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# Modeling Demand Response in the Residential Sector for the Provision of Reserves

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**Abstract**—Penetrations of variable renewable generation are increasing globally. While this trend is creating challenges for power systems, improved communication technologies are providing opportunities for the demand side to play a role in meeting some of these challenges. Commercial and industrial customers have long participated in demand response, but residential demand response is a largely untapped resource. Smart grid solutions provide the residential sector with the potential to respond to the systems needs over short time scales. A number of residential loads are well suited to providing reserves with minimal impact on consumers. In this paper the potential response from the residential sector in a heating dominated climate is estimated by modeling relevant responsive loads. The potential response is significant (6% of system demand on average). The aggregate interruptible load is expected to fall by approximately 19% by 2020. The modeling captures the daily and seasonal variations of the available resource.

**Index Terms**—demand response, load modeling, smart grid, reserve.

## I. INTRODUCTION

LARGE scale integration of variable renewable generation leads to a number of challenges for the grid, including difficulties in the provision of ancillary services. Significant reserves must be held at all times in order to maintain security under contingency conditions. The stochastic nature of wind supply introduces increased flexibility requirements on the system [1] and puts increased pressure on the reserve levels required. The erosion of conventional thermal generation reduces the inertia (and hence the stability) of the system and also erodes the traditional methods of providing reserve.

There is a growing realization that the demand side is being underutilized, and that the participation of the demand side has potential to bring considerable benefits to the electricity market [2]. As the generation portfolio becomes less controllable, and emerging technologies permit cost effective control methods for the demand side, new methods for providing system balancing are emerging.

Demand response can be used to reshape the load curve in a desirable way [3]. Demand response has the potential to address a number of challenges the grid is facing, including

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frequency response, system balancing, system ramping, over generation, resource adequacy and grid investments. As well as the established and proven methods of load shifting, peak clipping and valley filling, there is an increased interest in using demand response programs to provide spinning reserve [4]. The potential for loads to provide response to system needs is influenced by another demand side measure - energy efficiency improvements. At the same time, the monitoring and control equipment used to facilitate demand response efforts can often be used to bring about long term energy efficiency improvements [5], so these demand side measures should not be considered in isolation.

Demand response can broadly be broken down into two categories - price based demand response and incentive based demand response [6]. This paper largely focuses on the second category of incentive based demand response, looking specifically at the ability of residential loads to provide reserves, through the use of direct load control by a third party aggregator.

This paper provides an insight into the nature of responsive load in the residential sector in a heating dominated climate. In order to achieve this, load curves for the most responsive loads have been constructed. Using these load curves, estimates of the potential response for residential loads using direct load control are made. These estimates give an insight into amounts of load which could be made available and how the resource varies throughout the day. The paper also examines the impacts of energy efficiency measures on the potential response. The load curves and response estimates are repeated using projections for 2020.

In section II the methodology used to create the residential load curves for both 2011 and 2020 are outlined. The main drivers of change for the two years considered are energy efficiency trends and the electrification of space heating through the growing stock of heat pumps in the residential sector. The subsequent sensitivity analysis which was completed is also discussed. Section III discusses the data sources used to create the load profiles in more detail. Section IV discusses the results achieved and examines the potential response which could be achieved through direct load control of residential loads. Section V summarizes the main conclusions.

## II. METHODOLOGY

In order to assess the potential for demand response in the residential sector, load curves by specific end use have been modeled. Typically the data available for residential loads does not contain any information about end uses but rather the data

consists of aggregated consumption for multiple households. A number of top-down econometric models as well as more novel methods using fuzzy logic and genetic algorithms are used by utilities to forecast residential loads [7]. A bottom-up approach is required in order to assess the impact of controlling or shifting different types of loads. The accuracy depends on the availability of detailed consumption details. This is a growing area of research and recent advances in non-intrusive appliance load monitoring (NIALM) are likely to provide a rich source of data in the future. The household loads which have been modeled have been divided into 3 broad categories - interruptible loads, deferrable loads and reducible loads. The focus of this paper is on interruptible loads which possess some form of energy storage, usually thermal. To provide the required service to the customer a certain amount of energy is required over time, but the instantaneous power supply is not important, making them well suited to brief interruptions in power supply. Household loads which fall into this category include refrigeration appliances and space and water heating. Loads from other categories have also been modeled, but are not discussed in detail as they are not considered suitable for a direct load control program (the future evolution of smart appliances is not considered at this time). Loads in the other categories would be more likely to respond to a price signal used in a demand response program such as critical peak pricing or real time pricing. Load profiles have been developed for 10 different residential end uses, which when combined represent approximately 50% of the total residential load.

The Smart A project, led by the Oeko Institut completed a study on the potential synergies of a range of smart appliances with local sustainable energy generation [8]. A similar method has been used in this paper to create the residential load curves.

Typical load curves are built up using the following equation:

$$p_i(t) = v_i(t)p_i^{max} \quad (1)$$

For each load type  $i$ , a variation factor  $v$  is defined for each 15 minute time interval throughout the 24 hours of the day.  $p_i^{max}$  represents the max power for a particular load type  $i$  in a typical household. The variation factor,  $v$  represents the aggregate load shape. It is defined for each 15 minute interval over the 24 hours of the day and reaches a maximum value of 1.

The aggregate load curves for the residential sector are built up using the following equation:

$$P(t) = \sum_{i=1}^n p_i(t)hs_i \quad (2)$$

where  $h$  is the number of households and  $s$  is the penetration level for each load type  $i$ .

Once estimates were achieved for a base case for 2011, a new set of load curves were modeled for 2020, including energy efficiency improvements, changes in housing stock and penetration levels of appliances and the introduction of heat pumps as a sizeable new load. Large scale penetration of electric vehicle's has not been considered at this time.

TABLE I  
ESTIMATED ELECTRICITY BY END-USE PER DWELLING

End Use	% of total	kWh/year	kWh/day
Space Heating	14	773.78	2.12
Hot Water	23	1271.21	3.48
Cooking	12	663.24	1.82
Refrigeration	11	607.97	1.67
Wet Appliances	9	497.43	1.36
Lighting	18	994.86	2.73
Other	13	718.51	1.97

A number of sensitivities were also considered for the interruptible loads which are suited to participating in a direct load control program. When considering the energy efficiency improvements, load curves for a high demand and low demand scenario were modeled and compared to the base case. Assumptions made and figures used will be discussed in more detail in section III. These scenarios consider the potential of the rebound effect, additional policy measures and non compliance with regulation.

As many residential loads are highly temperature dependant, large seasonal swings in demand occur. Three new scenarios are considered, both for 2011 and 2020. These scenarios represent a typical winter day, a typical summer day and a summer day minimum, which represents the expected load for an exceptionally warm day. Temperature sensitive loads have been assumed to vary according to typical variations in temperature. The average temperature for the coldest three months has been used to create the winter day demands, while the summer demand is created using the temperatures for the warmest three months. For the summer minimum extreme daily weather conditions are considered. For space heating, the load has been assumed to be proportional to the number of heating degree days for each month. Variation in demand of the other loads is discussed further in section III.

Using the modeled load curves, direct load control estimates are made for loads which are suited to short interruptions. Devices considered suitable for direct load control include refrigeration loads and space and water heating loads. The residential resource available for direct load control was estimated for each hour throughout the day, by applying a selected participation rate to the relevant loads. An ambitious participation rate of 80% was assumed, based on survey results [9] which indicate high acceptance rates among residential customers.

### III. DATA SOURCES

Relevant data sources have been selected to build up load curves by end use representative of the residential sector in Ireland. The data available on residential electricity end uses is very limited. Estimates were made by an SEAI working group [10], and the results of this analysis are summarised in table I. This data is used as a cross reference for the model outputs.

Two main data sources have been used to build up the load curves for the individual appliances; the previously referenced

TABLE II  
CHANGES IN DEMAND FOR DIFFERENT ENERGY EFFICIENCY SCENARIOS

	2020 Base <sup>a</sup>	Low Demand <sup>b</sup>	High Demand <sup>b</sup>
Refrigeration	-40.5%	13.5%	-13.5%
Space Heating	-18%	10%	-20%
Water Heating	-9%	50%	-20%
Circ Pump	-31.5%	33.3%	-17%

<sup>a</sup>expressed as % change in 2011 base demand per appliance

<sup>b</sup>expressed as % change in demand reduction per appliance

Smart-A project and the REMODECE project [11], a European project examining energy consumption in the EU27 households. Other studies have been used for certain appliances and are referenced where appropriate. The number of occupied households is taken from 2011 census results for Ireland, while the penetration levels are largely taken from a 2009 study [12]. Due to the economic downturn in Ireland and the current turmoil in the construction sector, it is impossible to predict accurately housing figures for 2020. The number of occupied households for 2020 is based on estimates by Dineen and Ó Gallachóir [13]. Tables II and III summarize the changes in demand for the different scenarios considered.

#### A. Appliances

The variation factor and demand for appliances, including refrigeration and wet appliances were created using data from the Smart A [8] and REMODECE [11] projects. 2011 Penetration levels were taken from Leahy and Lyons [12].

Reduced energy demand per appliance for the 2020 base case has been estimated based on the ‘Policy Scenario’ figures in a paper published by the Department for Environment, Food and Rural Affairs in the United Kingdom [14].

For the high demand scenario, the percentage efficiency improvements were taken from defra’s ‘Reference Scenario’ [14], which considers the market evolution without the introduction of any new policies. The low demand scenario assumes efficiency improvements between projections from the ‘Policy Scenario’ and ‘Best Available Technology Scenario’, which presents an upper limit of the maximum available energy savings. No rebound effect has been considered for the appliances as this is not expected to be significant.

When modeling seasonal variations for refrigeration loads the demand variations are based on measured data reported in an Australian study [15].

#### B. Primary Space Heating

Primary space and water heating demand was estimated using figures published in a recent paper by Dineen and Ó Gallachóir [13]. This demand was weighted to represent the prevalence of electrical space and water heating in apartments. The penetration level for storage heaters was assumed to be 2% based on published data and recent trends [10].

Significant energy efficiency improvements in the residential sector have been targeted by the government. The Department of Communications, Energy and Natural Resources published

TABLE III  
CHANGES IN DEMAND FOR DIFFERENT SEASONS

	Winter <sup>a</sup>	Summer <sup>a</sup>	Summer min <sup>a</sup>
Fridges	-6.1%	6.9%	10.8%
Freezers	-12.8%	14.6%	22.7%
Space Heating <sup>b</sup>	86%	-84%	-100%
Water Heating Cont	5.3%	-6.1%	-9.5%
Water Heating Night	6.3%	-7.2%	-11.2%

<sup>a</sup>expressed as % change in 2020 base demand per appliance

<sup>b</sup>including circulation pumps

a National Energy Efficiency Action Plan (NEEAP) in 2009 [16] outlining its objective to reduce the energy demand across the whole economy by 20% by 2020. The action plan was submitted to the European Commission as part of Ireland’s obligations under the Energy Services Directive 2006/32/EC. The residential sector has been targeted as the largest source of energy savings.

When calculating typical space heating demands for 2020, the main driver of efficiency improvements will be improved building regulations and, to a lesser extent, the retrofitting of existing buildings.

Expected heating demands published by Dineen and Ó Gallachóir under three different sets of building regulations were used to calculate a typical primary space heating demand in 2020. While building regulations account for the majority of the savings in space and water heating, retrofitting of existing buildings will also play a role. It has been assumed that a further reduction (16% of the total savings under building regulations) is achieved based on projected estimates for the different policy measures outlined in the NEEAP [16]. Penetration levels for storage heaters has been left unchanged. While penetration of storage heaters has been in decline in recent years, it is possible that this trend will reverse with reduced heating demand due to improved insulation and improved controllability of newer models.

For the high demand scenario, the energy efficiency savings have been reduced to account for a potential rebound effect and also non-compliance with regulations. For the low demand scenario, the savings have been increased to allow for future policy measures.

When considering seasonal variations demand was assumed to be proportional to the number of heating degree days typical for each season. 25 years’ worth of heating degree days data [17] has been used to model the seasonal variations. For the summer minimum day it has been assumed that the heating demand is reduced to zero.

#### C. Primary Water Heating

As mentioned above, water heating demand was estimated using figures published in a recent paper by Dineen and Ó Gallachóir [13] and weighted as above. A penetration level of 10.2% for electrical primary water heaters was taken from Leahy and Lyons [12]. A penetration level of 2% was assumed for night time water heaters.

When calculating typical water heating demands for 2020, reduced system losses under 2010 building regulations [13] are the main driver of efficiency improvements. As with the space heating, the aggregate projected savings are increased by a further 16% to account for retrofitting. Although solar heating is expected to have a significant impact on domestic water heating demand, the impact is assumed to be less significant in apartments which dominate the stock of electrically heated dwellings, and is not considered for the 2020 base case.

A potential rebound effect has not been considered in the base case scenario. In the high demand scenario the energy efficiency savings have been reduced to account for this and also the possibility of non-compliance with new regulations. In the low demand scenario the energy efficiency savings have been increased to account for demand reductions by the use of solar water heaters and also potential savings that could be brought about by water conservation measures.

For seasonal variations, demand variations are based on measured data reported in an Australian study [15].

#### D. Circulation Pumps

The SEAI [17] published a report on energy forecasts in Ireland to 2020. The variation factor for circulation pumps was derived from the space heating demand profile used in this report which is representative of a typical weekday. The energy consumption estimates in Smart A have been significantly reduced as 6000 run hours were assumed. In Ireland this would be closer to 2000 hours as circulation pumps only operate when there is demand for heat (either for space or water heating).

To create the base case for 2020, significant energy efficiency improvements which are expected [18] are included. This will be achieved through a combination of the use of variable speed drives and the emergence of new high efficiency pump technologies. Planned EU regulations for minimum efficiency standards and an energy labeling scheme will ensure that significant demand reductions occur. It has been assumed that pumps installed between now and 2020 will use on average 60% less electricity than the existing stock. Penetration levels have been left unchanged.

For the low demand scenario, efficiency improvements for new units installed are assumed to be 80%. This is reduced to 50% for the high demand scenario.

For seasonal variations, demand was assumed to be proportional to the heating degree days for each season as outlined for primary space heating.

#### E. Lighting

For lighting a number of sources were used to create the variation factor. Measured data from the REMODECE project agreed closely with modeled data [19], [20]. SEAI have estimated that lighting is responsible for 18% of the domestic load [10]. However since the publication of this report, stringent regulations in Ireland banning the sale of incandescent lightbulbs have led to significant reductions to the estimated 2.73 kWh per day per dwelling. Bertoldi and Atanasiu [21] estimated the potential reductions in the lighting

load across the European Union by 2010. It has been assumed that these reductions have been met, with the residential lighting load being reduced by about one third for the 2011 base case.

Lighting loads are expected to reduce further over the coming decades due to more stringent EU regulations, and new lighting technologies such as LED's gaining acceptance in the residential market. Expected reductions in the lighting load, for the 2020 base case were calculated based on UK estimates by Daniel Curtis [22] of the Environmental Change Institute in the University of Oxford. The 2011 lighting load was reduced by 48%, which results in a reduction of 1.215 GWh per day in Ireland, despite the increasing housing stock.

#### F. Heat Pumps

Heat pumps do not appear in the 2011 load curves as penetrations are not large enough at present to have a significant impact on the system. However, use of heat pumps in the residential sector is on the increase, as a well designed system can provide a very cost effective means of space heating. Heat pump technology is expected to play a significant role in meeting the EU's 20% renewable energy sources target by 2020. The EU has recognized heat pumps as a renewable energy source, provided that the heat energy provided significantly exceeds the energy input required to drive the pump [23]. In 2008 the Department of Communications, Energy and Natural Resources published the National Renewable Energy Action Plan [24], submitted under Article 4 of Directive 2009/28/EC. In this plan, it is estimated that heat pumps will generate 84 ktoe of renewable energy in Ireland by 2020 - almost 1 TWh [24]. Heat pumps have a market share in both the residential and commercial sectors. It has been assumed that the renewable energy per sector will reflect the sectors share of thermal energy demand as published by SEAI [25]. A coefficient of performance (COP) of 4 has been assumed for all heat pumps. Combining a COP of 4 with the estimated generation of renewable energy in 2020 yields a total electric load of 213 GWh in the residential sector. It has been assumed that heat pumps will typically be installed in new buildings (or buildings retrofitted to 2010 building regulations). Using the average heat demand for a typical building built to 2010 building regulation standards and dividing by 4 gives the typical electrical demand per dwelling. This gives a heat pump stock in the residential sector of 88,000 units.

Based on UK projections, it has been assumed that 60% of heat pumps will be air source heat pumps, with the remaining 40% ground source heat pumps [23]. The Air source heat pumps have been further broken down to 30% air-air heat pumps and 30% air to water heat pumps. Demands for the different heat pump types have been weighted to reflect their likely market share in the different dwelling types. The variation factor is broadly based on that used for circulation pumps. Some adjustments have been made to account for expected changes in the demand profile due to certain characteristics of heat pump systems. For air source heat pumps the COP will vary depending on the outdoor air temperature, and the expected COP will follow a typical diurnal pattern.

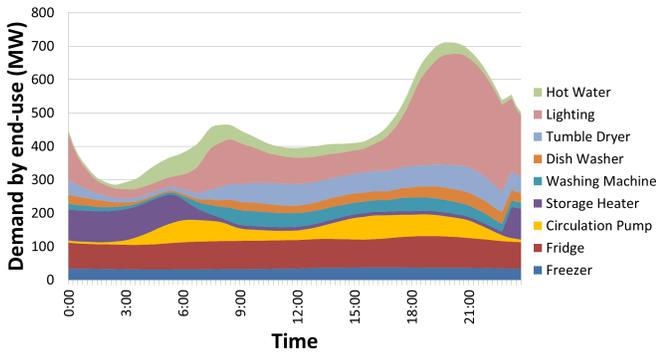


Fig. 1. Daily load curve - modeled residential demand in Ireland - 2011

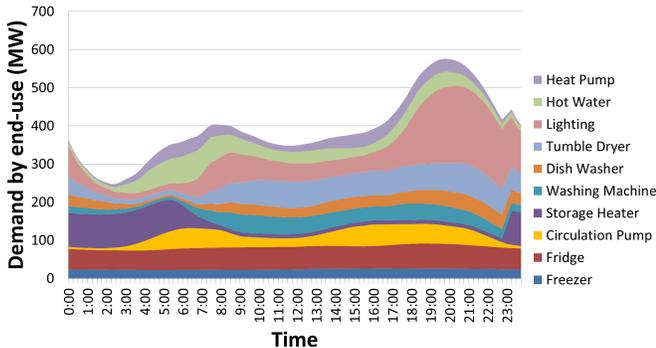


Fig. 2. Daily load curve - modeled residential demand in Ireland - 2020

EnergyPlus<sup>TM</sup> [26] simulations of a well insulated test cell were used to gain an insight into this pattern. Also, it has been assumed that low temperature water based heating systems will be used, typically for underfloor heating. These are slow response systems, so the demand curve has been shifted to reflect this.

The same assumptions have been made for the heat pump sensitivity analysis as has already been described in the space heating section.

## IV. RESULTS AND DISCUSSION

### A. Residential Load Curves

Combining all the modeled loads, the resulting 2011 profile is shown in Fig. 1. Demand is concentrated throughout the day with a large evening peak, slightly later than the known system peak. Despite significant energy efficiency improvements in recent years, lighting is the largest of the modeled loads, followed by refrigerators.

The modeled loads account for approximately 50% of the total for the residential sector. The remaining loads have been considered non-deferrable, non-interruptible or consist of smaller miscellaneous loads. These include cooking and home entertainment equipment, secondary space and water heating and miscellaneous loads such as vacuum cleaners and cell phone chargers.

Fig. 2 shows the modeled loads for 2020. Comparing the results to the curves in Fig. 1 shows that average modeled demand falls from 456 MW to 369 MW in 2020, despite a

significant increase in housing stock. Maximum demand falls from 711 MW to 542 MW. These results should not be seen as indicative of electricity demand in the residential sector as a whole, as trends in home entertainment and home computing are likely to see increases in demand due to increases in penetration of certain types of equipment, and increasing demand of certain devices due to increasing size (e.g. LCD and plasma televisions). Also, the growing demand for electric vehicles has also not been considered in this paper.

Domestic appliances have improved their energy efficiency performance in recent years with this trend expected to continue up to 2020 and beyond. Despite a number of trends which increase energy consumption per unit (such as increased refrigerator capacities) large energy efficiency gains are expected between now and 2020. This is largely being driven by EU regulations which set minimum efficiency standards for manufacturers and enforce an energy labeling scheme which increases awareness among consumers.

Demand per dwelling drops for all modeled appliances with the exception of dishwashers which remains unchanged. This is due to the energy efficiency improvements being eroded by increased penetration. For the wet appliances, the increase in housing stock leads to a larger aggregate demand for each appliance type. However, the total demand is expected to fall for the refrigeration loads, as these appliances are expected to experience larger efficiency gains in percentage terms. The expected efficiency improvements are due to improved insulation and increased pump efficiencies.

An average reduction in space heating demand of 18% per dwelling was calculated, reflecting the enormous efficiency gains achieved through the new building regulations, with the heating demand of new buildings being less than a quarter of the demand of homes built before the 2002 regulations [13]. Despite the increase in housing stock, and the penetration levels, the total demand for Ireland is seen to fall by almost 5% by 2020.

For circulation pumps the demand per dwelling drops by 32%. Despite the increase in housing stock, overall demand drops by 20%.

### B. Direct Load Control Estimates

Direct load control is the most widely used demand response strategy in the residential sector. For decades, direct load control has been used on domestic loads such as air conditioners and water heaters, typically to achieve peak reductions in demand. Such programs have been popular, particularly in the US but also in Europe, Australia and New Zealand [27]. This paper considers control of domestic loads as a means to provide reserves. Kirby [4] explains how many responsive loads are more suited to providing ancillary services for shorter periods than peak reductions over a number of hours. This would be the case for many household loads such as refrigeration and space heating loads. The appliances targeted are less likely to participate in a dynamic pricing strategy (without enabling technology), but are capable of power interruptions for relatively short periods of time (which could largely go unnoticed by the consumer) due to their thermal storage capabilities.

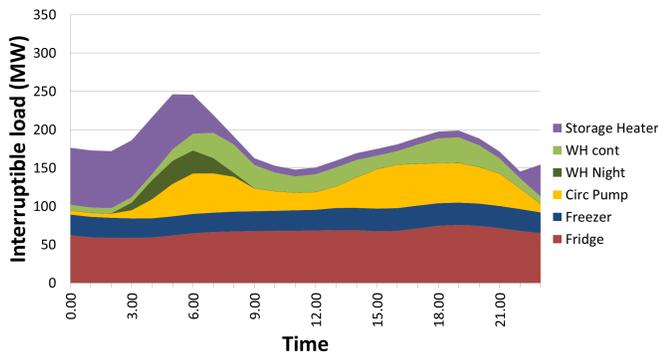


Fig. 3. Direct Load Control potential in MW - 2011

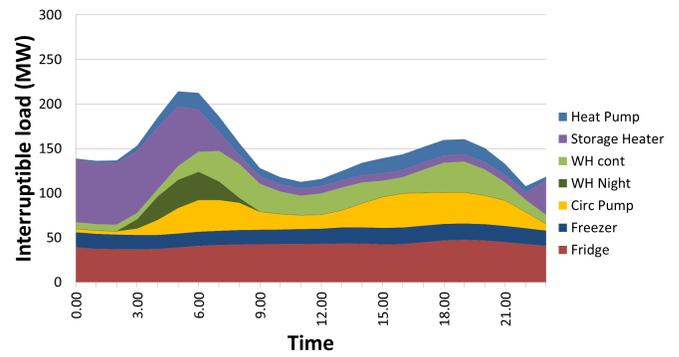


Fig. 5. Direct Load Control potential in MW - Low Demand Scenario

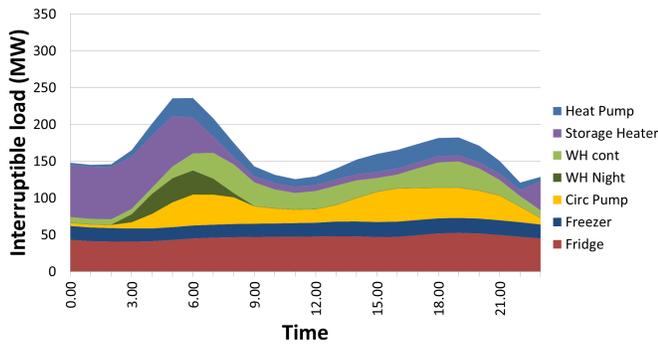


Fig. 4. Direct Load Control potential in MW - 2020

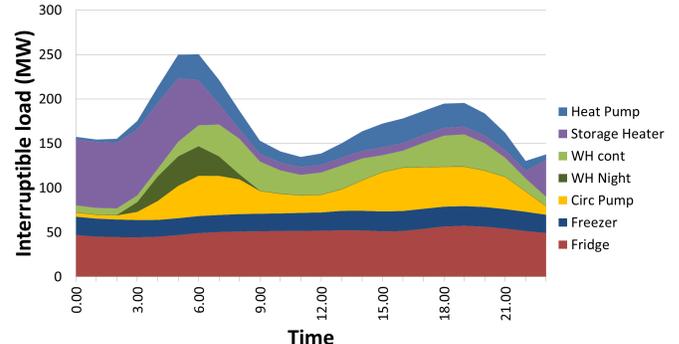


Fig. 6. Direct Load Control potential in MW - High Demand Scenario

The results (see Fig. 3 and Fig. 4) show a large resource is available throughout the day with an average of 182 MW available for interruption in 2011, which represents on average 6% of system demand. The interruptible load drops by approximately 19% in 2020 to 147 MW, despite the increase in housing stock, and the additional interruptible load provided by heat pumps. This is due to the large efficiency gains both in refrigeration and space heating. Minimum loads of 145 /111 MW are seen in 2011 / 2020. The resource is largest at night due to the large potential delivered by storage heaters. The total amount of energy which can be provided is dependent on the load type, with loads such as storage heaters well-disposed to longer interruption durations than other loads such as circulation pumps or refrigerators.

The results discussed so far are representative of a typical day considering a base case scenario. Different sensitivities are now considered. Firstly, different energy efficiency scenarios are considered, with the base case compared to a high demand and low demand scenario.

Fig. 5 and Fig. 6 show how the available load for direct load control changes in the high and low demand scenarios. The changes in minimum load available for direct load control and average demand available for direct load control for the 3 different scenarios are shown in Fig. 7. The low demand scenario shows further reductions in the minimum interruptible load of approximately 9% from the base case, with the minimum interruptible load dropping to 101 MW.

Seasonal variations are also considered. Domestic load experiences large seasonal swings with a high dependence

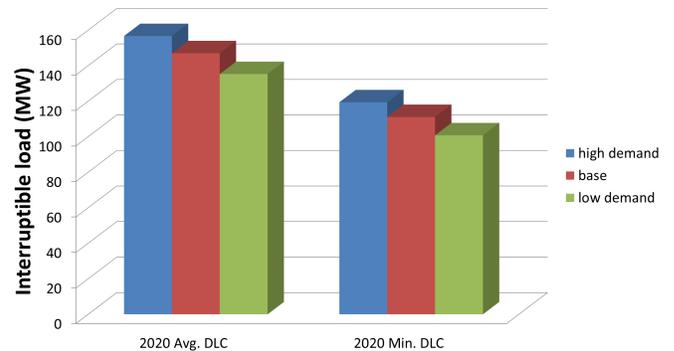


Fig. 7. Direct Load Control potential in MW - Energy Efficiency Scenarios

on temperature. When considering the potential for residential interruptible loads to provide reserves, the minimum availability is of particular interest. While the base case demonstrates typical availability of interruptible loads, and how this varies throughout the day, the seasonal variations are not addressed. Here, three additional cases are considered alongside the base case. A typical winter day and a typical summer day, as well as a summer minimum day where extreme temperatures are considered, providing the minimum interruptible load.

Historical heating degree days data has been used to model the seasonal variations. This shows an 86% increase in space heating demand for the winter months and an 84% decrease for the summer months. For the summer minimum day, the heating load has been reduced to zero. Refrigeration and water heating loads are also sensitive to temperature changes, with

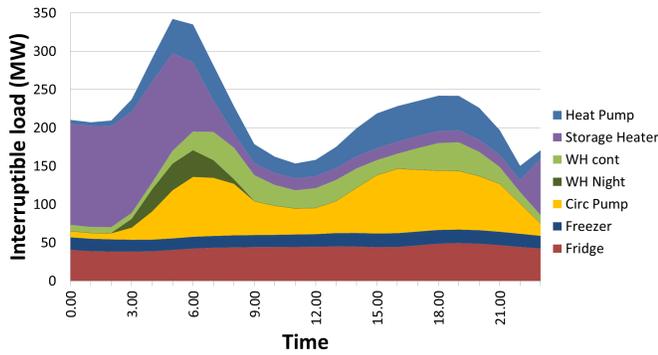


Fig. 8. Direct Load Control potential in MW - 2020 winter day

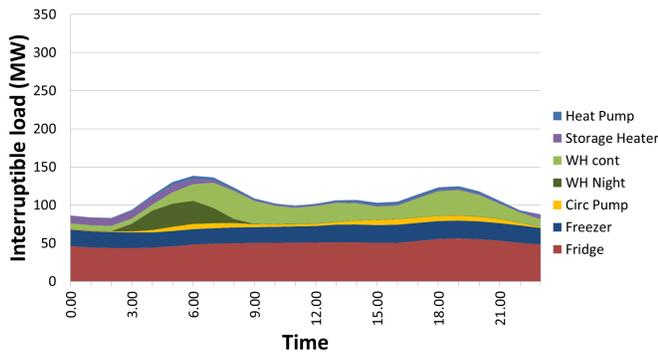


Fig. 9. Direct Load Control potential in MW - 2020 summer day

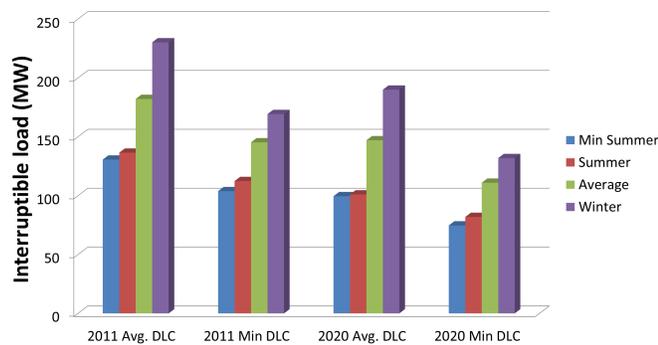


Fig. 10. Direct Load Control potential for 4 different day types

changes in demand shown in Table III.

Sample results are shown for direct load control for 2 of the 3 new cases in 2020 in Fig. 8 and Fig. 9. Fig. 10 shows the changes in both average available load for direct load control and minimum available load for direct load control. Considering extreme weather conditions in the summer minimum day, the minimum interruptible load falls to 75 MW.

For the base case a participation rate of 80% has been assumed. Actual participation rates will depend on the incentive provided and also the marketing effort of the provider. The 80% figure was based on survey results and best case international experience. The actual amount of load available for direct load control will vary linearly with varying participation rates.

In order to use residential loads for reserves, it is essential that they are controllable and that the response is predictable and accurate. Using thousands of smaller aggregated loads, rather than a smaller number of large generators to provide reserve, can in fact provide greater reliability as outlined by Kirby [4]. Providing reserves in a power system with high penetrations of wind will be crucial. Increased reserves will be required to compensate for variations in wind plant outputs, and also forecast errors. Direct load control could also play a role in compensating for large multiple hour ramps when the ramping capability of the conventional generation is not sufficient. However, due to the time limitations on the resource, it's greatest potential may lie in providing spinning reserves for such events, with less expensive replacement reserves taking over. Alternatively, for markets with intra-day trading, direct load control could provide the necessary balancing until the next dispatch period.

Reserve categories and definitions vary from region to region. EirGrid, the system operator in Ireland, have defined five reserve categories; four operating reserve categories and a further replacement reserve category. At present, minimum reserve requirements are set at 120 MW between 8.30 am and 10.30 pm and 75 MW throughout the night [28]. The total all island requirement is set as a percentage of the largest in-feed (75% for primary and secondary operating reserve and 100% for the remaining reserve categories) which is up to 432 MW at present. Comparing these figures to the expected response through direct load control (average of 182 MW), it is evident that residential demand response could play a significant role in meeting the systems reserve requirements. Although the resource is weakened in 2020, the total figure is still significant (average of 147 MW) compared to the system requirements.

While the modeling provides an insight into typical amounts of reserve which could be made available through a direct load control program, further research is required in order to understand the precise nature of the response. At the end of the control period demand spikes will occur as the loads are reconnected and the energy is reclaimed. This is particularly the case for refrigeration loads which will reclaim the shifted energy over a relatively short period of time after reconnection. The precise nature of this response requires more detailed attention, and severe demand spikes will need to be managed with time delays.

A fast response time is critical in the provision of spinning reserves. The response time of interruptible loads in the residential sector is currently limited by communication technologies rather than the loads themselves. The reliability and length of the response time will determine the category of reserve which residential loads will supply. The duration of the interruption is also critical which will vary by load type and customer preferences.

In order to provide a business case for the provision of reserves by the demand side, it is essential that flexibility is adequately valued in the electricity markets, and that payments for ancillary services are sufficient to encourage participation, where it is required. Further analysis is required into the benefit that such programs would offer to the system in terms

of improved efficiencies and reliability. Keane et. al. [1] have already demonstrated, using a unit commitment model, that demand side resources can improve system adequacy and contribute to the increased flexibility needs of the system with high levels of wind penetration. Wide scale rollout of smart meters will mean secure two-way communication to residential customers becomes the norm. The additional cost of enabling technologies for the direct load control of residential loads could be relatively modest, particularly in a mass market situation.

Further research is also required into the overall costs and reliability of such programs. Ideally, to gain proper insight into the nature of the response, trial data would be required.

## V. CONCLUSIONS

The modeled responses demonstrate a large potential resource from the residential demand side for the provision of reserves. An average of 182 MW of interruptible load is available in 2011, which represents 6% of system demand. Demand from interruptible loads is expected to fall by 2020 due to energy efficiency improvements. However, minimum interruptible load does not fall below 75 MW, even under extreme weather conditions. This will be crucial in future power systems with large penetrations of variable renewable generation. Results from this study indicate that the large potential for demand response in the residential sector requires further attention and should be considered a potential valuable resource in meeting the system needs in the future.

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