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Assessing demand response with heat pumps for efficient grid operation in smart grids

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ABSTRACT

Renewable power generation will increase and more heat pumps (HP) will be installed in the UK causing challenges regarding balancing electricity supply and demand. Demand Response (DR) can help overcoming this issue. This paper investigates how DR with HP can be used for efficient grid operation and which potential exists in the UK. A model has been developed. It allows estimating the impact of introducing HP on the half-hourly load profile on both single dwelling and UK grid level. In the base case scenario it has been shown that grid peak loads would increase by about 6 GW in the winter. On household level, peak loads would approximately triple. DR has the potential to avoid the new peak loads on grid level. On household level, new peak loads can only be reduced. In an ideal case, in the winter peak loads would rise by 2 GW on grid level. In single dwellings peak loads would increase by one quarter. In both cases DR can avoid the new peak loads. The findings confirm results of previous studies regarding future challenges for grid operators. DR can be one of several solutions that help overcoming these obstacles and it should thus be promoted.

1. Introduction

In the UK, the aim is reducing greenhouse gas emissions by 80% from 1990 levels by 2050 (CCCFCBR, 2014). One element that helps achieving these climate targets is producing power from renewable energy carriers. However, this causes challenges regarding the matching of electricity supply and demand leading to an increased need for flexibility (Holttinen et al., 2013).

Another trend that can help reducing greenhouse gas emissions is the electrification of heating homes by utilising heat pumps. It is predicted that 2.5 to 4 million HP might be in operation in the UK in 2030 (CCCFCBR, 2014). This development can be used for balancing demand and supply by utilising DR. Through shifting loads away from times of insufficient supply or high grid load to times where a surplus of electricity exists or grid load is low DR has the effect of a virtual electricity storage on the electricity grid. Since around 27 million households exist in the UK (DECC, 2014a) a huge potential for shifting electrical heat loads might arise. This paper investigates the use of residential DR with HP for efficient grid operation and its potentials in the UK.

The literature review revealed that several studies (REDPOINT, 2014; Prüggler, 2013; Buber, von Roon, Gruber, & Conrad, 2013; Brunner, Tenbohlen, & Braun, 2013; Pudjianto et al., 2013; Barton et al., 2013) identified vast potentials for utilising DR with HP. However, there is still a general need for quantification of costs and benefits of DR (USDE, 2014; Strbac, 2008) and business cases for DR with HP should be investigated further (Prüggler, 2013). In the UK, Department of Energy and Climate Change (DECC) (DECC, 2014b) recognised that more research is required in the context of electrification of heat and transport.

The paper reviews the literature in Section 2 and presents the modelling methodology in Section 3. Afterwards, the results are summarised in Section 4. Following the discussion in Section 5, conclusions will be made in Section 6.

2. Theory

2.1. The case for demand response

Demand Side Management (DSM) is a measure that aims at affecting a consumer's electricity demand (Evans & Meagher, 1993). DSM can be subdivided into three categories. Energy efficiency targets on reducing the overall demand for electricity. On-site generation is used to flatten load curves. DR focuses on changing the electricity demand during peak times in order to balance supply and demand (Warren, 2014).

Fig. 1 shows the effects that DSM has on load curves. The load shapes depicted in curves 1–3 are DR measures. The effect of

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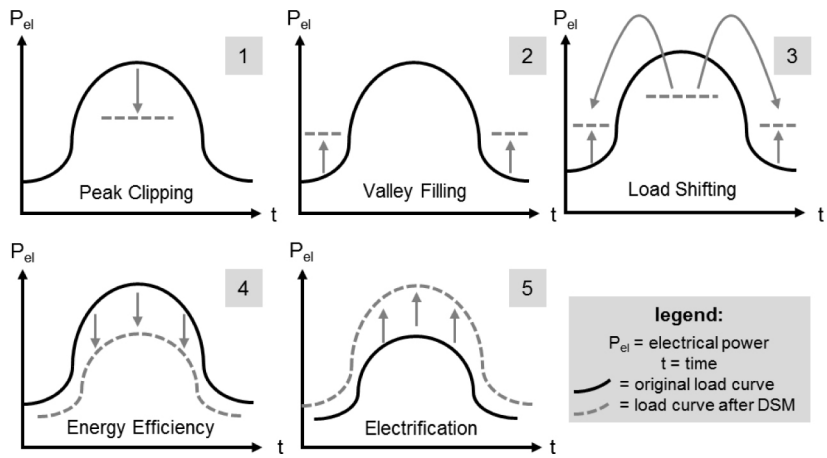

Fig. 1. Load shaping opportunities (World Bank, 2014).

energy efficiency is visualised in curve 4. Electrification results from increasing electricity consumption. The effect is shown in curve 5 (World Bank, 2014).

Utilising DR has multiple benefits. It lowers the need for investments in peak load power plants and grid reinforcements. Implementing DR helps increasing the security of supply. Moreover, transmission losses can be lowered since congestions are being reduced (Strbac, 2008; Bradley, Leach, & Torriti, 2013; Ofgem, 2014). DR can decrease the costs of electricity. This results from the investments avoided (DECC, 2014b) and the fact that wholesale electricity prices can be reduced through DR (Bradley et al., 2013; Ofgem, 2014). Also, it helps balancing the fluctuating feed-in of renewable power generators (Bradley et al., 2013) which is particularly important to systems with low-flexibility generation (Strbac, 2008).

Several barriers to the diffusion of DR exist. Missing Information and Communication Technology (ICT) is reported in Strbac (2008). The planned roll-out of smart appliances and home automation is uncertain (ENAE, 2014). A lack of understanding of the business case for DR is observed since the benefits of DR are not quantified (Strbac, 2008). This also results from the absence of incentives and the general market structure (Strbac, 2008; ENAE, 2014). Since DR depends on user behaviour, social barriers to the diffusion of DR exist. Consumers have to be motivated to conduct DR. This is threatened by a lack of awareness of and consumer interest in DR (ENAE, 2014). Thus, the DR potential is uncertain from a socio-demographic perspective (Jochem et al., 2014).

2.2. Eligible residential consumers

In the domestic sector, loads that have a high elasticity like heating, wet and cold appliances are eligible for DR. This is because customer satisfaction is less affected when shifting these loads (Hamidi, Li, & Robinson, 2009). Using appliances like computers or audio devices for DR would have a higher impact on customer satisfaction. Thus, these consumers are less suitable for DR (Timpe, 2014).

Wet and cold appliances were investigated in Timpe (2014) regarding their DR opportunities. Potentials in terms of shifting or interrupting appliances operation were found (Timpe, 2014). These potentials are questioned by Prüggler (2013). She investigates the DR business model in European electricity spot markets and concludes that DR with household appliances like refrigerators or washing machines is not economically feasible. Economically, only DR with HP is found to be viable (Prüggler, 2013).

Arteconi, Hewitt, and Polonara (2013) have investigated the DR potential of HP in Northern Ireland. They state that HP are suitable for DR and that they can be turned off for 3 h. However, if the household has a heating system with a low thermal inertia such as radiator systems it might become necessary to retrofit a thermal energy storage. This is not the case if the household uses an underfloor heating system (Arteconi et al., 2013). Buber et al. (2013) assessed the potential of HP in Germany. They found high load shifting potentials and highlight that these are dependent on external temperature (Buber et al., 2013). Moreover, HP DR potentials are constrained by building type and the building's thermal characteristics in terms of insulation and heat capacity (Prüggler, 2013).

2.3. The market for HP in the UK

In the UK, domestic heating is dominated by gas boilers (IEA, 2014). A market for HP did not exist before 2005. However, since then a steady market growth could be observed (Staffell, Brett, Brandon, & Hawkes, 2012). In 2012, around 86,000 HP were in operation (EurObserver, 2014).

HP have several opportunities. Since electrical energy is being used HP are theoretically suitable for delivering zero-carbon heating energy (Hawkes et al., 2014). The market potential in the UK is vast and depends on the new-built housing and boiler-replacement rates. In the UK yearly 200,000 to 300,000 new dwellings are being built and about 1.4 million boilers are being replaced (Singh, Muetze, & Eames, 2010).

Nevertheless, HP uptake is slow due to barriers to growth. The net present value of HP is currently often lower than the one of conventional heating alternatives (FEEEP, 2014). Poor building insulation is an obstacle (National Grid, 2014a). Also, grid challenges will arise as a consequence of potential high HP installation rates (Ecuity, 2014). Moreover, an uncertainty regarding future policy developments in the field of HP exists (Kreuder, 2014). Other barriers cover behavioural aspects like a lack of awareness (FEEEP, 2014; Ecuity, 2014).

Different HP diffusion scenarios until 2030 in the UK exist. Fig. 2 summarises them.

National Grid's scenarios vary almost by factor 10 from each other. Within gone green 5.7 million HP will be in use in 2030 whereas slow progression assumes only 0.6 million HP. Committee on Climate Change (CCC) have a base case scenario with 4 million HP in 2030 and a bad case scenario estimating the diffusion of 2.5 million HP. Kreuder (2014) has derived a scenario for the UK from historic growth rates in Switzerland and Sweden. By applying these growth rates to the UK a diffusion of 1 million HP has been projected. The high spread of these scenarios represents the uncertainty connected with forecasting HP diffusion.

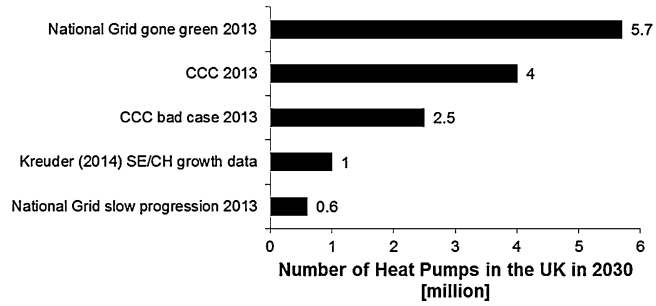

Fig. 2. HP diffusion scenarios (CCCFCBR, 2014; National Grid, 2014a; Kreuder, 2014).

2.4. DR potentials in the UK

Publications (REDPOINT, 2014; Pudjianto et al., 2013; Barton et al., 2013) quantify potentials of DR in the UK. All studies take a long-term perspective. A future electrification of residential heating by using HP as well as an electrification of passenger transport through electric vehicles (EV) is assumed in all investigations. A market-oriented approach taking into account the effects of different DR tariffs is discussed in REDPOINT (2014). Modelling the effects of DR on distribution grid level and the impact on the electricity system is investigated in Pudjianto et al. (2013); Barton et al. (2013).

All publications state high potentials for DR in the UK. Redpoint & Element Energy (REDPOINT, 2014) claim that the domestic sector has a peak demand reduction potential of 0.5 to 2.5 GW in 2030. Pudjianto et al. (2013) conclude that peak loads in the distribution grid increase by factor 2 to 3 and DR can save £ 10 bn across 40 years. Barton et al. (2013) state that net peak demand can be reduced by 10 GW through DR. Moreover, maximum surplus power can be reduced by 10 to 16 GW. The results are dependent on the modelling assumptions as well as on the diffusion of HP and EV. Moreover, the development of the entire electricity system in the next decades is unclear and thus causes uncertainty.

3. Methodology

3.1. Modelling approach

A model has been developed to quantify the impact of installing air source heat pumps (in the following called HP) on the electrical load curves on dwelling and UK grid level. Fig. 3 summarises the approach.

For the dwelling heating need the variables building heat loss coefficient (H), balance temperature (T_{bal}) and ambient temperature (T_{am}) have been considered. An average daily dwelling heating need $\dot{Q}$ in kW_{th} was derived by multiplying H with the delta of T_{bal} and daily mean T_{am} as shown in Fig. 4.

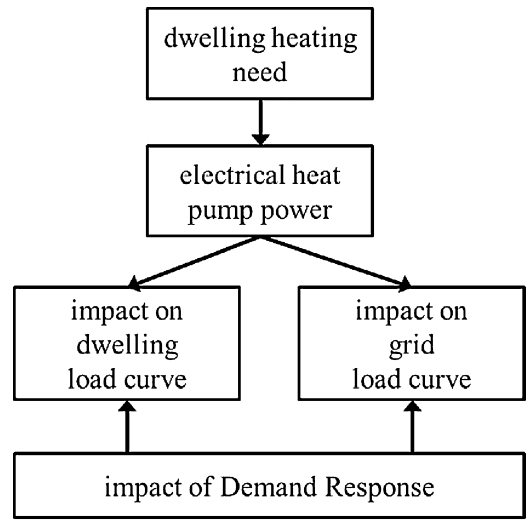

Fig. 3. Methodology.

The electrical HP power P_{HP} has been estimated by the method shown in Fig. 5. The dwelling heating need was multiplied by (1 + l) whereas l takes into account losses in the heat distribution system. Afterwards, the product was divided by the COP.

Regarding DR, the methodology presented in Hawkes et al. (2014) was developed further. They suggest fitting the HP load curve to the underlying load curve in a way that peak load is being minimised (Hawkes et al., 2014). Two cases were investigated. The first case assumed a constant HP operation over the day. The second case assumed perfect DR. Subject to the underlying load curve (either household or system load curve), P_{HP} was increased or reduced. The following logic was applied to calculate the second case P_{HP} values for every half-hour of the day:

if

current value of underlying load curve < daily mean of underlying load curve

then

constant heat pump operation P_{HP} + (daily mean of underlying load curve – current value of underlying load curve)

else

constant heat pump operation P_{HP} – | current value of underlying load curve – daily mean of underlying load curve |

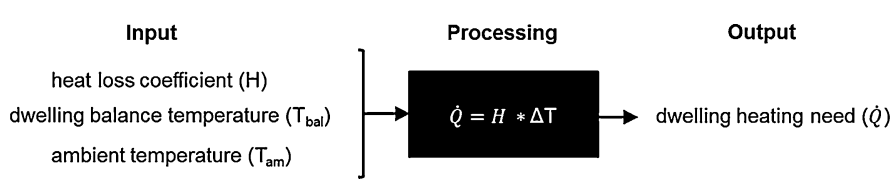

Fig. 4. Modelling dwelling heating need.

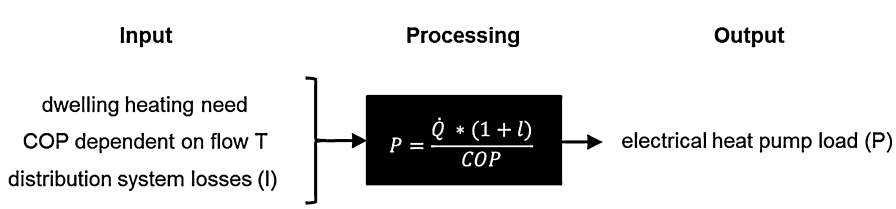

Fig. 5. Modelling heat pump power.

This logic can produce a load curve that has negative values. Since P_{HP} can never be negative, the optimum was assumed to be a mix of the values of the load of the constant operation and the theoretical best case DR scenario. This mix was estimated by generating 99 cases. In each case the optimal DR load curve and the constant HP operation load curve were weighted with a value between 1 and 99%. For instance, the values of the constant HP operation load curve were multiplied by 0.99 whereas the values of the optimal DR load curve were multiplied by 0.01. Afterwards, the values of the constant HP operation load curve were multiplied by 0.98 whereas the values of the optimal DR load curve were multiplied by 0.02. This has been done until the resulting load curve only contained positive values.

It was assumed that HP are centrally controlled by a third party such as a DR aggregator or a grid operator. Moreover, Dwellings are equipped with a hot water storage tank and the ICT that is required for DR. Occupant behaviour, technological aspects of HP operation, economic constraints and the interplay with other technologies or renewable electricity feed-in were neglected. Lastly, it was assumed that the HP modelled cover the building heating need whereas hot water supply was not considered.

3.2. Data

COP data were derived from equations in Energie (2014) subject to T_{am} and flow temperature. The source was verified against a function that is based on measured values for a UK dwelling by Ross (2014). Results were found to be in a similar range.

Household load curve data from English Housing Survey (EHS) measurements provided by a tool developed in Palmer et al. (2014) were used. These are available as monthly average values in 10 min intervals. The data were summarised to half-hourly values by taking the mean. Only load profiles for households with a ground floor area between 99 and 149 m^2 and without electrical heating were used. For the UK's grid load curves, half-hourly National Grid data referred to as i014_TGSD were used (National Grid, 2014b). This gross system demand is calculated from Elexon generation data and contains station load, pump storage pumping and interconnector exports.

Data from another EHS dataset containing physical building characteristics of dwellings in England have been used for H. For ambient temperature, daily mean values from Weather Underground for London have been utilised (Weather Underground, 2014).

3.3. Scenario definition

First, a base case scenario was developed. Table 1 summarises its inputs. The value for H represents the median of the 2.5 million dwellings with the lowest H in the EHS dataset. A sensitivity analysis of the base case has been conducted varying the parameters H and COP. The effect on the load curves has been assessed on both household and system level. Moreover, the impact of different HP diffusion scenarios has been investigated on UK grid level. Finally, an ideal case has been modelled. This case assumed the highest HP diffusion stated in the literature. Furthermore, the dwellings in which the HP are being operated are assumed to be highly energy efficient. The parameters of the ideal case are also shown in Table 1.

Table 1
Base and ideal case parameters.

Parameter	Base case value	Ideal case value	Unit
Building heat loss coefficient	250	100	W/K
Building balance temperature	15.5	11	°C
HP flow temperature	55	35	°C
Losses of heat distribution system	10	5	%
HP COP	Variable	Variable	–
Heat pump market diffusion	2.5	5.7	Million

The scenarios were applied to workdays and holidays on both household and UK grid level. The following coldest days of 2012 as well as average autumn days were selected:

- Coldest winter workday: Friday 03/02/2012, −2 °C London mean T_{am}.
- Coldest winter holiday: Saturday 11/02/2012, −3 °C London mean T_{am}.
- Average autumn workday: Thursday 15/11/2012, +8 °C London mean T_{am}.
- Average autumn holiday: Saturday 24/11/2012, +6 °C London mean T_{am}.

On household level, for the autumn days load profiles for November and for the winter days load profiles for January were used. January profiles were preferred over February profiles since data is consistent with the autumn profiles. On UK grid level, for each day the specific grid load curve was taken from the National Grid dataset.

4. Results

4.1. Base case

4.1.1. Household level

Fig. 6 depicts the results of the base case scenario for the two winter days on household level. The top chart shows the coldest holiday and the bottom one the coldest workday 2012. Both charts illustrate the underlying household load curves as black areas. The dashed curve represents the household load curve that would result from operating a HP constantly. After shifting HP load from peak to off-peak hours the grey area results.

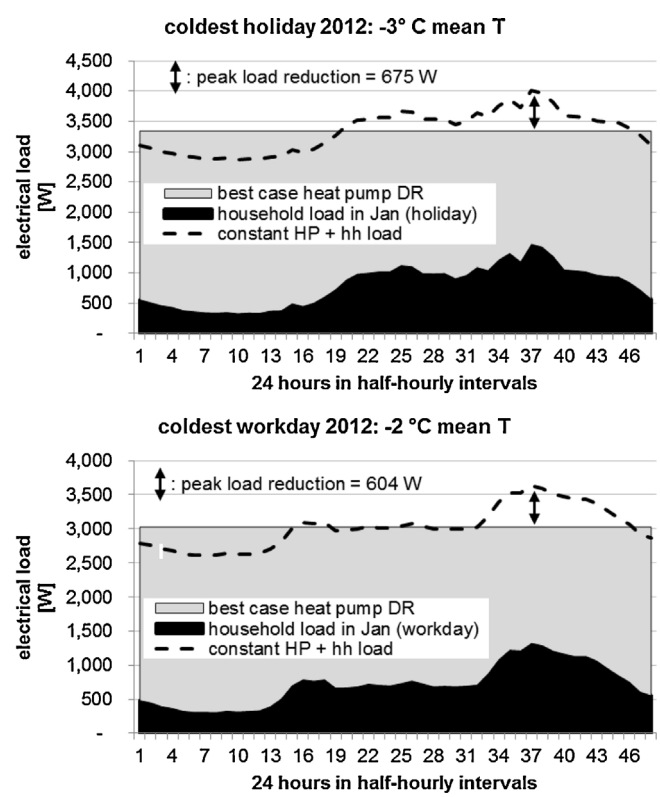

Fig. 6. Base case result—Household Winter.

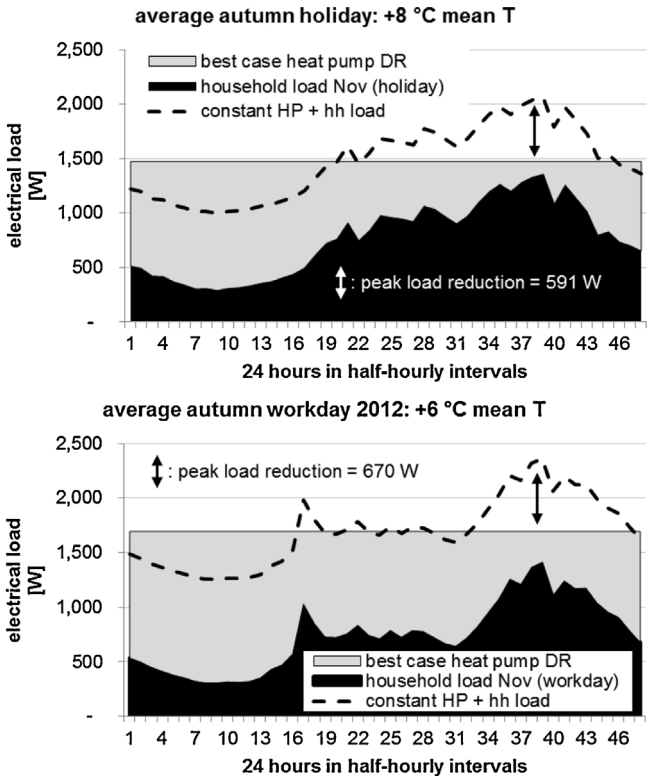

Fig. 7. Base case result—Household Autumn.

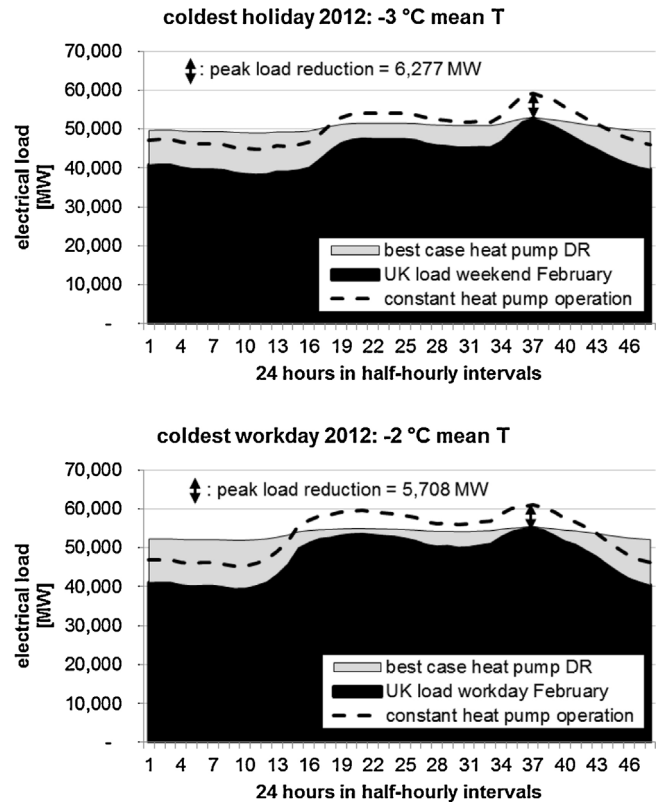

Fig. 8. Base case result—Grid Winter.

Both graphs show that using HP increases the need for electrical power of a household. During constant operation on the coldest holiday peak load increases by the HP load of about 2500 W. This leads to an increase of daily peak load from circa 1500 W to 4000 W. On the coldest workday, peak load increases from around 1300 W to circa 3600 W. HP load is 200 W lower in that case in comparison to the coldest holiday due to the higher daily mean temperature. Summarising, in both cases peak load on household level rises by around factor 2.70 through HP utilisation.

Through applying the load shift logic described, peak load can be reduced by 675 W on the coldest holiday and by 604 W on the coldest workday. This is marked by an arrow. In both charts a horizontal load curve is the result of shifting HP loads. Peak load increase can be lowered through DR from factor 2.70 to 2.30 and therefore by 17% in both cases.

Fig. 7 depicts the results for the two autumn days. The new peak loads resulting from constant HP operation are clearly lower when being compared to the winter.

On the autumn holiday (top chart) peak load through constantly operated HP is increased by circa 700 W from 1350 W to a bit more than 2000 W. Due to colder mean temperature, 950 W are added to the domestic load curve on the autumn workday. Peak load rises from 1400 W to 2350 W. Therefore, it increases by factor 1.50 on the holiday and factor 1.70 on the workday. DR reduces peak loads by 591 W on the holiday and by 670 W on the workday. Therefore, the absolute DR potential is in a similar range as the one estimated for the winter days. DR brings down the peak load increase factors 1.09 on the holiday and 1.20 on the workday.

Summarising, the base case results on household level indicate that electrical load would increase drastically if HP were introduced. Due to the dependency of the COP of HP on ambient temperature, this effect is stronger the colder it gets. Load shifting can contribute to lowering peak loads but especially in the winter grid operators still have to deal with higher loads.

4.1.2. UK electricity grid level

Fig. 8 depicts the base case results on grid level. The top chart represents the results for the coldest holiday and the bottom one refers to the coldest workday 2012.

Without DR, the 2.5 million HP would increase peak load by circa 6.3 GW on the holiday and 5.7 GW on the workday. The deviation, again, results from the temperature difference (−3 °C on the holiday versus −2 °C on the workday). Through constant HP operation peak load would increase by factor 1.12 on the holiday and 1.10 on the workday.

Through DR this new peak can be avoided. This results from the fact that the valleys in the underlying grid load profiles can be 'filled' with the electrical energy needed by the HP. The load is mainly being shifted away from the peaks in the morning and the evening to the valleys at night-time.

The results for the base case for the autumn are summarised in Fig. 9. Due to milder temperatures a constant HP operation rises peak loads by circa 2.3 GW on the workday and 1.7 GW on the holiday. In comparison to the winter days peak loads through constant HP operation are around three times lower in the autumn. As in the winter, through DR the new peaks can be avoided by shifting HP load to hours of lower system load.

Concluding, as well as on household level UK grid peak loads would increase significantly through constant HP operation. However, in contrast to the situation for households new peaks can be avoided by load shifting HP load.

4.2. Sensitivity analysis

The sensitivity analysis was conducted with the variables *H*, COP and HP diffusion. Regarding *H*, the impact on peak loads of both household and grid load curves was strong during the winter due to low temperatures. Increasing *H* from 100 to 350 W/K leads to doubling peak loads in the winter on household level. On grid level,

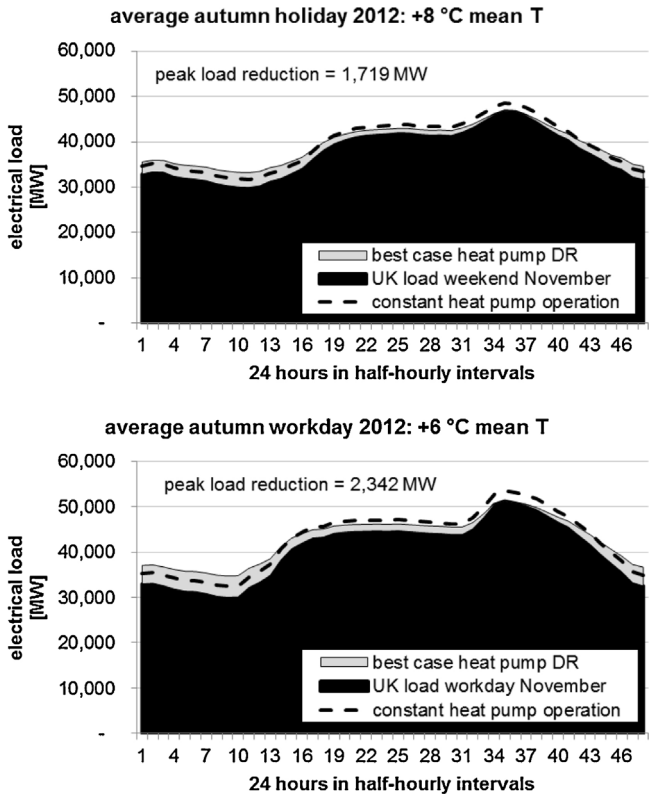

Fig. 9. Base case result—Grid Autumn.

the same increase of *H* leads to a peak load rise by factor 1.10 in the winter. In the autumn, peak load increase was less strong on both household and grid level.

The impact of reducing or increasing the HP COP was also observed to be stronger in the winter than in the autumn. Household peak load without DR in the winter varies by 1350 W between −25 and +25% COP. On grid level, the same COP variation leads to around 3 GW difference in peak loads in the winter. During the autumn, these values go down to 350–500 W on household and 0.9–1.3 GW on grid level.

Analysing different cases of HP diffusion revealed that even for 0.6 million HP DR can reduce peak loads on a winter day by a bit less than 1.5 GW on grid level. If 5.7 million HP are used, winter peak loads could be reduced by 8.6 GW through DR. Therefore, the impact of the number of HP on DR potential is high.

4.3. Ideal case

The ideal case assumes 5.7 million HP in operation in highly insulated dwellings. In the winter, peak loads would increase by 2 GW on grid level. In single dwellings peak loads would increase by one quarter. The new peak loads can be completely avoided through DR in both cases. This shows that even in the ideal case it makes sense to utilise DR.

5. Discussion

5.1. Interpretation and context

The fact that HP load is higher in the winter than in the rest of the year is a drawback because renewable feed-in also occurs in milder seasons. Since HP load is low or does not exist during that time, it cannot be used to balance supply and demand. However, it still makes sense to utilise DR in order to reduce peak loads through HP operation. Nevertheless, the idea of a virtual electricity storage is only feasible if further technologies are added. Integrating additional electricity consumers such as EV would increase the reliability and usability of this storage.

The modelling reveals future challenges for Distribution Grid Operators (DNO). Through HP electrical load in the distribution grid increases. This can be derived from the strong impact of HP on household load curves that was observed. It could be shown that DR has the capability of reducing new peaks on household level but the remaining peak load increase is still significant in most cases. Therefore, DNO should consider using additional concepts that help dealing with peak loads such as direct consumption of electricity from solar photovoltaic generation. Also, using conventional back-up generation like gas boilers to support the HP during the coldest days of the year would be helpful.

On the other hand, the situation is less critical for Transmission Grid Operators (TSO). The load curve on system level has a high capability regarding the integration of new electrical heating loads. However, DR concepts should be implemented since a constant HP operation would increase peak load by around 10%. Moreover, EV were excluded from the analysis. It is likely that these in combination with HP will intensify the challenges for both DNO and TSO.

The literature review showed that DR with HP can be economically feasible in contrast to appliances (Prüggler, 2013). Moreover, Hamidi et al. (2009) and Timpe (2014) state that utilising DR with heat loads makes sense since customer satisfaction is not being affected. These findings support the recommendation that grid operators should foster the use of DR with heat loads.

The peak load increases and DR potentials found are higher than the results in REDPOINT (2014). Here, the authors conclude that the domestic sector has a peak load reduction potential of 0.5–2.5 GW. The potentials stated in the base case of this paper showed that peak load reduction potential amounts for circa 6 GW. The authors in REDPOINT (2014) take into account economic and technological aspects as well as future load curve development and EV diffusion that were neglected within this paper. These points might cause the different results.

Pudjianto et al. (2013) conclude that distribution grid peak load increases by factor 2 to 3. This fits to the effect of constant HP operation on the load curve on household level which was also found to be within this range. However, it has to be mentioned that the authors of Pudjianto et al. (2013) also included EV as well as future load growth modelling in their investigations.

5.2. Limitations and future work

The results have limitations and uncertainties which can be subdivided into the categories data, modelling and other.

The sensitivity analysis has shown the importance of valid input data. The modelling conducted has uncertainties regarding COP, weather data and the household load curves. The COP data used were not taken from a peer-reviewed journal and did not specifically state performance under UK climate conditions. However, the data were verified against a dataset for the UK which provided values in the same range. Nevertheless, the COP dataset still contains uncertainty and should therefore be improved in the future. Regarding weather data the daily mean temperature for London was used. Since London is not representative for the UK this approach also adds uncertainty to the analysis. In future analyses, more representative weather data for the UK should be used. The household load curves were based on measurements for 14 to 19 households. If these load curves represent UK dwellings adequately, has to be validated in the future. This could be done by using the Dynamic Energy Agents Model (DEAM) developed by Barrett and Spataru (Barrett, 2012).

The modelling itself underlies simplifications. The dwelling heating need is being calculated with mean H and T_{bal} and daily mean T_{am}. This approach neglects the variety of physical building characteristics of the housing stock. Thus, real world heat load profiles have to be integrated into the model. Moreover, the variation of T_{am} during the day is being neglected. These aspects should be considered in the future for improving the modelling validity. The same applies for the HP model. Technological aspects of the HP in terms of the ability to shift load or efficiency losses in part-load operation were not considered and should be subject of future investigations. DR with HP can help integrating renewable power generators into the grid. However, this has not been respected in the model. Future research should thus take into account half-hourly feed-in data of renewable power plants.

Other limitations result from the fact that economic, political and behavioural aspects addressed in the literature review were not respected. HP diffusion scenarios range from 0.6 to 5.7 million HP in the UK in 2030 (CCCFCBR, 2014; National Grid, 2014a; Kreuder, 2014) which shows the uncertainty in terms of future HP use. Furthermore, it has been assumed that the necessary ICT for shifting HP loads is available in the dwellings. As seen in ENAE (2014), the required ICT is not yet available in most dwellings. This leads to a lack of planning reliability for grid operators that would invest in infrastructure for DR with HP.

Only air source heat pumps were considered. However, other HP technologies will also be used in the future. Future work should integrate a mix of different HP technologies. Lastly, the interplay with other technologies was not taken into account. Especially, the relation between EV charging and HP operation is worth looking at.

6. Conclusion

The paper investigated the research question how residential DR with HP can be used for efficient grid operation and which potentials exist in the UK. The literature review revealed that HP are eligible for DR and that high potentials exist in the UK. The base case modelled showed that peak loads on grid level would increase by around 6 GW in the winter. Through DR, these new peak loads can be avoided. On household level, peak loads would increase by factor 2.70 in the winter. Here, DR cannot avoid peak loads but it can reduce the factor to 2.30. In the ideal case, grid peak load on the coldest winter days would increase by 2 GW which could be avoided by DR. Therefore, DR with HP has a high potential on grid level and a lower impact on single household level. Uncertainties are caused by data quality, modelling approach and the sensitivities H, COP and HP diffusion. Moreover, limitations result from the neglected economic, political and behavioural framework conditions.

The modelling conducted confirms that grid operators face the challenge of increasing peak loads. DR can provide one part of a solution of dealing with this issue. However, especially on household level DR alone does not solve the problem. Therefore, grid operators should consider additional concepts like self-consumption or back-up generation. Concluding, DR can help reducing peak loads through HP in the future. This will reduce the need for grid reinforcements. Nevertheless, investments in new grid infrastructure are likely to become necessary since electricity demand will grow and balancing demand and supply will become more complex.

Future research should address the research needs in terms of data and modelling approach mentioned in the discussion section. Also, the interplay with other heating technologies, renewable feed-in and EV should be respected in futures studies.

References

Arteconi, A., Hewitt, N., & Polonara, F. (2013). Domestic demand-side management (DSM): Role of heat pumps and thermal energy storage (TES) systems. *Applied Thermal Engineering*, 155–165.

Barrett, M., & Spataru, C. (2012). *Dynamic Energy Agents Model, Model Description Report, part of Falcon Project funded by Western Power Distribution*. London: University College.

Barton, J., Huang, S., Infield, D., Leach, M., Ogunkunle, D., Torriti, J., et al. (2013). The evolution of electricity demand and the role for demand side participation in buildings and transport. *Energy Policy*, *52*, 85–102.

Bradley, P., Leach, M., & Torriti, J. (2013). A review of the costs and benefits of demand response for electricity in the UK. *Energy Policy*, *52*, 312–327.

Brunner, M., Tenbohlen, S., & Braun, M. (2013). Heat pumps as important contributors to local demand-side management. *PowerTech IEEE Grenoble*, 1–7.

Buber, T., von Roon, S., Gruber, A., & Conrad, J. (2013). Demand response potential of electrical heat pumps and electric storage heaters, proceedings of the industrial electronics society. In *IECON—39th Annual conference of the IEEE* Vienna.

Committee on Climate Change, Fourth Carbon Budget Review—Part 2. (2014). *The cost-effective path to the 2050 target*. Available from: ⟨http://www.theccc.org.uk/wp-content/uploads/2013/12/1785a-CCC_AdviceRep_Singles_1.pdf⟩ (accessed: 27/08/2014) (Online).

Department of Energy & Climate Change. (2014a). *All, ECUK data tables in terawatt hours*. Available from: ⟨https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/339292/All_ECUK_data_tables_in_TWh.xlsx⟩ (accessed: 27/08/2014) (Online).

Department of Energy & Climate Change. (2014b). *Demand side response in the domestic sector a literature review of major trials*. ⟨https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48552/5756-demand-side-response-in-the-domestic-sector-a-lit.pdf⟩ (accessed: 27/08/2014) (Online).

Ecuity. (2014). *6.8 million heat pumps by 2030; from vision to reality*. ⟨http://www.ecuity.com/wp-content/uploads/2012/05/6-8-million-Heat-Pumps-by-2030-from-Vision-to-Reality-Final.pdf⟩ (accessed: 28/07/2014) [Online].

Energy Networks Association, Energy, U.K. (2014). *Smart demand response: A discussion paper*. ⟨http://www.energynetworks.org/modx/assets/files/news/publications/Smart_Demand_Response_A_Discussion_Paper_July12.pdf⟩ (accessed: 28/08/2014) [Online].

Energie.ch, Wärmepumpe, [Online], http://www.energie.ch/waermepumpe,. [Accessed: 29/08/2014].

EurObserver. (2014). *Heat pump barometer*. ⟨http://www.energies-renouvelables.org/observ-er/stat_baro/observ/baro218_en.pdf⟩ (accessed: 28/05/2014) [Online].

Evans, M., & Meagher, P. (1993). *Principles and practice of demand-side management*. Oakland: EPRI - Electrical Power Research Institute.

Frontier Economics Element Energy. (2014). *Pathways to high penetration of heat pumps*. ⟨http://www.theccc.org.uk/wp-content/uploads/2013/12/Frontier-Economics-Element-Energy-Pathways-to-high-penetration-of-heat-pumps.pdf⟩ (accessed: 28/07/2014) [Online].

Hamidi, V., Li, F., & Robinson, F. (2009). Demand response in the UK's domestic sector. *Electric Power Systems Research*, 1722–1726.

Hawkes, A., Munuera, L., & Strbac, G. G. (2014). *Low carbon residential heating*. ⟨https://workspace.imperial.ac.uk/climatechange/Public/pdfs/Briefing%20Papers/Low%20carbon%20residential%20heating.pdf⟩ (accessed: 28/07/2014) [Online].

Holttinen, H., Tuohy, A., Milligan, M., Lannoye, E., Silva, V., Müller, S., et al. (2013). The flexibility workout. *IEEE Power & Energy Magazine*, *163*, 53–62.

IEA. (2014). *Heat pump center, retrofit heat pumps for buildings*. ⟨http://www.heatpumpcentre.org/en/projects/completedprojects/annex30/publications/Documents/AN30_finalreport.pdf⟩ (accessed: 28/05/2014) [Online].

Jochem, P., Kaschub, T., & Fichtner, W. (2014). *How to integrate electric vehicles in the future energy system?* ⟨http://www.iip.kit.edu/downloads/No_03_062013_How_to_integrate_electric_vehicles_in_the_future_energy_system.pdf⟩ (accessed: 07/05/2014) [Online].

Kreuder, L. (2014). *Diffusion of domestic heat pumps in the UK until 2030*. London: Paper submitted in part fulfillment of the Degree of Master of Research in Energy Demand Studies Energy Institute University College London.

National Grid. (2014a). *U.K. future energy scenarios*. ⟨http://www.nationalgrid.com/NR/rdonlyres/2450AADD-FBA3-49C1-8D63-7160A081C1F2/61591/UKFES2013FINAL2.pdf⟩ (accessed: 28/07/2014) [Online].

National Grid. (2014b). *Historical demand data*. ⟨http://www2.nationalgrid.com/WorkArea/DownloadAsset.aspx?id=31629⟩ (accessed: 15/05/2014) [Online].

Ofgem. (2014). *Demand side response—A discussion paper*. ⟨https://www.ofgem.gov.uk/ofgem-publications/57026/dsr-150710.pdf⟩ (accessed: 28/08/2014) (Online).

Palmer, J., Terry, N., & Kane, T. (2014). *Further analysis of the household electricity survey—Early findings: Demand side management*. ⟨https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/275483/early_findings_revised.pdf⟩ (accessed: 30/05/2014) [Online].

Prüggler, N. (2013). Economic potential of demand response at household level—Are Central-European market conditions sufficient? *Energy Policy*, *60*, 487–498.

Pudjianto, D., Djapic, P., Aunedi, M., Gan, C., Strbac, G., Huang, S., et al. (2013). Smart control for minimizing distribution network reinforcement cost due to electrification. *Energy Policy*, *52*, 76–84.

REDPOINT. (2014). REDPOINT & element energy. In *Electricity system analysis—Future system benefits from selected DSR scenarios*. ⟨https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48551/5759-electricity-system-analysis–future-system-benefit.pdf⟩ (accessed: 27/08/2014) (Online).

Ross, C. (2014). *Air source heat pump installation performance review*. ⟨http://www.esru.strath.ac.uk/Documents/MSc_2008/Craig_Ross.pdf⟩ (accessed: 29/08/2014) [Online].

Singh, H., Muetze, A., & Eames, P. (2010). Factors influencing the uptake of heat pump technology by the UK domestic sector. *Renewable Energy*, 873–878.

Staffell, I., Brett, D., Brandon, N., & Hawkes, A. (2012). A review of domestic heat pumps. *Energy & Environmental Science*, 929–19306.

Strbac, G. (2008). Demand side management: Benefits and challenges. *Energy Policy*, *36*, 4419–4426.

Timpe, C. (2014). *Smart domestic appliances supporting the system integration of renewable energy*. ⟨http://www.smart-a.org/SmartA_Project_Final_Brochure_2009.pdf⟩ (accessed: 28/05/2014) [Online].

U.S. Department of Energy. (2014). *Benefits for demand response in electricity markets and recommendations for achieving them*. ⟨http://energy.gov/sites/prod/files/oeprod/DocumentsandMedia/DOE_Benefits_of_Demand_Response_in_Electricity_Markets_and_Recommendations_for_Achieving_Them_Report_to_Congress.pdf⟩ (accessed: 27/08/2014) (Online).

Warren, P. (2014). A review of demand-side management policy in the UK. *Energy Reviews*, *29*, 941–951.

Weather Underground. (2014). *Weather history for London, United Kingdom year 2012*. ⟨http://www.wunderground.com/history/airport/EGLL/2012/1/1/CustomHistory., html?dayend=31&monthend=12&yearend=2012&req_city=NA&req_state=NA&req_statename=NA⟩ (accessed: 29/08/2014) [Online].

The World Bank. (2014). *Primer on demand-side management with an emphasis on price-responsive programs*. ⟨http://siteresources.worldbank.org/INTENERGY/Resources/PrimeronDemand-SideManagement.pdf⟩ (accessed: 28/08/2014) (Online).