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Demand Side Management Potential of Domestic Water Heaters and Space Heaters

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Abstract: Demand Side Management (DSM) is a viable strategy for facilitating integration of renewable energy into power systems. The demand resource from water and space heating can be used to reduce or delay system demand peaks, and in combination with other flexible loads, reshape the aggregate demand profile and manage system ramping. In this paper, the aggregate power draw profiles for heat pump based water heating and under floor space heating systems for the Irish domestic sector have been synthesized and the effects of daily and seasonal variations, the type of dwelling and control / usage patterns on demand are discussed. The results show a significant seasonal and daily variation of the demand profile for water and space heating, indicating its viability as a DSM resource on the Irish power system, but also the challenges of operation.

Keywords: DSM, Load Resource, Heat Pump, Water Heater, Under Floor Heating

1. INTRODUCTION

Depleting fossil fuel reserves and environmental concerns, coupled with the technical and economic feasibility of renewable technologies, have shifted power system focus towards renewable energy resources, with the highest growth rate for wind energy (EWEA, 2008). Despite the obvious benefits of zero fuel costs and carbon emissions, a large share of wind energy on the grid introduces complexities such as reduced system inertia, increased requirements on conventional plants to carry contingency and regulating reserves (Fox, et al., 2007; Kirby and Milligan, 2008) and more dispatchable ramping capability leading to depleted system flexibility, particularly on small systems with limited import/export capability (Söder, et al., 2007).

Demand side management (DSM) has been presented as providing a number of power system related benefits such as a reduction in demand for new power system infrastructure (generation, transmission, distribution), with an overall reduced system demand and financial benefits to customers (Albadi and El-Saadany, 2008). It has also been considered as a strategy to manage wind variability (NORDEL, 2005) through peak shifting and peak shaving. Large scale deployment of any DSM program requires sufficient technical infrastructure which includes smart meters, communication infrastructure, programmable thermostats for appliances along with economic incentives for consumers to participate (Strbac, 2008). A first step in estimating the technical benefits of DSM is to analyse the available resource and its daily/weekly/seasonal and inter-year variability. Daily customer load profiles can be combined through a demand side aggregator to forecast the available demand resource. Alternatively, the aggregated daily load profile of a number of devices in a geographical area can be used to justify the feasibility of a DSM program. Historically the major target loads for obtaining demand response services have been those loads that possess thermal inertia. This is because of their ability to be turned off for some time (depending on system size, ambient temperature and many other factors) causing minimal customer discomfort. Despite variations in consumption and seasonal effects introducing challenges for demand control, these loads have high penetration levels in the domestic sector making them a significant demand resource (Parliamentary Office of Science & Technology, 2005). Against this background, Ireland has set an aggressive renewable energy target of 40% by 2020 which requires strategies to mitigate the flexibility issues arising from a high renewable penetration. Since the Irish power system is synchronously isolated and has a small overall size, DSM offers a potential solution to address flexibility issues arising from wind variability.

This work investigates the daily electricity demand profile for electrical heating loads, with a focus placed on under floor space heating systems using heat pumps and heat pump based domestic water heaters. Modelling focus is ultimately at a system level with a greater focus on aggregated day to day variations, rather than individual house behaviour. Heat pump based loads have been investigated since they are likely to become more common relative to gas or oil based central heating systems. The models developed predict the daily electricity consumption load profiles at different times of day, week and year with variations in ambient temperature. Aggregate heat pump based space heating load profiles and heat pump based water heating load profiles have been developed for the Irish household sector, considering different types of dwellings, their thermal insulation levels and occupant behaviour. The impacts of time shifting on loads, their thermal inertia, and the underlying variability and predictability of the aggregated load are also discussed.

2. WATER HEATING

Thermostatically controlled loads such as water heaters, space heating systems, fridges/freezers have been considered as a suitable choice for providing a demand resource due to their thermal inertia, with most direct load control programs employing thermostatically controlled loads (Andreolas, 2004). Water heaters in particular have been considered as suitable candidates for providing a demand resource. In cold and wet climates, domestic water heaters (DWHs) along with refrigeration usually constitute that part of the aggregate domestic load which is active throughout the year, unlike space heating and cooling loads. DWH usage may be postponed at peak hours in exchange for a financial incentive, subject to operation at a later time, implying load shifting rather than peak load clipping.

In Ireland 28% of total electricity demand in 2020 is expected to come from the domestic sector (Walker, et al., 2009) which indicates the potential for acquiring a demand resource from domestic electrical appliances provided the technical infrastructure and favourable policies are in place. 98% of households have hot running water (Watson, et al., 2003), indicating a high penetration level of domestic water heaters. It is however important to note that only 10% of water heating is carried out using immersion heaters, whereas 82% of households use central heating systems for domestic water heating (Sustainable Energy Ireland, 2008a). It is also estimated that the potential electricity peak demand saving from the residential sector is about 349 MW against a peak demand of 7800 MW for all loads including space heating, water heating, appliances and lighting. DWHs have long been considered as a suitable load for demand resource; with various aggregate stochastic and regression models having been developed (Ericsson, 2009; Lu, 2005), Monte Carlo based aggregate models have also been proposed (Dolanand, 1996). However, while the aggregate models provide a good estimate of DWH power consumption they do not consider individual DWHs independently. Consequently, customer discomfort, which is an extremely important variable in ensuring the success of a DSM program may not be considered (Sepulveda, et al., 2010). The behaviour of individual water heaters and domestic loading should therefore be recognised. Existing models tend to adopt a bottom up approach based on model energy flow balance in a tank, linking to tank water temperature set by the customer. Nehrir (2007) uses the same physical model for water heaters based on energy balance equations. Xu, et al., (2011) considers this consumption as white noise, while Paull, et al. (2009), Sepulveda, et al. (2010), and Kondoh, et al. (2011) utilise collected customer end use data as a basis for water usage estimates, which is likely to be more accurate. All of the works described above model resistive DWHs.

In this work a model for heat pump based water heater has been developed, which may be used for standalone heat pump water heaters as well as water heaters connected to heat pump based central heating systems. Irish households have been analysed in terms of hot water consumption patterns at various times of day and times of week, tank sizes and duration and flow rate of various hot water draw events.

2.1 Model Description

Since the aggregate electric load profile for the Irish domestic sector is ultimately of interest, we need to recognise variations in ambient temperature, dwelling size, water consumption, storage tank and heating system characteristics. The thermodynamic behaviour of hot water tanks has been based on Kara, et al. (2004). Parameters such as water tank size and thermal insulation level have been diversified to represent the device population. Heat pump system sizing has been carried out based on dwelling size and the number of occupants, based upon the four major types of dwellings in Ireland (Watson, et al., 2003), namely terraced houses, semi-detached houses, detached houses and flats. In Rischmuller (2009) the average number of people in each type of household and the net hot water consumption per person has been given for the U.K. Since such data is unavailable for Ireland, and both countries have similar weather and social conditions, this data has been used in the model. Four major water draw events are considered; hand wash, dish wash, shower and bath with different flow rates and durations. The frequency of occurrence of each water draw event has been based on a probability distribution for the occurrence of each event (Jordan, et al., 2001).

Individual DWHs have been modelled and then aggregated by randomly assigning the distribution of model parameters to a population, with the objective of meeting customer comfort constraints. The model has been implemented in Simulink with a 20 second resolution and can predict the DWH load profile over a time horizon of 24 hours given variables such as the dwelling type, ambient temperature, weekday, and thermostat settings. From Watson, et al. (2003), there are approximately 1.4 million households in Ireland, suggesting that about 140,000 households would possess a heat pump based DWH. Since water usage decision making for each of the simulated houses is stochastic, while also recognising that dwelling characteristics impact the DWH load profile, it follows that each house will have a different water draw pattern. Individual dwelling models (with different randomized parameters) for 7000 households were scaled to system level. At this level it was observed that the number of households was sufficiently large that the DWH demand profile shape did not change if the number of DWHs were further increased, only the magnitude changed. The aggregation benefits thus obtained meant that a scaling factor could be used to upscale simulations results from the 7000 heaters to 140,000 DWHs representative of the Irish household sector.

2.2 Simulation Results

It has been assumed that detached dwellings are most common forming 46% of the dwellings, while semi-detached cover 27.2%, terraced 19.8% and apartments 6.4% (Watson, et al., 2003). From Fig. 1, detached houses introduce a morning peak of about 160 MW (between 8 to 9 a.m.) and an evening peak of about 75 MW (8 p.m.). Since the number of semi-detached houses is less than detached, the former morning peak of 90 MW is 56% of the latter. Similarly, the semi-detached evening peak of approximately 40 MW is only 49% of the detached house evening peak. The period from 10 a.m. to 5 p.m. constitutes mainly low intensity water draw events (hand wash and dish washing events), and thus differences in power consumption are less pronounced. The duration of the morning and evening peaks is broader for the larger dwellings, due to higher occupancy and thus larger water consumption, linked to a larger water storage tank.

Fig. 2 shows how the power consumption of DWHs for a particular weekday changes when the thermostat set point is raised by 2 ℃ - the morning peak at the higher thermostat setting is about 380 MW while the lower thermostat setting has a morning peak of 290 MW. Similarly, the evening DWH demand peak for the higher thermostat setting (187 MW) and lower thermostat setting (127 MW) signifies a smaller difference of 60 MW. This difference between morning and evening peaks in DWH peak power draw is clearly due to the amount of water being drawn, which tends to be higher in the morning due to showering activity. The duration of the morning and evening peaks for the higher thermostat setting based DWH profile is also extended due to the increased energy requirement for operation at a higher water temperature. The difference in hot water usage patterns and its influence on the DWH power draw profile is best illustrated by comparing typical weekday and weekend DWH power profiles. On a weekend, due to the occupants tending to wake up later, the morning peak is likely to occur later than on a weekday, as observed in Fig. 3. In addition, due to a greater number of people likely to be at home on a weekend, general usage tends to be higher during the day, corresponding to small and medium water draw events such as hand or dish washing. The evening peak on a weekend is much higher, at 250 MW, as compared to a typical weekday evening peak that stands at 125 MW, due to the higher probability of people taking a bath in the evening. Since a bath is a hot water draw event that draws large volumes of water, the DWH power draw corresponding to this variation in usage is more accentuated. A demand dispatch utility may underutilize the demand resource potential if it assumes the same forecast for a weekend and a weekday.

An additional factor causing variations in the DWH power draw is the temperature of the water coming into the water tank from the main water supply which will tend to be cooler in winter, as a function of ambient temperature. The DWH power draw has been estimated for a sample temperature profile recorded at Dublin airport and is compared with the corresponding DWH power draw based on a seasonal change scenario where the average hourly temperature is reduced by 10 ℃, Fig. 4. The morning peak shows a change in consumption from 290 MW to about 340 MW, representing a 14% increase in peak power due to the temperature reduction. The steep rise in power consumption from 2 to 6 p.m. captures the effects of water consumed for hand washing, and afternoon baths, of low probability but requiring high water consumption.

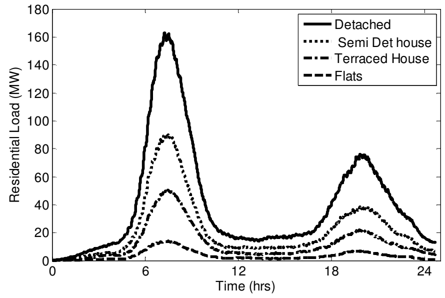

Fig. 1. Power consumption variation with dwelling type

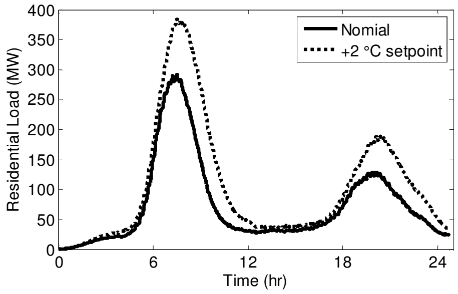

Fig. 2. Power consumption variation with thermostat set point

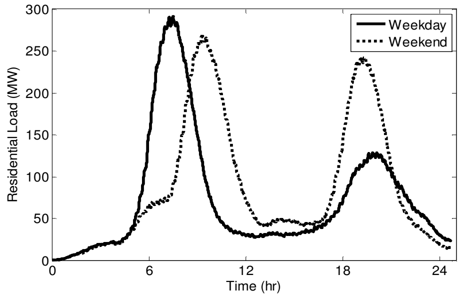

Fig. 3. Power consumption variation for weekday/weekend

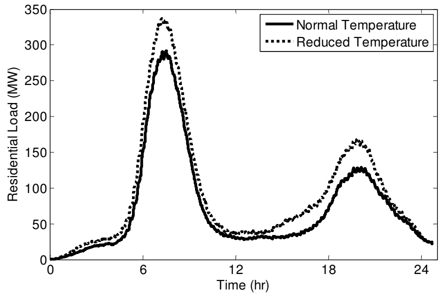

Fig. 4. Power consumption variation with seasonal change

It is evident from all the DWH demand profiles that there are two high demand periods per day, one in the morning when people are getting ready to leave for work, taking a shower, washing hands, washing breakfast dishes, etc., while the other peak occurs when people come back from work, take an evening shower / bath and washing dishes after dinner. Since the highest electrical demand from DWHs occurs at these two points, they also represent the highest potential for obtaining a demand resource. Moreover, both peaks consist mainly of discretionary loads, such as taking a shower or a bath and could be postponed (or possibly advanced) by customers in response to a real-time price signal, or as a result of a utility signal compelling customers to curtail usage based on a prior agreement in exchange for a lower overall electricity tariff. Another scenario, implemented in various utility load resource programs, is direct load control whereby a load aggregator adjusts thermostat settings, or switches on/off, consumer DWHs. As demonstrated in Fig. 2, a minor variation in the thermostat setting (1 ℃) can provide almost 50 MW headroom during morning peak hours, although there would be a later increase in load when the thermostat setting are returned to normal. What is also clear is that the flexible resource availability varies significantly across the day, and is of reduced benefit during overnight and mid-afternoon periods.

3. SPACE HEATING

In Ireland 74% of energy used in the domestic sector is for space heating (Sustainable Energy Ireland, 2008b). Although electricity based space heating systems currently have a penetration of 10% (Sustainable Energy Ireland, 2008a), this figure is expected to grow in the future; primarily due to their underlying efficiency. Amongst the options for electricity based central heating systems, underfloor heating systems are probably most interesting from a demand resource point of view. Heat pump based space heating systems are extremely efficient, and can be considered as renewable systems as they extract energy from the outside air (in the case of air to water heat pumps) or from the ground (in the case of geothermal heat pumps). There is already a high penetration of such systems in the Irish household sector, with a growth rate of 300% (DCENR, 2009). Akmal, et al. (2009) showed a thermal time constant of 25 hours for a building room temperature, using heat pump based under floor heating systems, suggesting opportunities for flexible demand shifting. Gustafsson, et al. (2008) present a detailed thermodynamic model of a building heated using district heating, while Mendes, et al. (2001) present a thermodynamic performance model using Simulink of one building. Akmal, et al. (2009) simulate an underfloor heating system and investigate its suitability for managing wind variability in Ireland. Rautiainen, et al. (2009) examine electric space heating loads and consider the application of space heaters to manage frequency disturbances.

All of the above models are fairly detailed but tend not to recognise the full impact of occupant behaviour and building occupancy as a function of time of day. It is also noticeable that these models present a thermodynamic simulation of individual buildings and do not consider the aggregate behaviour of a population of buildings. Consequently, this work investigates a daily underfloor space heating load profile using detailed thermodynamic models for individual houses, including factors such as house size, house characteristics, occupancy patterns, and user behaviour for entire Irish domestic sector.

3.1 Model Description

A model is required which represents the aggregate underfloor space heating power draw profile for the Irish domestic sector, over a period of 24 hours, for different times of the year. The power consumed by heat pump based underfloor space heating systems depends on many factors including occupant behaviour, house occupancy at various times of the day, building characteristics, house floor area, space heating system capacity, building characteristics (wall area, number of windows, ceiling area) and air exchange rates. A thermodynamic model for underfloor heating is based on one dimensional heat conduction according to Fourier's law, while also considering the concrete layer heat storage capability. It has been assumed that the heat from the floor is transferred to the room through convection. Heat flows from inside the house to the outside cold air through the walls, ceiling and windows through convection and conduction (Gustafsson, et al., 2008). House occupancy patterns have been based on Central Statistics Office (2006). Similar to the DWH modelling, individual houses are represented and then aggregated, such that for each house the indoor air temperature stays within the thermostat settings. A time step of 300 seconds is utilised when simulating the response of each individual house and the associated underfloor heating system.

3.2 Simulation Results

The number of heat pump based space heating systems in 2001 in Ireland was approximately 4,200, i.e. 0.3% penetration (Watson, et al., 2003). Results are presented assuming that heat pump based space heating systems have a penetration rate of 0.5% (70,000 units). Fig. 5 shows the daily electricity consumption from heat pump based space heating systems for various types of Irish building stock. Two peak periods can be seen, one in the morning when people wake up and turn their heating system on after keeping it off overnight - each building has maximum occupancy, and will be cold due to heating system inactivity over the night. The peak then reduces as people leave for work, and heating systems are switched off. The evening peak occurs as people arrive home, and the outside air temperature may also be low. Later in the evening most heating systems are switched off, as people go to sleep and thus a drop in aggregate power draw for space heating can be observed.

For a typical weekday, the morning peak for detached houses occurs at about 6 a.m. at almost 50 MW, while the evening peak is approximately 60 MW and occurs at about 9 p.m. Since they form a smaller percentage of the total Irish household stock and tend to have a smaller building envelope area (roof, walls, windows) semi-detached houses, terraced houses and flats have smaller peaks at approximately 26, 13 and 5 MW respectively. Similar to water heating, the daily demand profile on a typical weekday for a sample temperature profile recorded at Dublin airport is considered and compared with a 10 ℃ reduction in temperature, which could represent a seasonal change. As expected, both the morning and evening peaks, along with the entire load profile throughout the day, rise to a higher level. From Fig. 6 it can be seen that the morning peak rises from almost 90 MW to around 250 MW while the evening peak also rises from almost 100 MW to around 260 MW.

As the air temperature falls, its impact on the power draw profile for space heating becomes greater. For the normal temperature profile, a decrease in temperature from 1 p.m. to 3 p.m. is less noticeable, whereas in the reduced temperature profile it is more evident as the heating demand increases. So, for example, for the normal temperature profile, the heating demand rises by 10 MW from 1 p.m. to 3 p.m., whereas for the reduced temperature profile the demand rises by 27 MW over the same period.

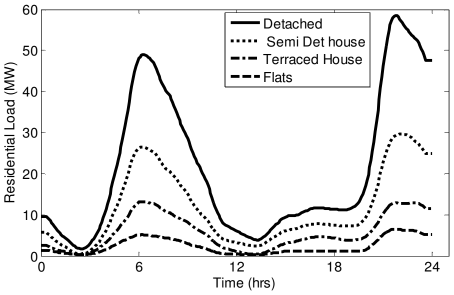

Fig. 5. Power consumption variation with dwelling type

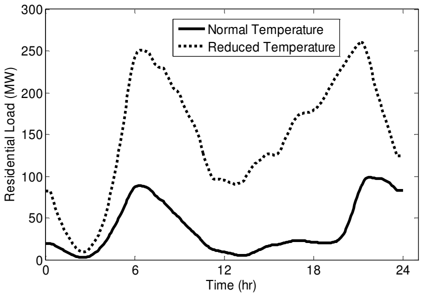

Fig. 6. Power consumption variation with seasonal change

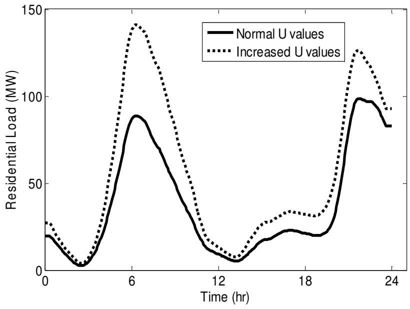

Fig. 7. Power consumption variation with insulation level

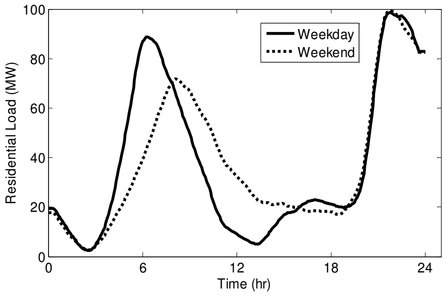

Fig. 8. Power consumption variation on weekday/weekend

A comparison can also be made between normal insulation levels for building envelopes in the country with a decrease in their insulation levels, achieved by increasing the building U value by 25% (the U value quantifies the rate at which a building loses heat through its envelope). From Fig. 7, a 25% increment in U value, results in an almost 50 MW increase in the morning peak, indicating the variation in load profiles which may exist across different building types. The power draw profile for space heating also varies significantly with the day of the week, as seen in Fig. 8 which depicts typical weekday and weekend profiles. On a weekend, the morning peak tends to occur later (at 8 a.m.) as compared to a weekday morning peak of 6 a.m., since most people tend to turn their heating systems on when they wake up. During daytime hours at the weekend electricity consumption for space heating is also higher as more people tend to be at home compared to a weekday. Similar to the aggregate daily load profile, the space heating profile has two periods of high consumption, i.e. 5 a.m. to 12 a.m. and 8 p.m. to 11 p.m, again presenting the most suitable intervals for providing a demand resource. Linking with the long time constants associated with building heating systems, it may be possible to advance/delay heating control system activation to reduce the magnitude of the peak periods and fill the troughs of low power consumption, e.g. 12 p.m. to 6 a.m.

6. CONCLUSIONS

As a part of using demand side management as a strategy for the mitigation of short-term power system flexibility under high wind penetration levels, the contribution from domestic flexible loads is of importance. This paper has investigated the aggregate load profile of electricity consumption using water heaters and under floor space heating systems over a 24 hour time horizon considering the variation in global (ambient temperature, time of day, time of year) and local (dwelling size, occupancy, occupant behaviour, system characteristics) using a detailed thermodynamic model. Each individual house is simulated and its power consumption aggregated to maximize the prediction capability, since the errors will tend to cancel out. Space heating and water heating both present high consumption during the morning and evening, coincident with system peak demands indicating the potential for shaping, and both tend to introduce higher demand in winters. The weekend demand profiles for both space and water heating are distinct with the weekend morning peak occurring later in the day in comparison with a weekday. Pre-heating water and residences at night provides the opportunity to avoid switching off baseload units – particularly beneficial if wind penetration levels are high. In addition, the magnitude of the daily morning rise may be reduced, limiting the ramping requirements placed on baseload units.

The demand profiles for space and water heating show that, between the evening and morning peaks, the aggregate power consumption for both load types reduces, indicating their limitations in providing system services at those times. Other flexible loads, such as fridges/freezers, may be able to partially provide these services when demand from space and water heating is insufficient to contribute significantly to the demand resource. The extent to which the aggregate demand profile for the entire system can be reshaped depends on the composition of flexible load resources. As demonstrated in the case of water and space heaters, the demand resource provided varies with the underlying nature of the flexible load and the net demand resource is likely to be composed of a number of flexible load categories. All such loads do not necessarily have to be thermostatically controlled loads; electric vehicles may provide significant demand resource at particular times of the day by adjusting battery charging patterns. As part of future work, the models thus developed will be improved by quantifying the variation in aggregate available demand resource from one day to the next and establishing confidence intervals for aggregate demand on a particular day.

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