THE NEW ROLE OF NIGHT STORAGE HEATERS IN RESIDENTIAL DEMAND SIDE MANAGEMENT

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ABSTRACT

Electric night storage heaters (NSHs) were once used as the earliest form of residential demand side management in Germany. However, today NSHs are considered expensive and inefficient. Still, as the share of renewable energies in the German electricity production increases and the challenge of matching electricity production and consumption arises, the potential and usage of NSH for demand side management is reconsidered. Therefore, in this analysis the heat supply of an existing building with NSHs is analyzed by comparing the traditional operation with a scenario of NSHs coupled with a photovoltaic system and another scenario in which the NSHs receives signals indicating overproduction of renewable electricity in Germany. It is found, that for the market situation of the year 2020, the primary energy demand and resulting CO_2 emission of a NSH can be reduced by up to 30 % and costs can be lowered by almost 19 % if the system is charged at times of high RE generation.

INTRODUCTION

With the growing share of renewable non-dispatchable energy generation, the challenge of matching electricity production and consumption arises. Thereby, residential and commercial buildings, accounting for up to 30 % of Germany's end energy consumption, could potentially provide flexibility to balance fluctuating electricity supply (BMWi, 2011). The majority of the required end energy in buildings is used for heating purposes, thus a smart interconnection of the electricity grid with domestic thermal supply systems introduces a huge Demand Side Management (DSM) potential. While heat pumps (HP) and combined heat and power (CHP) systems are very promising for such concepts, the installed capacity of these units in the market is yet very low (2012: approx. 1 GW CHP and 2 GW installed HP capacity). (Ecofys, 2011; Prognos, 2013)

A technical component that can play a major role in residential DSM is the Night Storage Heater (NSH), especially if combined with a modern alternative control mechanism. When Germany's electricity generation relied mostly on continuously operating lignite and nuclear power plants with low electricity production costs, excess energy was available at night-time. To flatten the German electricity demand profile and prevent expensive shut downs of base load plants, NSHs were wildly promoted and installed. Thus, NSHs can be considered as one of the earliest forms of DSM in residential buildings. Further, NSHs are characterized by very low maintenance costs and require no oil tanks or gas connections, compared to conventional boilers. The accumulated electrical capacity increased in Germany from 10 GW in 1970s to 40 GW in 1995. This resulted in an electric power consumption of 27 TWh in 1996 through NSHs (Stadler, 2008). Still, it is assumed that the remaining NSH units have an installed capacity of more than 16 GW in Germany (Bundeskartellamt, 2010). The resulting potential for load shifting was also recognized by the German government, which suspended in 2013 a law intending to prohibit operation of most types of NSHs after 2019 (Bundesgesetzblatt, 2013).

However, the technological infrastructure for alternative control of these units is not widespread today. Therefore, almost all systems are still operated in night storage mode instead of a renewable energy storage mode, as part of a demand side management scheme. In this paper we investigate the potential of an alternative and innovative operation of night storage heating systems. Opposed to the current operation strategy, in which NSHs are charged typically between 10 p.m. and 6 a.m., the storage process is not controlled by a static timer. Instead, the charging module adapts dynamically to the system's requirements and to the availability of renewable electricity generation. In this analysis the thermal supply of an existing building with traditional NSH operation is compared with a NSH coupled with a photovoltaic (PV) system and a NSH receiving signals indicating overproduction of renewable electricity in Germany. Further, the supply of the observed building through a condensing gas boiler is analyzed as a benchmark. The latter is by far the most common heating system in Germany and often installed when NSH systems are exchanged. The analysis is based on a dynamic simulation of the thermal building behavior and the thermal supply system in Dymola/ Modelica (Modelica Association et al., 2014).

In the following sections, the approach of this analysis and the underlying models are introduced. Afterwards, the simulation results are presented and discussed. Finally, the potential for domestic DSM with NSH is analyzed and general indications for the future of this technology are given.

APPROACH AND MODELLING

This section presents the procedure for the investigation of the DSM potential of NSH. In this analysis, an existing single family building from Bottrop, Germany is used as a test case. A model of the building's energy system in Dymola/ Modelica is developed to simulate the heating demand and dynamic behavior in the different supply scenarios. The most important data of this building is presented in Table 1. The dwelling is simulated using a low order thermal network building model, which is based on the VDI 6007-1. This model was created and validated at our institute and detailed information on the model's design and properties were published (Lauster, M., et al., 2014; Teichmann, Jens, et al., 2013). The underlying weather data for the simulation is based on the German Test Reference Year (TRY; DWD, 2012). Thereby, data for the TRY Region 5, which comprises the city of Bottrop, was used. Furthermore, a dynamic occupancy profile with corresponding electrical demands for domestic appliances and lighting was generated for the analyzed building, based on the approach of Richardson (Richardson, 2010).

The building is supplied by an NSH, which consists of an electrical heater integrated in clay bricks that serve as thermal storage. Set temperatures in the building are 21 °C for the day-time operation from 6 a.m. till 11 p.m. and 18 °C for the remaining night-time. The NSH is loaded according to different operating strategies, all of which ensure that enough energy is stored, to cover the expected heating demand. Therefore, in the charging module, the energy demand of the past days and the weather forecast for the next day is used as an input to calculate the required state of charge (SoC) for the next day's corresponding heat demand. Thereby, if outdoor temperatures are expected to be as low as -14 °C, the storage heater's charging duration is set to 8 hours at which the full storage capacity is reached, while at expected 20 °C the charging duration is set to zero. The charging module takes into consideration the remaining heat from the previous charging period and reduces the new charging duration accordingly. An overheating safety module is implemented to interrupt the charging if the inner temperature exceeds 600 °C. The heat transfer model comprises heat delivery through radiation and free convection or in combination with forced convection through a fan.

The implemented model is based on the data of the AEG WSP 2010 and WSP 4010 NSHs (EHT, 2014). The number of units needed is determined according to the nominal heat load of the dwelling. The model comprises a charging module and a room temperature control unit. The room temperature is regulated by a fan which is operated in a non-modulated mode using a hysteresis of 2 °C to maintain the indoor temperature within the thermal comfort standards. Basic technical data of the used NSH can be found in Table 1.

Table 1
Properties of the modelled building and NSH

Construction year	1905
Total heated area	106 m²
Nominal heating load	9 kW
Installed NSH	6 x 2 kW, 2 x 4 kW, 2 x 1 kW
NSH nominal capacity	176 kWh
NSH charging power	22 kW
NSH heating power	10 kW

Traditional operating strategy

In the traditional operation scenario, the NSH stores the required energy for the upcoming heating demand during night-time only. The calculated charging time will start at 10 p.m. and end once the required SoC is reached. Since the calculation of the required energy is based on an ideal model of heat demand prediction, the stored energy is always sufficient to cover the next day heat demand. Thus, additional heating phases during the day or a back-up heater are not necessary.

Flexible operating strategy

Two different scenarios of active DSM operation are applied to the NSH. In the first scenario, it is assumed that the roof of the modelled building is equipped with a PV system with a peak power rating of 10 kWp and an expected yearly electricity generation of 8.7 MWh. These values are taken from the solar potential map "Solar Atlas" for the city of Bottrop (Figure 1). The detailed PV generation is than dynamically calculated and the electricity consumption of the domestic appliances and lighting is subtracted. The remaining PV electricity will be used to load the NSH, if the charging module indicates that heating energy would be required within the next 24 hours.

It is uncertain whether the current German feed-in compensation will last beyond 2020, since the German government plans to promote direct marketing of PV systems by slowly reducing the compensation to the market price.

Therefore, it is assumed that instead of the PV self-consumption for the NSH the produced electricity could be sold to the grid at 57.30 €/ MWh, which is the estimated average EEX price for 2020 (IE Leipzig, 2012). Thus, 0.0573 € opportunity costs are calculated for every kWh of PV electricity used to charge the NSH.

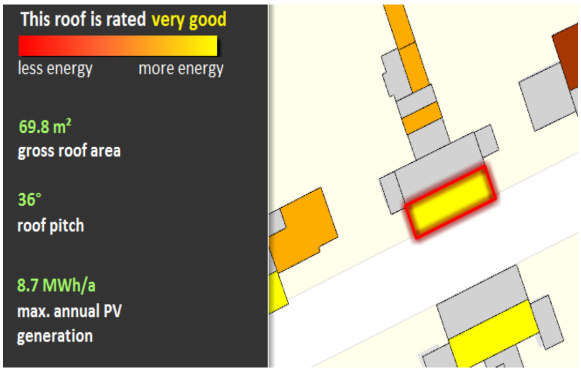


Figure 1
Solar potential for the modelled house from "Solar Atlas" (Stadt Bottrop, 2014)

The second DSM strategy is based on calculations for German-wide excess renewable energy (RE) generation in 2020. The further expansions of RE generation capacities are estimated according to the 2020 target of 35 % renewable energy generation in §1 of the German Renewable Energy Act (BDEW, 2013). Dynamic RE generation is deduced from the typical generation profiles for REs and combined with the assumed capacity of "must-run" power plants like nuclear or lignite plants, which cannot be easily shut down in temporary occurrence of available RE. The available total capacity is then compared to a German-wide electricity demand estimation, which is based on the addition of weighted typical profiles for residential, industrial, and commercial customers (EWE Netz, 2014). The resulting daily hours of excess RE energy generation for the whole year are presented in Figure 2.

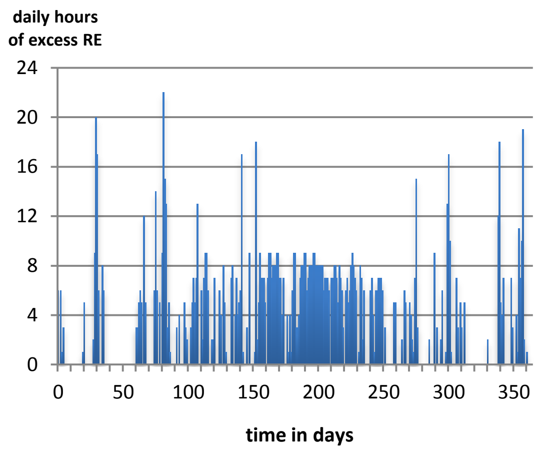


Figure 2
Daily hours of expected excess electricity from RE in the year 2020 in Germany

In the simulation, this excess electricity is made available for charging the NSH systems, if heating demand is indicated. For this excess generation, a basic minimal price of 0.02 € is assumed. Additionally, charges for transmission and distribution of the electricity as well as the VAT have to be paid. All these costs are considered to have similar magnitude as today.

Finally, as a benchmark, we assume that the NSH system could be exchanged with a typical condensing gas boiler (Viessmann, 2014), which is the most common heating system in Germany. In fact, over the past years most NSHs taken out of operation were replaced by such a boiler. The underlying electricity prices, the used primary energy factors, and the expected CO_2 emission factors for all scenarios are presented in Table 2. To ensure a fair comparison, all scenarios and underlying factors are calculated for the year 2020.

Table 2
Boundary conditions for the 2020 scenarios

	NSH	***PV***	***RE***	***Gas***
Annual basic charge	44 €	44 €	44 €	142 €
Price per kWh	23.3 ct	5.7ct	10.2 ct	8.7 ct
Primary energy factor per kWh	1.35	0.39	0.16	1.1
CO_2 emissions per kWh	355 g	75 g	41.5 g	233 g

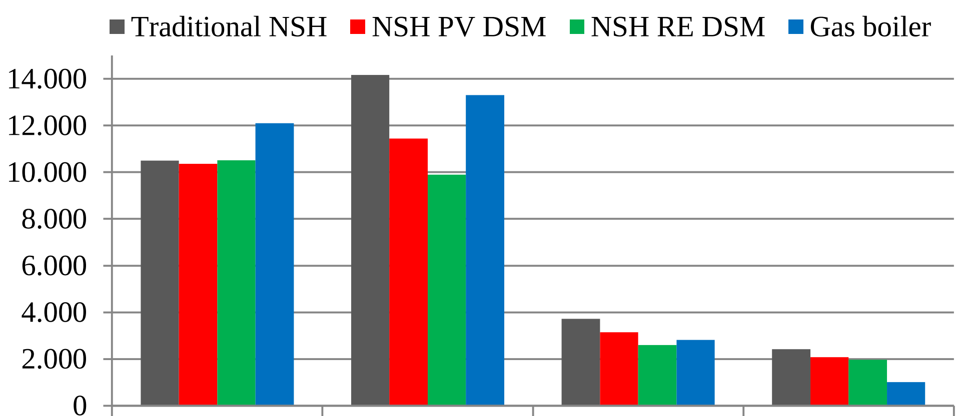
The underlying gas and night storage electricity prices are taken from the local energy provider (ELE, 2014). The adaption of prices as of 2020 is performed by taking into account an increase of 13 % for end-consumer electricity and 10.5 % for end-consumer gas into account (IE Leipzig, 2012). The primary energy factors are used to calculate the primary energy required for one kWh of the final energy. These factors depend mainly on the primary energy source (fossil fuel or RE) and the efficiency of the used energy conversion. Values are taken from German Energy Saving Ordinance (EnEV) and other studies (IINAS, 2012; Wagner, U., et al., 2013). The CO_2 emissions are calculated based on the type of energy used to cover the demand and the corresponding CO_2 emission of the energy source (Wagner, H.-J., et al., 2007; Wagner, U., et al., 2013). The primary energy and CO_2 factors of excess renewable energy are based on the share of solar and wind energy production in the residual load.

SIMULATION RESULTS

In the following section, the results of a dynamic one year simulation for the four scenarios - traditional NSH operation, NSH PV DSM, NSH RE DSM, and gas boiler - will be presented. In all NSH scenarios the building's final energy demand was approx. 10,500 kWh_{el}. Only minimal variations due the NSH's heat losses were identified, which are depended of the time when the NSHs were charged.

In the case of PV DSM 18 % of RE and in the case of the RE DSM 34 % of RE was used to load the NSHs. Accordingly, the primary energy demand of the NSHs was reduced by 19 % for the PV and 30 % for the RE scenario. The values for PV/ RE usage and reduction of the primary energy demand are not similar, since the primary energy factors for PV and for the RE in 2020 differ. Furthermore, through the DSM control the CO_2 emissions could be reduced by 15 % for the PV and 30 % for the RE scenario. Finally, the energy costs of the NSH could be reduced by 14 % when own excess PV electricity was used and by 18.5 %, when German-wide excess RE was consumed.

The comparison with the condensing gas boiler shows the boiler's higher energy consumption and the resulting large primary energy demand. This difference comes from the boiler's efficiency, which is on average only 93 %, while 100 % of the used electricity is converted to heat in the NSHs. However, the CO_2 emissions and the energy costs are very competitive, even in comparison with the dynamic DSM scenarios, which utilize renewable energies. While the CO_2 emissions of the boiler can be just undercut by the NSH RE DSM operation, the energy costs for any NSH operation are about double of these for the gas boiler operation. The detailed results for the performed simulations can be found in Figure 3.



	Energy demand in kWh	Primary energy demand in kWh	CO2 emissions in kg	Energy costs in Euro
Traditional NSH	10.494	14.167	3.725	2.421
NSH PV DSM	10.366	11.444	3.151	2.074
NSH RE DSM	10.511	9.893	2.604	1.972
Gas boiler	12.101	13.311	2.820	1.005

Figure 3
Comparison of the results for a one-year simulation with different NSH strategies and a gas boiler

DISCUSSION

Lately, the use of NSHs has become very controversial owners of such heating systems were often advised to exchange it for a gas boiler as soon as possible. Due to the rising electricity prices and electricity generation powered mainly by fossil fuels NSHs are considered expensive and inefficient, especially in comparison to other electricity driven heating systems, such as heat pumps. However, the sinking primary energy factor of the German electricity mix and the rising share of RE in the electricity mix improve the performance of NSHs distinctly. Even without any change in the traditional operation mode the primary energy consumption and CO_2 emissions of the analyzed building's NSH would be reduced by approx. 40 % between 2013 and 2020, if primary energy factors of the German electricity mix are applied as given in the EnEV and estimated for 2020. (Wagner, U., et al., 2013)

However, our analysis shows that even with the changing RE share in the electricity mix, the traditional operation of NSH will still require more primary energy, cause higher CO_2 emissions and distinctly higher costs than a gas boiler.

The combination of NSHs with a PV system allows for distinct reductions of the primary energy demand, the CO_2 emission, and the energy costs. However, since PV electricity generation is limited in winter when heating is mostly required, the impact is not strong enough to compete with the gas boiler's low operation cost and the small amount of CO_2 emissions. Yet, the primary energy demand is already distinctly lower. If the NSH is operated in the RE DSM mode, 34 % of the required energy can be supplied by RE. Thus, the lowest values in primary energy demand and CO_2 emissions in this analysis can be reached. In difference to the local PV scenario, the German-wide RE generation has a large share of wind power which is first, available also in winter time and second, has lower associated CO_2 emissions than PV. Nevertheless, the energy costs are almost double the costs of the gas boiler scenario. Still, it has to be taken into account, that the NSH has almost no additional operation costs while the gas boiler itself and the associated chimney require yearly maintenance. Taking this into account, yearly costs of the gas boiler could be as high as 1,250 € (BDEW, 2010). However, even if excess RE electricity would be considered free instead of the assumed 0,102 € for grid charges and VAT, the resulting yearly NSH cost would still be approx. 1600 €.

Thus, while the smart controlled operation of a NSH is beneficial for CO_2 emissions and primary energy demand it will still have higher energy costs, at least for a typical one family building with relatively high heating demand. Still, it is important to keep in mind, that the NSH is already installed and paid off, while retrofitting a new gas boiler brings additional costs. In particular, it requires new piping within the building and potentially a new connection to the gas grid. Thus, in cases where major refurbishment is required, keeping a NSH might still be the cost-efficient alternative, especially if operation cost can be reduced through smart control of the units.

Further, today typically older buildings with high demand are equipped with NSHs, however new constructions go more and more in the direction of passive and nearly zero energy buildings. Such houses have only very limited heating demand and therefore the higher maintenance cost of a gas boiler can overcompensate the lower energy prices. Additionally, considering that additional costs for the connection to the gas grid and the piping infrastructure within the building can be saved, the economic benefits of NSHs could improve further. Moreover, once Germany reaches its 2050 target of 80 % renewable generation, it can be expected that balancing the fluctuating electricity generation in Germany will be a valuable service and owners of NSHs could expect a financial compensation for including their heating system in DSM activities.

In particular, in this analysis it was assumed that RE could be transferred across Germany without limitations. However, in reality not only German-wide balancing will be required. In fact, in the future every local grid operator will require huge balancing capacities to balance local decentralized renewable energy generation. Therefore, decentralized and flexible storage capacities, like these offered by NSHs will become very valuable (Wolisz, 2014).

CONCLUSIONS

Electric night storage heaters were once used as the earliest form of residential demand side management in Germany. However, in the 1970's till 1990's when up to 40 GW of these systems were installed the main challenge was to flatten the electricity demand across the day, allowing stable operation of base load power plants. Today, NSH are very controversial being considered expensive and inefficient. Therefore, it was foreseen that these systems will be substituted by condensing gas boilers in the future. In this analysis, we have shown that smart control of NSHs can be a very promising DSM application. NSH systems controlled according to the availability of RE can reduce their primary energy demand and CO_2 emission by approx. 30 %. The analyzed NSH system was supplied by up to 34 % RE in a scenario with a German-wide signal for excess RE generation, and still by 18 % RE if coupled with a local PV system.

While the environmental impact of NSH systems can be distinctly improved though smart operation, the energy costs are still higher than for a gas boiler. However, if major refurbishment is required to exchange the heating system, keeping the NSH and improving the operation strategy might become a promising alternative. Moreover, for new buildings with very low heating demand a heat supply system based on smart controlled NSHs could be cost efficient as of today.

Furthermore, such DSM with NSHs can help balancing the fluctuating renewable electricity generation, thus enabling the approaching "Energiewende". Especially in the future it is expected that the demand for centralized and decentralized storage technologies will grow distinctly, making NSHs a valuable component in the electricity grid. Therefore, the decision of the German Government to stop policy against NSHs is a good starting point to reconsider future roles of this heat supply technology. Further analysis should focus on more sophisticated control strategies and assess the potential of new designs for electricity driven storage heaters (i.e. direct electricity driven concrete core activation or similar systems).

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