
Hamidreza Heidar Esfehani#1, Martin Kriegel#2, Hatef Madani*3

# Hermann-Rietschel-Institut, Department of Energy Technology, Technical University of Berlin, Marchstraße 4, 10587 Berlin, Germany
1 hamidreza.heidaresfehani@tu-berlin.de
2 m.kriegel@tu-berlin.de
* Department of Energy Technology, KTH Royal Institute of Technology
Brinellvägen 68, 10044 Stockholm, Sweden
3 hatef.madani@energy.kth.se

Abstract
Fast growing adaptation rate of renewable electricity mainly through windmills, causes high rates of fluctuations and electricity surplus in power grid network and energy utility. Considering the diversity of demand sides in residential sector including space heating and domestic hot water and their high load shifting potential, electrification of heating sector through heat pumps is seen as one of the most promising solutions for flexible demand side management. In this paper an off-peak load management strategy through large scale ground source heat pump system coupled with heat storage is presented to offer the flexibility by time shifting of thermal demand of multi-family building and harvesting electricity surplus generated through integration of wind power. By considering different scenarios the role of thermal storage in load shifting and peak shaving of demand profile is evaluated. The case study is carried out for Berlin within German electricity network to increase the possibility of adaptation of more wind power in energy market.

Keywords- Off-peak load management, renewable electricity, ground source heat pump, thermal energy storage, sizing

1. Introduction

Due to the fluctuating residual loads, increasing rate of electricity surplus and consequently high instability of power grid, renewable electricity is not yet considered as a reliable source to be integrated in base load supply in order to reduce the share of conventional power plants and fossil fuels. Considering the fact that utility network cannot store excess energy and electrical storage technologies are still not proven in large scale, recently developing load management strategies has been seen as one of the cheapest and most reliable methods for resolving power mismatch and balancing
generation profiles. This would give the possibility of increasing the renewable share in energy utility.

According to German government’s energy and climate policy (Energiewende), by 2020 renewable energies are to have a share of at least 35% in gross electricity consumption, 50% share by 2030, 65% by 2040 and 80% by 2050[1]. This represents the importance of a resistant and reliable solution for upcoming challenges in German energy network.

In the 27 EU member states, building sector consumes 68% of the total final energy consumption where space heating is responsible for 70% of this share [2]. This represents the substantial flexibility potential of load management in residential sector.

Implementing heat pumps for supplying domestic hot water (DHW) and space heating can ease and accelerate the integration of renewable energy.

In this paper the role of a large scale ground source heat pump couples with thermal energy storage in balancing the fluctuation of electricity network by shifting electricity overproduction to cover thermal consumption is investigated. This combined system supplies a multi-family building during heating season. In order to optimize the pick shaving potential of system a load management strategy for different scenarios has been introduced. Taking the advantage of surplus electricity during off-peak hours to cover the peak demand is the basis of developing this load management strategy.

To evaluate the flexibility potential of the proposed system and strategy a numerical model of the system together with corresponding reference generation and demand profiles is developed in TRNSYS (Transient System Simulation) environment and the simulation is carried out for different cases.

Next section elaborates the methodology of this research work.

2. Methodology

2.1. Load management strategy

Basically the aim of load management is to flatten and smooth the load profile by shifting the load from peak time to off-peak time where there is over production. Due to the power grid constraints in Germany nowadays the heat pump manufacturers provide heat pump with heat storage that can handle two blocked hours of electricity three times a day [3]. This already offers a load shifting potential by the heat pump and heat storage.
In this paper it is aimed to increase the load shifting potential of the system by introducing off-peak control strategy for heat pump and heat storage. Basically surplus electricity and power exchange between regions are challenges that are currently faced and prevent the stable and balanced electricity utilization.

More than one third of Germany’s 21,500 wind turbines are installed in eastern side of the country; this concentration of generating capacity regularly overloads the region's electricity grid [6]. According to 50Hertz, the major power network operator in north and east of Germany, wind energy surplus threatens electricity transmission with power outages and blackouts; in extreme cases the produced power by conventional power plants and windmills is three to four times the total amount of actual consumption (Figure 1).

![Figure 1: Increasing surplus renewable electricity in Germany: current and future situations [7]](image)

Therefore electricity surplus offers considerable potential which can be harvested through heat pump to supply thermal demand of residential buildings in Germany. Figure 1 represents the excess electricity potential and average thermal demand of multi-family house located in Berlin during heating seasons (January-March, October-December). These are chosen as reference generation and load profiles for numerical analysis.
The demand load profile of the building is calculated based on DIN EN 832 and VDI 4655 norm [8, 9].

For the calculation a Test Reference Year (TRY) for Berlin provided by DWD (German Metrological Service) is considered; it consists of eight typical-day categories as combination of three different time and weather indicators (Workday/Weekend, Fall(Transition season)/Winter and Bright/Cloudy) and identified as thermal demand factors that generate the daily thermal demand of the building as below:

\[
Q_{\text{th, daily}} = Q_{\text{th, a}} \cdot F_{\text{th,tdc}}
\]  
(1)

Where \(Q_{\text{th, daily}}\) and \(Q_{\text{th, a}}\) are daily and annual thermal demand of the building and \(F_{\text{th,tdc}}\) is thermal demand factor for each typical-day category.

Table 1 represents more information about the building as well as annual DHW and space heating consumption of the building:

<table>
<thead>
<tr>
<th>Consumption</th>
<th>kWh/m²</th>
<th>Unit Size/Nr. of Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>DHW</td>
<td>14</td>
<td>68 m²/12</td>
</tr>
<tr>
<td>Space heating</td>
<td>142</td>
<td></td>
</tr>
</tbody>
</table>

By introducing load control scenario heat pump system is operated based on the hours where surplus electricity is generated in low voltage grid. As surplus rate is fluctuating throughout the year it might affect the operation trend of the heat pump, therefor the amount and distribution of surplus (heat pump blocked hours) are deciding factors in developing the control scenarios.
In this work heat pump system supplies building in monovalent operation where the entire thermal demand is covered by the system. According to German heat pump manufacturers standards \[3\] in monovalent mode the capacity of the heat pump is calculated as:

\[
Q_{\text{HP}} = f_{\text{extra}} (Q_{\text{DHW}} + Q_{\text{Sh}})
\]  
(2)

Where:

\[
f_{\text{extra}} = \frac{24}{24} \text{(blocked hours)}
\]  
(3)

\(Q_{\text{HP}}\) is heating capacity of the heat pump, \(Q_{\text{DHW}}\) is DHW demand and \(Q_{\text{Sh}}\) is space heating demand. \(f_{\text{extra}}\) is safety factor and determined based on the blocked hours where heat pump is not utilized by power grid, as it is mentioned before this period cannot exceed six hours on daily based.

As the overall peak demand of the building is about 55 kW the maximum needed capacity of the heat pump is:

\[
Q_{\text{HP}} = 1.1 \times 55 \text{ kW} = 60.5 \text{ kW}
\]  
(4)

As ground source heat pump Vitocal 350-G pro from Viessmann group \[10\] is selected and according to EN 14511\[4\] norm at source temperature (brine temperature) of 0°C and temperature deference of 5°C performs as follows:

\[
\text{COP} = \frac{Q_{\text{HP}}}{Q_{\text{el}}} = 4.4
\]  
(5)

\[
Q_{\text{el}} = \frac{Q_{\text{HP}}}{\text{COP}} = 13.6 \text{ kW}
\]

Where COP is coefficient of performance and \(Q_{\text{el}}\) is electricity demand of the heat pump.

Therefore 13.6 kW is then considered as the lower dead band of the excess electricity per building to supply the heat pump system.

The hysteresis control method is selected for the strategy where in each 15 minutes time step the availability of electricity surplus is observed and supply temperature of the storage tank is evaluated and compared with considered set point temperatures for DHW and space heating within the dead band of \(\pm 2^\circ\text{C}\); the corresponding ON/OFF control signal is then generated for the heat pump; Figure 3 illustrates the simplified load control process of the heat pump:
The 5°C reduction in set point temperature in case of normal control is according to the LowEx concept for district heating [5] in order to reach least possible drawn power from the grid during peak load hours.

2.2. Model

Basically the system consists of a ground source heat pump equipped with a storage tank. Heat pump charges thermal storage based on operation signal given from surplus load controller, storage temperature sensor and heating curve; afterwards storage tank fulfills the DHW and space heating profiles.

A stratified storage tank with four thermal layers (node) is applied for this model where how water supplied by heat pump enters the first node (top node), DHW flow stream is taken from the second node and space heating demand is supplied by third node of the tank. A bypass valve is implemented on return stream to the storage tank in order to balance the supply temperature range of the space heating according to space heating curve.

It is to be noticed that the deviation or consistency of the supply power of the storage tank from the heat demand is one of the key factors considered for evaluation of load shifting potential of the system.

As it is mentioned before the demand profiles of the multi-family residential complex located in Berlin is calculated according to DIN EN 832 and VDI 4655 norm and integrated in the model.

The dynamic simulation is carried out by TRNSYS (Transient System Simulation) [11] and the considered results are for the period of six months.
(January-March and October-December) where the heating demand has the highest rate during the year.

Figure 3 illustrates the schematic of the system model:

![Diagram of the system model](image)

**2.3. Operational Scenarios**

In order to analyze the impact of different load management strategies on load balancing and thermal performance of the system there are two main scenarios considered in this work as follows:

- **Base case scenario:** Where heat pump is controlled though normal ON/OFF control method with daily determined blocked hours by power utility, in this case thermal storage is sized in order to overcome maximum two continues hours per day where heat pump is not operating [3].

- **Surplus (off-peak) scenario:** Where the priority is to utilize heat pump by electricity surplus. For this purpose, the system is controlled to operate during off-peak hours; in case of uncovered thermal demand heat pump will continue operating despite of absence of excess electricity. Furthermore the effect of increasing heat storage volume on load shifting ability and energy supply of the heat pump is evaluated.

It is to be noticed that for both scenarios the 60 kW ground source heat pump is applied.
3. Results and Discussions

As it is mentioned in previous section the ability of heat pump system with heat storage in shifting and balancing the load profile is aimed to be proven through comparing two scenarios. As it can be seen in Figure 4 operating heat pump under surplus control scenario leads to substantially reduction of base load (conventional) share in power consumption of the heat pump up to 70% of the same case in base case scenario. It indicates that the main advantage of surplus scenario over base case control scenario is to reduce the base load power generated by coal and fossil fuel power plants and compensate it by electricity surplus.

![Fig. 4 Monthly Base load Power Consumption of the heat pump for both scenarios]

Table 2 represents that with the same storage volume, total energy supply and seasonal performance factor stay almost constant for two scenarios.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Base Case</th>
<th>Surplus</th>
</tr>
</thead>
<tbody>
<tr>
<td>HP capacity, kW</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Heat Storage Volume, m³</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Total Supplied Heat, kWh</td>
<td>95796</td>
<td>95956.8</td>
</tr>
<tr>
<td>Total HP Consumption, kWh</td>
<td>30406.7</td>
<td>30878.6</td>
</tr>
<tr>
<td>Seasonal Performance Factor</td>
<td>3.1</td>
<td>3.1</td>
</tr>
</tbody>
</table>

Figure 5 illustrates the distribution of electricity consumption of heat pump through surplus control scenario. As it can be seen up to 75% of the total electricity demand is utilized by electricity surplus. The reason of less surplus share for November and December is the lower fluctuation of electricity utilization in the grid and less available surplus respectively. This shows the
capability of heat pump system in balancing low voltage grid profile by shifting electricity overproduction during heating season.

In the next step the effect of increasing thermal storage volume within surplus control scenario on the system performance is evaluated; thermal storage volume is increased in 5 steps from 8 m$^3$ to 20 m$^3$. 20 m$^3$ storage tank is sized as worst case scenario where the entire demand is supplied during extreme long heat pump supply gaps (blocked hours) [12]. As it is shown in Figure 6 by increasing the storage volume heat pump is able to harvest more electricity surplus and thus consume less normal electricity. The reason is larger storage tank is able to supply the thermal demand for more hours and therefore cover longer heat pump blocked hours, this leads to less normal power consumption of HP and more taken surplus consequently.

Fig. 5 Monthly distribution of the Power Consumption of heat pump in Surplus scenario

Fig. 6 Monthly variation of shifted electricity surplus by heat pump for different storage volume
An important criteria considered in evaluating load balancing ability of the system is the energy storage potential as a difference between the energy supplied by heat pump and thermal demand of the building. Comparing different storage sizes for the heat pump within surplus scenario it is understood that using larger tank increases the energy supply and thus storage potential of the system which enhances the supply time consequently (Figure 6).

Fig. 6 Monthly variation of thermal storage potential for different storage volumes

4. Conclusions

As it is seen in the results, applying the proposed load management scenario and harvesting electricity surplus by heat pump system gives the possibility to adapt more renewable electricity in grid network; moreover thermal storage size plays an important role in load shifting capacity and thermal performance of the heat pump system within surplus scenario. This research work is as the part of ongoing PhD project where in next phase the variable speed heat pump will be applied in model to increase the flexibility of the control scenario; moreover in order to evaluate the environmental impact of the system in terms of CO2 mitigation, the consumption of primary energy sources and adapting renewables in large scale will be included and analysed at final stage of the project.

Acknowledgment

This research work is done as a part of the PhD project granted by Climate-KIC as an initiative of EIT lab of EU under the task number: APED0003.
References


