope, we carried out the calculation for four locations in Germany. The analyzed locations were in the North (Glücksburg-Meierwik), South (Freiburg), West (Nideggen-Schmidt) and East (Dresden-Hosterwitz) of the country. We first extracted the degree-day numbers from the IWU for each month of the year 2021 for the respective location. Then, we calculated the share of each month by dividing the monthly degree-day numbers by the sum of all values of the year. With this as a factor, we distributed yearly energy demands for heating to all months to obtain an estimation of the monthly heat demand. Similarly, we extracted monthly horizontal global irradiation values from the IWU for the year 2021 for all four locations, calculated the monthly share and used this to distribute yearly PV generation to the corresponding months. With these monthly profiles and assuming a very conservative coefficient of performance (COP) of 3 for a heat pump, we calculated for each month how much of the energy required for heating could be provided through the PV system. Summing up the amount of thermal energy covered in each month and dividing it by the total heating demand leads to an approximation of how much of the heating demand can be supplied by PV over the course of the year, depending on the ratio between the yearly electrical energy provided through PV to the yearly thermal energy required for heating. Using monthly values also has the advantage of leveling out daily fluctuations, which provides a first approximation of the existence of heat storage and building thermal mass and reduces the calculation times for this first calculation to manageable amounts. We evaluate this relation for a range of yearly heat demands of between 5 and 35 MWh and yearly solar generation potentials of between 1 and 25 MWh. Finally, we can estimate a ratio of yearly PV generation to yearly heat demand that corresponds to a 50% electricity supply to the heat pump by PV over the course of a year.

### 2.6. Consolidation of the results

In a final step, the results from the outdoor space availability analysis, heat demand assignment, and rooftop PV potential analysis were consolidated. All buildings with sufficient outdoor space available were preselected. For those buildings, the ratio of yearly solar generation potential to yearly heat demand was calculated. Above the previously defined ratio threshold, buildings were deemed suitable for the installation of a combined heat pump–PV system. Based on this, we calculated the share of buildings that are suitable for the installation of a combined heat pump–PV system in both regions.

## 3. Results

### 3.1. Required space

The space requirements of the outside unit of 82 air source heat pumps from eight different producers is shown in Figure 2, in which the unit's depth is plotted against its width. The cluster at the bottom left comprises heat pumps of dimensions of up to 1m x 1.5m and the cluster to the top right comprises heat pumps of dimensions greater than this. The space requirements of the outside unit of split constructions are lower than those of monoblocs and these heat pumps all fall within the first cluster. However, as split constructions are more complex in their installation and our focus lies on quantifying the potential for easy-to-install systems, monobloc sizes are more relevant for our analysis. We therefore set the heat pump size for which we analyze the space availability to 1m x 1.5m, which is larger than that for split constructions but lies within a medium range for monoblocs.

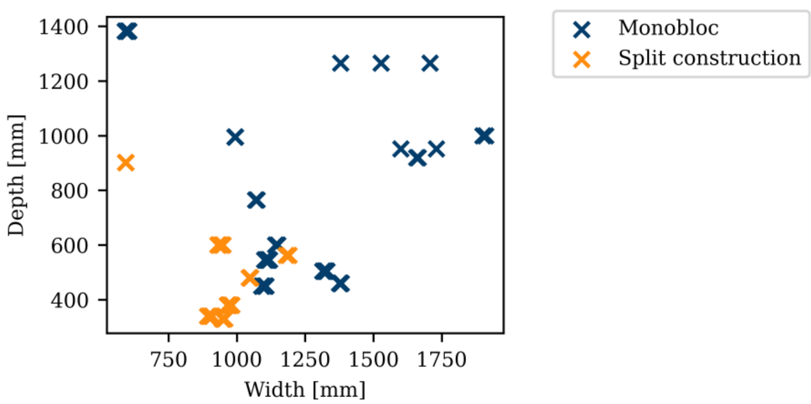


**Fig. 2: Dimensions of an outdoor unit of 82 air source heat pumps for both monoblocs and split constructions. A small scatter of a maximum 10mm has been added to the x-component of every point for better visibility of duplicates.**

### 3.2. Available space

The analysis of available space shows that after ignoring buildings to which no parcel could be assigned, only 3% of buildings have insufficient space for a heat pump with 1m x 1.5m dimensions in provincial/rural Winterberg (category 225 of RegioStaR17), whereas 18% of buildings in metropolitan Cologne (category 111 of RegioStaR17) have insufficient space (see Figure 3). We analyzed the space availability of 223,178 residential buildings in Cologne and 8,940 residential buildings in Winterberg.

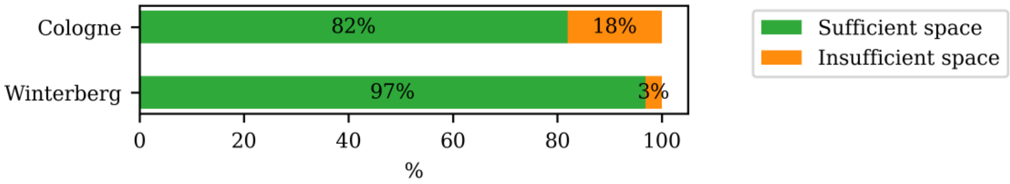


**Fig. 3: Percentage of buildings with and without sufficient outdoor space for installing a heat pump with dimensions of 1m x 1.5m in Cologne and Winterberg. The total numbers of classified buildings are 223,178 and 8,940 for Cologne and Winterberg, respectively.**

Figure 4 shows small extracts of the analyzed areas as an example of the spatial distribution of building footprints colored according to space availability, with buildings with insufficient space depicted in red and those with sufficient space in green. On the left is shown a densely built-up area in central Cologne, whereas the right depicts a more sparsely built-up area in Winterberg.


**Fig. 4: Buildings classified according to their space availability in small extracts from the analyzed areas. Red symbolizes insufficient space, whereas green represents sufficient space. The map on the left shows an area in central Cologne, and that to the right is in Winterberg.**

3.3. Ratio threshold estimation

Figure 5 illustrates the relationship between yearly solar electricity generation potential to the yearly heat demand ratio and the share of heat demand that can be covered by a PV-powered heat pump of COP 3, taking the yearly profiles into consideration. Results are shown for four locations in Germany. Approximately 50% of heat demand is met with a PV-powered heat pump over the course of a year, corresponding to a ratio of around 40% yearly solar generation potential to yearly heat demand. The values lie in similar ranges for all four locations, especially for lower yearly ratio values. The higher the yearly ratio, the more the values diverge. For a ratio of yearly electricity generation by PV to a yearly heat demand of 40%, the maximum and minimum still lie within a range of 7 percentage points.

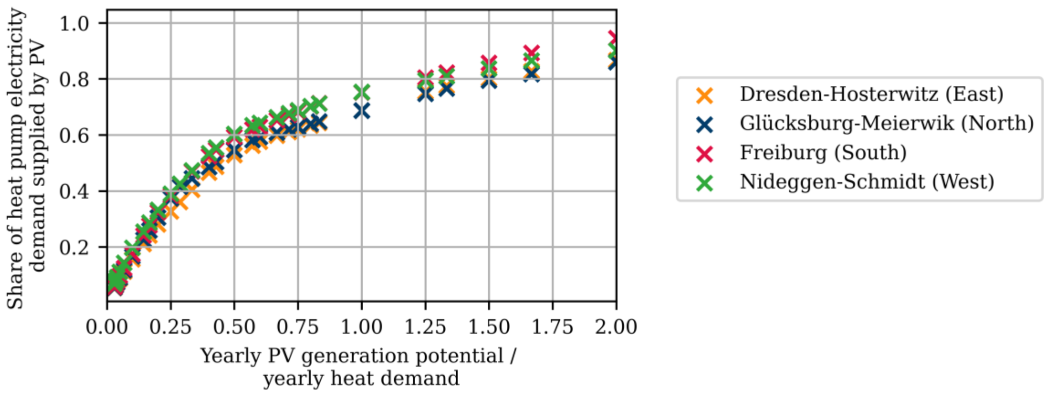


**Fig. 5: Relationship between the yearly solar generation potential to yearly heat demand ratio (x-axis) and the share of heat demand that can be covered by a PV powered heat pump of COP 3, taking the yearly profiles into consideration (y-axis) for four locations in Germany.**

3.4. Heat demand and solar potential ratio

Based on the yearly heat demand values and yearly solar generation potential values assigned to residential buildings, a ratio between the yearly potential for electrical energy generated via PV and yearly thermal energy demand for heating can be calculated. A histogram combined with a cumulative curve of these ratios for all buildings that have previously been found to have enough space and to which we could assign both a yearly solar generation potential and level of heat demand is shown in Figure 6. For most buildings, the ratio lies below a value of 1, meaning that the electrical energy provided via PV is lower than the thermal energy required for heating. The histogram of Winterberg has a peak at approximately 0.5, whereas that of Cologne is slightly shifted to the left and peaks at ca. 0.4. The dashed line represents the yearly value ratio threshold of 40% calculated in the previous step.

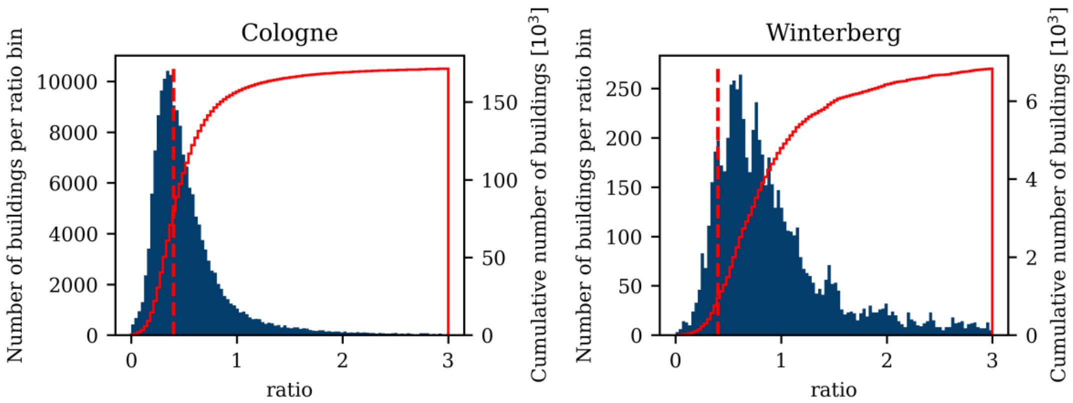


**Fig. 6: Histogram of ratios of electrical energy generation potential through rooftop PV to thermal energy demand for heating for each building (excluding missing values) in Cologne (left) and Winterberg (right). The dashed red line represents the 40% ratio threshold.**

As is shown in Figure 6, approximately 89% of buildings in Winterberg and 59% of buildings in Cologne lie above the 40% ratio threshold. However, the buildings depicted in Figure 6 are only those to which both PV generation and a heat demand profile could be assigned, and so we were able to calculate a ratio. We also calculated the share of buildings with a ratio above 50% when including the buildings without any ratio. This yields a share for Winterberg of 78%, and of 57% for Cologne.

3.5. Building stock suitability for a combined system

Figure 7 displays a summary of all results for both regions. It depicts the share of buildings with insufficient or undefined space availability and for buildings with sufficient space, it shows the share of buildings above and below our defined ratio, as well as the undefined share. The total share of buildings in Cologne with both enough space and a ratio above the threshold is 47%. The same category of buildings has a share of 74% in the building stock of Winterberg. A higher share of undefined values for both space availability and ratio can be observed in those in Winterberg.

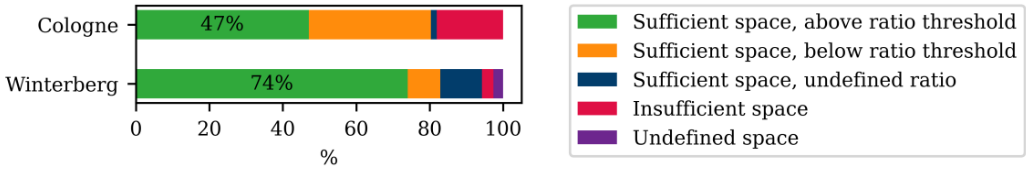


**Fig. 7: Share of buildings classified according to their space availability for a heat pump of dimensions 1m x1.5m, as well as the ratio between solar generation potential and heat demand in Cologne and Winterberg.**

## 4. Discussion

The results of the space availability analysis show that how large the share of buildings with sufficient outdoor space for an air source heat pump depends heavily on the region. Although space availability is generally not a major issue in the sparsely built-up rural area of Winterberg, it can become a challenge in densely populated urban areas such as Cologne. This difference is to be expected and can be understood intuitively by envisioning a typical city center with small, if any, garden patches and neighboring houses standing wall-to-wall and comparing this with a suburban or village setting in which many houses are single-family dwellings surrounded by larger gardens and standing several meters apart from neighboring houses. It can be concluded that space availability is a limiting factor for the large-scale rollout of heat pumps in Cologne, and likely in other urban areas of similar characteristics, which should be addressed to increase the number of buildings that qualify for the installation of air source heat pumps. One possible solution could be the use of split systems instead of monoblocs because of their smaller outside units. However, this has the drawback of entailing greater installation efforts. Roof installations are another option to consider, although they carry own challenges, e.g., permissible roof loads or competition for space with PV systems.

The ratio between PV generation potential and heat demand further reduces the number of houses that qualify for combined heat pump–PV systems according to our self-set energy threshold. Not only the space availability but also the ratio varies by region. The ratios of buildings in Cologne tend to be lower than those in Winterberg, which means that a smaller amount of the electric energy required by a heat pump could be provided by a PV installation. This is due to there being a significantly higher average heat demand per building in Cologne, combined with only slightly higher PV generation potential compared to Winterberg. One possible explanation for this could be the lower ratio of roof areas to living space in multi-level buildings in densely populated urban areas. To increase the share of buildings with a higher ratio, the energy demand of buildings would have to be reduced, e.g., through targeted energy retrofitting activities. It is also important to keep in mind that setting the amount of electricity that should be supplied by the PV system to 50% is arbitrary. Lower numbers, although resulting in a reduced level of self-sufficiency, could also be acceptable or even preferable. Furthermore, we calculated the ratio threshold based on degree-day numbers and irradiation values for one year only. Yearly weather variability, with cold and overcast years on the one hand and warm and sunny years on the other, could have a significant effect on the determined ratio. And, although we do not consider this in our analysis, it should not be forgotten that electricity generated by PV is not only useful for powering a heat pump but also for household appliances and, especially in a future transport system, battery electric vehicles.

Combining the results from both the space availability analysis and PV potential/heat demand ratio analysis, it can be stated that in rural Winterberg, there is not only more space available but also a large proportion of buildings (74%) exceed our defined ratio for being able to provide enough electricity for heating. In Cologne, many buildings are already excluded due to lack of available space. Of the share remaining, only approximately half (47%) of the buildings have the potential to provide sufficient electricity for heating with PV. The difference in results for Winterberg and Cologne underlines the importance of taking regional disparities into account when analyzing the practical feasibility of the large-scale roll-out of heat pumps. It also emphasizes the relevance of spatial analyses at the building level compared to statistical analyses at an aggregated one. Even within regions, characteristics vary. And although we did not quantify them, a qualitative visual analysis showed that space availability is less of an issue in the suburbs of Cologne than in the city center. Although the potential for combined air-sourced heat pump–PV systems is high in rural areas, it is limited in urban ones by both space availability and the ratio between solar potential and heat demand. At the same time, the absolute number of buildings in urban areas is significantly higher than in rural ones. Therefore, when aiming for a large-scale roll-out of combined systems, the absolute number of buildings in cities where the installation of a combined system is feasible will still be considerable. It is also important to note that the amount of PV-generated electricity we base our calculations on constitutes the maximum electricity produced that is available for the heat pump, as in reality the heat pump will compete with other electricity-consuming household appliances.

Our study provides a first approximation regarding the potential for combined air-sourced heat pump–PV systems. By choosing two regions at the ends of the RegioStaR classification spectrum with very different characteristics, we can give an indication of the range of values we can expect for the entirety of Germany. However, the numbers we provide must be seen as preliminary, as this study is subject to several simplifications that require further research. First, all ground surface areas from the building data were taken as independent units. This results in an overestimation of the total number of buildings, which makes an analysis of the absolute numbers unreliable. This could be remedied by defining building complexes in which multiple smaller constructions are considered as one and the roof areas of buildings currently defined as irrelevant could be included as part of larger structures, leading to an increase in PV generation potential for some buildings. Furthermore, the ratio threshold we define is an approximation, as we only consider monthly values and do not take building-specific or regional characteristics into account. Additionally, solutions for inconsistencies between our building footprints and the Hotmaps raster data that leads to missing data for the heat demand of buildings must be found. A study addressing these issues and extending the analysis to all of Germany will follow in the form of a journal publication.

## 5. Conclusion and outlook

This study demonstrates the feasibility of the chosen approach. While we identified some areas that need further improvement, the preliminary results are very promising. It was possible to show that in metropolitan areas such as Cologne for about 47% of residential buildings a combined air source heat pump–rooftop PV system is feasible and can cover over 50% of the yearly heating demand. For rural areas such as Winterberg the share of buildings that can be supplied in the same way exceeds 70%. The results emphasize the importance of detailed spatial analyses for assessing the potential of decarbonization measures, such as the large-scale roll-out of heat pump–PV systems.

This research has far-reaching implications for the next few years. With rising gas prices, the option of switching to a hybrid system by installing a combined heat pump–PV system on top of an existing gas heating, which is feasible especially in rural areas, becomes increasingly attractive. If gas prices stay high, it is very economical in such a hybrid system to only draw gas from the grid during periods of extreme cold and low solar radiation, leading to significantly reduced full-load-hours of the gas grid. This means that the price per unit must be increased to cover the high fixed costs of the gas grid, which effectively leads to an additional rise in consumer prices. Given sufficiently high production and installation capacities for rooftop PV and heat pumps, this might even lead to a death spiral of the entire rural gas grid, in which rising gas prices and the switch to hybrid heating systems accelerate each other. This will be analyzed in detail in further studies.

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