INFLUENCE OF THE EXPANSION OF HEAT PUMPS ON THE DISTRIBUTION GRID

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Abstract

Due to the net-zero target of the Swiss federation's Energy Strategy 2050, fossil-fuel based heat generation is largely being replaced by heat pumps. The increase in the number of heat pumps means a significant increase in electricity demand and grid power. A working group of the Smart Grid Switzerland Association (VSGS) has examined the influence on the resulting grid load and the optimisation potential for reducing the necessary grid expansion. The study shows that the grid load across Switzerland will increase by around 60%, and possibly more or less in some regions. The potential for reducing the necessary grid expansion through control is limited. During cold spells, high loads occur throughout the day.

1 Introduction

According to the Energy Perspectives 2050+, updated in November 2020 [1], the electricity demand in Switzerland for heat pumps will increase from almost 3 TWh today to approximately 9 TWh by 2050. However, the Energy Perspectives do not include any analysis or forecast of how the expansion of heat pumps will affect the grid load. This would require statements on the maximum power consumption of the heat pumps, the simultaneity within the application group but also in comparison to other applications, and the flexibility and controllability of the heat applications.
The aim of the present study is to quantify the resulting future power demand from the grid and the possible influence of control on power. The study aims to provide grid operators with the necessary and relevant key figures to determine the expected grid load from heat pumps in their grid area, enabling them to integrate this into strategic grid expansion planning.

2 Fundamentals of heat pumps

Heat pumps extract heat from their surroundings and raise the temperature using a compressor. The heat source varies:
- Air heat pumps: extract heat from the air.
- Geothermal heat pumps: tap into the earth's temperature.
- Groundwater heat pumps: draw heat from groundwater.

Heat pumps need a second energy source, like electricity or gas, and some can also cool buildings. The heating capacity is crucial for sizing the heat pump, while power consumption, determined by the coefficient of performance (COP), affects electrical grid sizing. Ground or groundwater heat pumps are more efficient and cost-effective than air source heat pumps due to smaller temperature differences.
The seasonal performance factor (SPF) indicates overall efficiency over a year in a real heating system. Heat pumps can be used for space heating and domestic hot water, requiring different temperature levels (around 50°C for domestic water and 30°C for underfloor heating). Energy needs depend on both the flow temperature and the amount of water to be heated, with space heating requiring significantly more energy.
Conventional heat pumps operate in an on/off mode, while modern ones use inverter technology to maintain stable temperatures. According to suppliers, heat pumps are not over-dimensioned but designed to meet maximum demand. Disabling them for over 2 hours can inconvenience customer.

3 Analysis of reported installed power vs. effective maximal power

3.1 Reported installed power via the technical connection request (TCR)

Depending on the heated living area, insulation and desired room temperature, the heating system must provide an appropriate heating output at different outside temperatures. The resulting electrical power required will vary accordingly from situation to situation. Distribution system operators rely on this power information, which installers are expected to provide in the TCR (technical connection request). However, experience and the present study show that this information is often inaccurate and not tailored to the specific situation.

3.1.1 Nominal power: The power of the heat pumps is specified by the manufacturer based on the heat source temperature and the flow temperature of the heating system in accordance with European standard EN 14511. For example, the nominal power of an air-to-water heat pump is often given as the power at A2W35, meaning 2°C outside air temperature and 35°C forward flow temperature.

3.1.2 Peak power: The power consumption of a heat pump varies under conditions that differ from standard conditions such as very low outdoor temperatures. While the maximum power consumption (peak power) is typically stated in data sheets, it depends on the respective situation and should be determined individually. Therefore, the peak power is not always recorded correctly in the TCR. Often, the nominal power value is entered. Furthermore, heat pumps are usually not designed to handle all critical conditions. Instead, an emergency or auxiliary heating system is often installed, which can influence the peak power requirements depending on the heat pump's design.

3.2 Analysis of power requirements based on load profile measurements

To verify the power values reported to the distribution system operator via the TCR, around 2'000 heat pump load profiles measured by smart meters in the distribution system areas of our member companies IWB and EKZ in 2021 and 2022 were analysed. Profiles with unrealistic peak values or measurements mixed with other consumer data were excluded. For the load profiles from the EKZ grid area, further contextual information from the individual TCRs was determined, including the reported nominal power and consumer class. Some analyses focused specifically on heat pumps without domestic hot water.

Table 1: Number of used electrical load profiles (15 min resolution) of separate measured heat pumps

Grid area	Total number	share with context info	without domestic hot water	measurement period
EKZ	1'937	1'239	695	Jan-Dec 2021
IWB	43			Jan 2021-Aug 2022

3.2.1 *Correlation to the outside temperature:* A regression analysis was conducted to examine the correlation between daily power consumption and the daily average outside temperature using the data set from IWB. Figure 1 shows that the energy consumption of the heat pump can be described relatively well with a linear dependence on the outdoor temperature. From an outside temperature of about 15°C, the scatter plot of daily energy consumption flattens and then runs horizontally. From this temperature, hot water is likely to be used more often than energy-intensive space heating, which is more dependent on the outside temperature in terms of electrical power.[…]

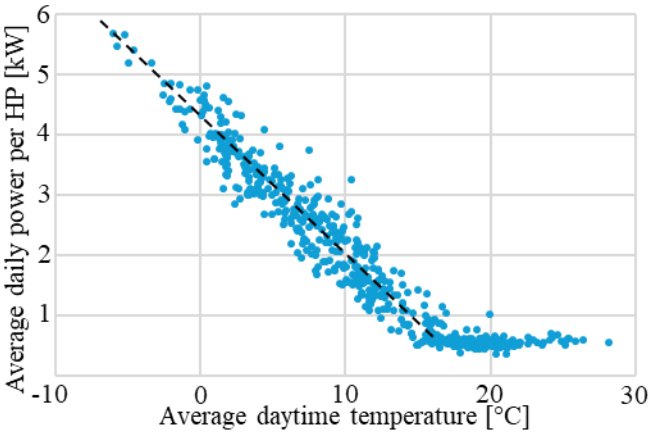


Fig. 1 Regression analysis of the average daily power as a function of outside temperature with data from IWB

3.2.2 *Comparison of declared power with measured power:* For grid expansion planning, understanding the statistical difference between the maximum power and the power reported via the TCR is crucial. For this purpose, approx. 700 load profile datasets for space heating without hot water were used, with contextual information from the TCR assigned. The results are displayed in Figure 2.

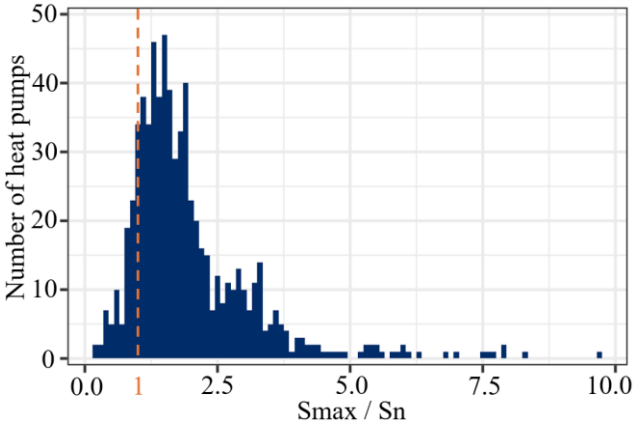


Fig. 2 Histogram of the ratio of measured maximum power over the entire measurement period to reported nominal power of 695 heat pumps (class without domestic hot water)

Most of the measured power values exceed the declared nominal power of the heat pump, as shown to the right of the dashed red line in Figure 2. The maximum measured power (Smax) is on average about 60% higher than the declared power (Sn).

Electrical equipment can transmit more than its nominal current for limited periods. Therefore, higher power drawn by heat pumps does not automatically require a correspondingly higher grid dimensioning. The duration and frequency with which the reported power is exceeded are crucial. Our evaluations of the TCR compared to the load profile data revealed that only 12% of the heat pumps operated within the reported power. This is contrasted by 70% of the heat pumps that exceeded the reported power at

least once for more than an hour and 18% at least once for more than 10 hours as shown in Figure 3.

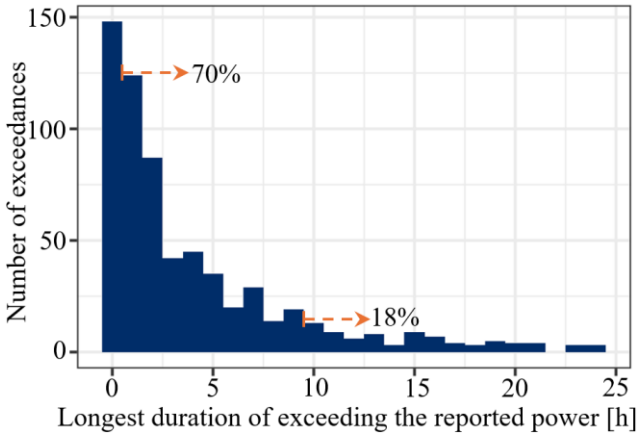


Fig. 3 Number and duration of the power consumption exceeding the reported nominal power during measurement period for the 695 heat pumps without domestic hot water

3.3 *Simultaneity analyses*

The maximum load occurring in a given area is relevant for grid planning. To assess the impact of heat pumps on the maximum grid load based on their individually reported or expected installation power, it is essential to understand two key factors: first, how the power demands of individual heat pumps occur simultaneously with each other and, second, how the maximum load of the heat pumps aligns with the remaining grid load.

3.3.1 Simultaneity with the rest of the grid load: The largest power draws by heat pumps occur mainly in the winter months due to the dependence on the outside temperature shown above. To determine the temporal occurrence of power peaks throughout the day, daytime was divided into six periods. During each period, the maximum of each heat pump was compared with its annual maximum.

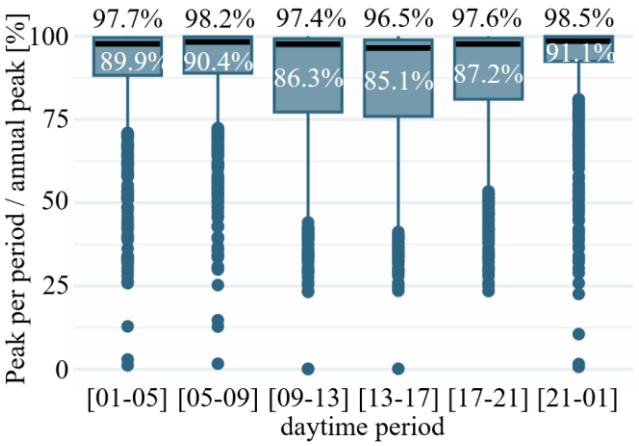


Fig. 4: Relative maxima per time period compared to their annual peak of the 695 heat pumps without domestic hot water; box shows 25th to 75th percentile, median in black at the top and mean in white below. Reading example: in each time period, maximum power of more then half of the heat pumps is close to their annual maximum

Figure 4 shows, that power peaks of the heat pumps occur at all times of the day, resulting in a *coincidence* factor near 1 between the heat pumps' maximum output and the maximum load of the remaining grid.

3.3.2 Simultaneity between the heat pumps: The simultaneity between multiple heat pumps was determined by comparing the maximum of the cumulative profile with the sum of the maximums of the individual heat pump profiles. The analysis was carried out with 50 different combinations of up to 1500 simultaneously operated heat pumps. Figure 5 shows the resulting coincidence factor for up to 100 heat pumps. The bottom line shows how the coincidence factor decreases as the number of heat pumps increases, stabilising at just under 50% from 50 heat pumps onward.

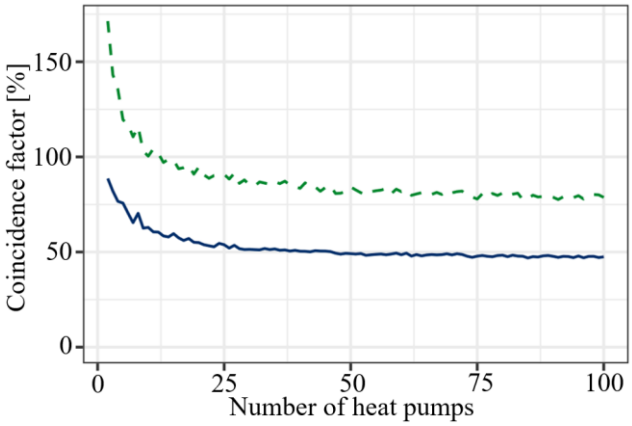


Fig. 5: Coincidence factor as the ratio of the measured maximum power of the sum profile to the sum of the measured maximums of each individual heat pump (lower line) or to the sum of the outputs reported via TCR (upper dashed line) of 695 heat pumps without domestic hot water

The simultaneity of power peaks among heat pumps is significantly higher than among other applications, such as charging electric vehicles, as shown by other sources [3].
As already mentioned, often only the nominal power ratings (and not the effective maximum power ratings) are available for grid planning. As shown in Section 3.2.2, the effective maximum power is on average around 60% higher than the reported nominal power rating. The coincidence factor in relation to the reported power has to be considered higher accordingly. It levels off at just above 75% considering 50 or more heat pumps (upper dashed line in Figure 5).

3.4 *Impact of blocking times on the load profile*

Distribution system operators often block heat pumps to reduce grid loads during peak load times, unless the customer objects. The effect of this measure is shown in Figure 6, where the daily profiles of the 695 heat pumps from the EKZ data set are summed up per season. The

blocking periods of around one hour twice a day (here at 11-12 a.m. and in the evening at 18 p.m.) are clearly visible.

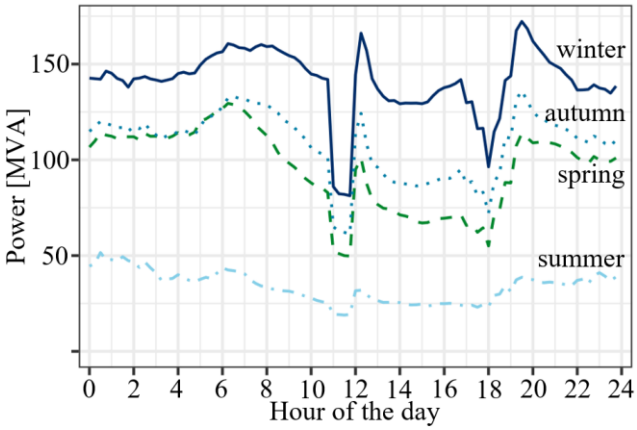


Fig. 6: Effects of blocking periods on the daily total profiles of 695 heat pumps summed up per season

It is expected that blocking heat pumps can relieve the grid during peak load times. However, it leads to higher power consumption after activation, as the heat loss due to the blockage must be compensated (rebound effect). This effect must be carefully analysed for each region when planning the grid expansion. Since blocking may only last 1–2 hours to avoid significant user discomfort, it often provides minimal relief to the grid.

4 Analysis of the resulting grid load

The federal government's energy perspectives [1] estimate a total electricity demand of 9.2 TWh for heat pumps in 2050, accounting for efficiency improvements from better insulation. However, the energy perspectives do not provide any information about the resulting maximum grid load.

4.1 Top-down analysis based on long-term heat demand measurements

To make a representative statement about the maximum grid load, an observation over several years is necessary, as temperatures and durations vary each year. Such data was provided by the Empa study [2] with measurements of the hourly heat demand of a district heating network over 8 years between 2009 and 2016. The district heating network covers a representative area for Switzerland, including both residential and commercial properties. The annual temperature cycle is also representative of Switzerland, including colder periods over the eight years. The study determined the hourly electrical power consumption when heat pumps cover the heating demand by dividing it by the COP according to the simultaneous outside temperature. The study predicts that heat pumps could cover 80% of Switzerland's heating needs by 2050, assuming an efficiency improvement of 42% in building envelopes (retrofit). This results in a thermal energy requirement of 28.6 TWh_{th} for space heating and 4.3 TWh_{th} for hot water. With an average COP of 3 an electrical energy requirement of around 10 TWh_{el} results. These values are comparable, albeit somewhat higher, to those of the Zero Basis scenario of the Swiss government's Energy Perspectives.

Similarly, the hourly electricity demand for Switzerland for heating was determined from the heat demand measured over eight years in the district heating area. These results were statistically evaluated and are depicted in Figure 7 as a box plot for each month. Since these are hourly energy demands and not the effective power, they are given in GWh/h instead of GW (as in the Empa study [2]).

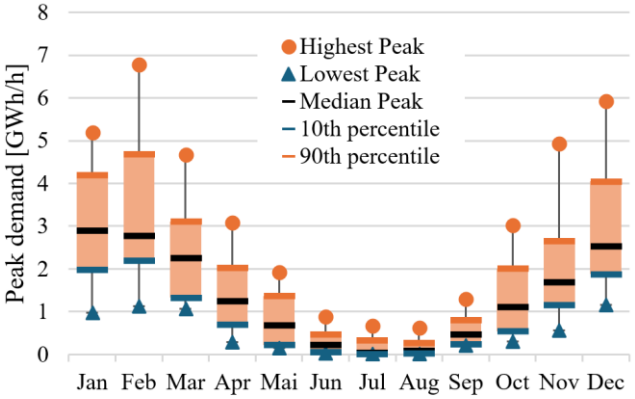


Fig. 7: Maximum hourly electricity demand for heat pumps if 80% of Switzerland's space heating needs are covered by heat pumps

From 2009 to 2016, the lowest temperatures occurred in February, with a peak of almost 7 GWh/h observed during that month. In February, the 90th percentile was just under 5 GWh/h. Electricity volumes of 5 to 7 GWh/h were therefore only reached on a few days per month. Nevertheless, between 2009 and 2016, demand of more than 5 GWh/h occurred for a total of 111 hours, spread over several days. The longest duration of electricity demand above 5 GWh/h was 17 hours. Other extreme situations lasted up to 10 hours. It must therefore be assumed that even with an optimisation of the load profile via demand side management, the additional grid load from heat pumps in 2050 will amount to around 5-7 GWh/h when scaled up to Switzerland, equivalent to 60% of today's maximum grid load. The effective peak power will be even higher than the hourly mean value. While this power does not occur simultaneously across all of Switzerland, it represents the average power requirement. Depending on the region, the increase in electricity demand due to heat pumps differs from this average.

4.2 Verification of the top-down analysis using the load profile data of heat pumps

The maximum hourly heat demand from the top-down analysis was verified using the measured load profile data of heat pumps. The measured load profiles from the IWB dataset were correlated with the hourly simultaneous outside temperature. During the period of around 1.5 years for which load profile data was available, temperatures below -5 degrees occurred only rarely. Therefore, only

power values at temperatures between 0 and -5 degrees were used for both the Empa study data and the load profile measurements.

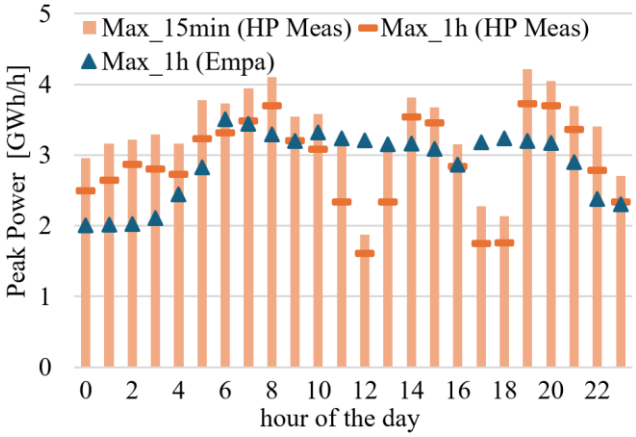


Fig 8: Hourly maximum values from Empa's top-down analysis compared with bottom-up analysis using measured heat pump load profiles (IWB data set) at an outside temperature between 0 and -5 degrees

To enable data comparison, the annual total demand was scaled to the value according to the zero-base scenario of the energy perspectives [1]. The average outside temperature at the IWB load profiles for 2021/2022 was around 3.5 degrees higher than the multi-year average from the Empa study. Consequently, the peak loads are rather overestimated when scaled to the same annual demand. In consideration of this, the maximum power values and their distribution over the day are very well confirmed, as shown Figure 8. The load profile data also shows heat pump blocking at midday and in the evening, which causes higher values after the block and during the remaining time. Compared to the maximum hourly values, the 15-minute maximum values of the measured heat pump load profiles were around 15% higher.

4.3 Power reduction by demand side management

The question arises whether insights into the frequency and duration of high-power consumption can be used to reduce grid demand, preventing the need for over-dimensioned grids. Since heat pumps cannot typically be blocked for more than 1-2 hours without noticeable comfort loss, reducing power to the 90th percentile (Figure 7) is challenging. This would require customers to accept lower room temperatures on very cold days. It can be assumed that power demand, relative to room temperature in cold weather, follows a similar pattern to the relationship with outside temperature shown in Figure 1. A 1°C reduction in room temperature would reduce maximum power by 3-5%. To align grid demand with the 90th percentile, users would need to accept a 2-3°C reduction in room temperature. Today, grid operators cannot estimate the extent to which a power limit will be accepted. However, this is relevant if grid expansion is to be reduced with the help of control.

5 Conclusion

The maximum measured power of heat pumps is on average around 60% higher than the nominal power reported in the TCR. These power overruns, which last several hours on average, are significant. The maximum power is additionally influenced by emergency or auxiliary heating. Therefore, in addition to the nominal power, the maximum heat pump power and the power of the emergency and auxiliary heating should also be requested with the installation notification or connection request (TCR).

The coincidence factor of the maximum heat pump powers across multiple heat pumps is nearly 50%, depending on the number of heat pumps considered. In relation to the specified nominal power, the simultaneity factor exceeds 75%. This simultaneous maximum load of the heat pumps coincides nearly 100% of the time with the remaining grid load**,** directly influencing grid expansion planning.

Extrapolating power demand in Switzerland for 2050 shows that the additional grid capacity required for the installation of heat pumps could be up to 60% higher on average than today's grid load. Regional variations in additional load will depend on grid structure and local temperatures.

The additional grid load from heat pumps can only be reduced to a limited extent by control measures. For example, limiting maximum supply load on cold days could reduce grid demand, but would require customers to accept reduced heating and must be implemented across a wide area to be effective.

6 Acknowledgements

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7 References

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