Department of Energy and Climate Change

The Potential for Dynamic Demand

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The Potential for Dynamic Demand

1. Introduction

1. The Secretary of State published an initial report on Dynamic Demand technology (DD) in August 2007 as required by Section 18 of the Climate Change and Sustainable Energy Act (report available on the BERR website[1] '*Dynamic Demand – Government Response to clause 18 of the Climate Change and Sustainable Energy Act*'). In it the Secretary of State recognised the potential of DD to reduce greenhouse gas emissions and provide security of supply and so committed to providing a further report on the potential for the technology in 2008.

2. Our original intention was for it to report the results from a multi-partner industry-led project to be funded under the Technology Strategy Board's Technology Programme (TSB). Unfortunately the TSB project did not subsequently proceed.

3. In order to further develop the evidence base, the Department of Energy and Climate Change (then the Department for Business and Regulatory Reform) therefore commissioned the UK Centre for Sustainable Electricity and Distributed Generation (SEDG),[2] based at Imperial College, to undertake a research project to evaluate the potential for DD.

4. The SEDG report is now complete and this allows the Secretary of State to produce this report, which provides an update on the potential for DD and describes the next steps in the evaluation of this technology.

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[1] See http://www.berr.gov.uk/files/file41011.pdf

[2] The Centre for Sustainable Electricity and Distributed Generation is a collaborative venture building on extensive on-going research at Imperial College London, The University of Cardiff and Strathclyde University and funded by the Department for Energy and Climate Change (DECC). The Centre undertakes a range of research to bridge the gap between academic research and the needs of industry to work towards meeting the 2020 targets on renewable energy for the UK.

2. Dynamic Demand Technology

Balancing the Grid

1. The National Grid Electricity Transmission (NGET)[3], is responsible for managing the operations of the GB transmission system. As GB System Operator it ensures the continuous real-time matching of electricity demand and generation output, ensuring the stability and security of the transmission system and the maintenance of satisfactory voltage and frequency. To help do this NGET needs to procure Balancing Services.

2. System Frequency is a continuously changing variable that is determined and controlled by the second by second balance between electricity supply and demand, its nominal value being 50Hz. If demand is greater than generation, the frequency falls while if generation is greater than demand, the frequency rises. The balance between demand and generation must be automatically and continually maintained in order to control system frequency deviations to within operational limits.

3. To do this the System Operator therefore needs to ensure that the system can withstand the largest credible generation loss, the size of which is currently up to 1320 MW. This is to avoid the system frequency being driven to the level at which staged automatic demand disconnection to customers would be initiated.

4. Automatic Frequency Response Services are a type of Balancing Service and are required for the management of frequency immediately after a sudden loss of generation. These services are provided by connected generating units specially selected to operate in frequency sensitive mode (i.e. running "part loaded" below maximum rated output) and by load disconnection from some industrial customers through contractual agreement. Part loading generating units to provide Frequency Response Services (that is the main subject of this report) reduces the efficiency of plant operation. This leads to increased fuel consumption with corresponding cost and CO_2 implications. The current market values the Frequency Response Services in the GB system at circa £200m[4] per annum.

Dynamic Demand Concept

5. Dynamic Demand technology would allow non-time critical electronic appliances such as domestic refrigerators to play a role in system balancing. An appliance fitted with DD would reduce its electricity demand in response to changes in the system frequency (i.e. power imbalances on the grid). Several million appliances acting collectively would provide the System Operator with an additional tool for ensuring the continuous second to second balancing of the grid.

6. The control algorithm of DD is designed to adjust dynamically the duty cycle[5] of refrigerators in response to changes in system frequency which changes the total load of the population of refrigerators as seen by the system ("load" is the terms used to describe the power needed by the appliance to function and is measured in

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[3] http://www.nationalgrid.com/

[4] Figure provided by National Grid

[5] "Duty Cycle" is the tem use to describe the proportion of time during which a refrigerator is in operation.

kilowatts). This is expected to make the aggregated behaviour of several thousands or millions of appliances emulate the Frequency Response Services provided by generating plant.

7. Appliances fitted with DD are therefore expected to reduce the number of "part loaded" generators needed to maintain system security and quality of supply. A reduction in the level of "part loaded" generators provides a number of benefits. These are summarised in Section 3 of this report and set out in detail in the SEDG report annexed.

Potential Benefits of Dynamic Demand

8. The draft European Union (EU) Renewables Directive published in January 2008 proposes a target of 20% of EU energy requirements (power, heat and transport) to be met from renewable sources. The UK's share of the EU renewable energy target has been set at 15%.

9. In June this year the Government published its Renewable Energy Strategy Consultation (RES). Analysis carried out in support of the consultation suggests that meeting our share of the target will require ~30-35% of electricity to come from renewables, with the majority of that generation being provided by an estimated 30-35GW of wind power.

10. The nature of wind generation is that it is variable depending on wind and weather conditions. An electricity system with an estimated 30-35 GWs of wind capacity will place additional requirements on the system operator to balance the system on a second-by-second and hour-by-hour basis. A study by consultants SKM[6] carried out to support the RES suggests that these high penetrations of variable generation will result in an increase in both the amount of generation plant needed to balance the system and the frequency of its use.

11. The research that has been carried out by SEDG on the potential for DD (key findings are presented in section 3) suggests that DD has the potential to reduce the costs of managing system frequency (particularly with the predicted growth in variable-output renewable generation), and reduce carbon emissions.

12. In summary, the potential benefits identified in the SEDG study are:

    - A reduction in system operation costs resulting from increased generation efficiency, particularly in a system with high penetrations of intermittent generation;

[6] "Growth Scenarios for UK Renewables Generation and Implications for future Developments and Operation of Electricity Networks" SKM
http://renewableconsultation.berr.gov.uk/related_documents

- An increase in the system's ability to absorb more wind power, in a scenario with a significant penetration of wind combined with potentially less flexible nuclear; and

- A corresponding reduction in CO_2 emissions from reduced fuel burnt as a result of increased generation efficiency.

3. Centre for Sustainable Electricity and Distributed Generation Research Project on the Potential for Dynamic Demand

SEDG Project Objectives

1. In April 2008 DECC commissioned[7] the Centre for Sustainable Electricity and Distributed Generation (SEDG) led by Imperial College to carry out a research project on the potential for DD.

   The principal objectives for the SEDG project were:

   - To assess the potential for DD to reduce the requirement for the System Operator to commission Balancing Services[8];
   - To estimate DD carbon saving potential, both in current electricity generation scenario and in scenarios featuring greater integration of renewable energy generation; and
   - To estimate the potential carbon savings on a per-appliance (refrigerator) basis.

Scope of SEDG Study

2. The aim of the SEDG work was to quantify the order of magnitude value of the DD concept, when used for providing Frequency Response Services in the GB electricity system under alternative future generation development scenarios. Given that the results are very sensitive to the process of the exchange of energy between generation and DD, the work points out that a more comprehensive analysis of the system economic and environmental performance is needed. In this context the results presented here are only estimates.

3. The SEDG project focused its work on domestic refrigerators, considered by SEDG to be the most attractive possible opportunity for DD, and by limiting the approach to using generic, simplified models of refrigerators and the generation system.

Key Results of the SEDG Project

4. The SEDG study has concluded that DD in refrigerators could make a useful contribution to system frequency control; the precise contribution it could make would depend on the numbers of DD refrigerators that would be deployed, the demand at the time of any loss of supply and the size of the loss of supply[9].

Contribution to Frequency Response Services

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[7] This section sets out the key results and conclusions of the SEDG study. The SEDG research and its results have not been subject to peer review nor independently verified. DECC does not endorse this technology.

[8] Supply and demand for power have to balance on a second-by-second basis, otherwise the frequency of power in the grid, normally 50Hz, could change outside desirable limits.

[9] In addition to technical uncertainties associated with the behaviour of a large population of DD devices, there are a number of other parameters that are subject to uncertainty and change, such as fuel costs, rates for discounting etc.

5. The results of a simplified modelling approach developed in the study indicate that the maximum contribution of DD refrigerators to Frequency Response Services ranges from **728MW to 1174 MW**, assuming 40 million appliances. However, these values are related to the different generation scenarios studied and the assumptions used for the ability of DD to sustain the delivery of the response and to have sufficiently fast recovery of diversity, which are yet to be established through further modelling. The subsequent assessments of the value of DD i.e. fuel and carbon savings, were carried out using a value from the bottom of this range as the central scenario, in order to reflect concerns associated with the above assumptions and practicalities

Fuel Savings

6. The potential value of the annual fuel savings from DD refrigerators has been modelled using a number of assumptions and were found to lie between **£0.70 and £5.60** per refrigerator per annum, dependant upon the precise mix of coal, gas, nuclear and wind generation in the electricity system and demand levels. These cost savings arise from reduced fuel consumption in power stations resulting from a reduction in the number of "part loaded" generation units that are needed to provide Frequency Response Services to the System Operator. The total value of fuel savings for 40 million appliances is per annum is **£28.8m-£222m per annum**

7. If a lifecycle of 10 years is assumed for a typical refrigerator, the annual saving figure can be converted using a discounted cash flow analysis into capitalised present value (essentially setting the capital cost target the DD must achieve if is to be an attractive option). Using a discount rate of 10%, this lies between **£4.40 and £34.10**, again depending on the precise coal/gas/nuclear/wind mix and energy demand levels.

8. For both gas and coal-dominated systems the lowest value was obtained in a system without wind, while the highest value was obtained in a CCGT-dominated system with additional nuclear capacity, lower demand level due to energy efficiency measures, and a high wind penetration (30 GW). The high value scenario most closely reflects the scenario set out in the Renewable Energy Strategy (RES) consultation document[10].

9. The SEDG modelling also suggests that DD would reduce the percentage of wind output that is potentially curtailed in scenarios where there is a very high penetration of wind i.e. 30GW. The value associated with this reduction in the curtailment of wind output has been included in the above figures.

Carbon Savings

10. The SEDG study has also modelled the carbon savings potential per refrigerator. The results indicate that a single refrigerator incorporating DD could potentially abate between **17 kg and 44 kg** of carbon dioxide per annum, again dependant upon the precise mix of coal, gas, nuclear and wind.

[10] Renewable Energy Strategy Consultation http://renewableconsultation.berr.gov.uk/

11. Assuming a value for CO2 of £16/tonne, this would imply an additional value of **£0.30-£0.70** per refrigerator per year, or **£1.70-£4.30** when capitalised over an assumed 10-year lifetime using a 10% discount rate.

The savings that can be assigned to a single DD appliance are summarised in the table below.

	CCGT-dominated system	Coal-dominated system
Highest value of DD per appliance (corresponding scenario)	**£5.55 p.a.** (Nuclear + Energy eff. + 30 GW wind)	**£1.12 p.a.** (Nuclear + 20 GW wind)
Lowest value of DD per appliance (corresponding scenario)	**£2.16 p.a.** (Baseline + no wind)	**£0.72 p.a.** (Energy eff. + no wind)
Highest CO_2 emission reduction per appliance (scenario)	**43.6 kg CO_2 p.a.** (Nuclear + Energy eff. + 30 GW wind)	**29.9 kg CO_2 p.a.** (Nuclear + 20 GW wind)
Lowest CO_2 emission reduction per appliance (scenario)	**17.0 kg CO_2 p.a.** (Baseline + no wind)	**19.6 kg CO_2 p.a.** (Energy eff. + no wind)

12. Under the assumptions used in the SEDG study, the total UK saturation of DD refrigerators (estimated to be 40 million) would provide a total CO_2 saving of **0.68-1.74 Mt** per annum.

13. Using a value for CO_2 of ~£16/t, the carbon savings have an annual value of **£0.30 - 0.70** per appliance and a total market value for 40 million appliances of **£10.9 - 27.9m** per annum.

Costs of DD

14. The SEDG report did not explore or quantify the costs of DD and so does not provide a full cost / benefit analysis.

Issues Identified by SEDG for Further Study

15. While the key results of the SEDG study, which was of limited scope, suggest that DD could be an attractive option, in the course of the study a number of further questions were identified that could impact on the value of DD. Gaining a better understanding of these will help ensure that any future decisions by stakeholders are more informed. These areas of uncertainty identified by the SEDG study are set out below and so can be considered as guidelines in the further investigation of DD:

Modelling

16. The SEDG work suggests that, given the significant sensitivity of the value of DD to the energy exchange processes between DD and generators, a more detailed modelling research exercise would be important for the investigation of the behaviour, and impact of, a very large number of refrigerators. Such modelling can provide understanding about a number of key questions identified including:

- The capability of appliances to sustain response for sufficient time for the system reserve to become available (typically in the order of 30 minutes in the present system, but other timescales need to be investigated);

- Potential increased reserve requirements that could be needed as a result of DD which is termed the "recovery effect" (the increase in generation that will be required as appliances recommence operation);

- Synchronisation effects upon recovery and time required to establish full diversity; and

- Impact of alternative control algorithms for DD on providing frequency response.

Demonstration

17. Demonstration of DD technology would provide a number of benefits, including facilitating verification of models, gathering data for populating the models and understanding various practical issues such as:

- Impact of DD on the overall efficiency of appliances operation including wear and tear and associated costs;

- Impact of the pattern of use of refrigerators (door opening) on the value of DD;

- The effect of possible changes in future design of appliances on DD potential (a future shift towards appliances with lower rating and longer duty cycles may reduce the potential of DD to provide response).

This would also inform more detailed modeling of thermal behavior of the refrigerator.

Alternative sources of Frequency Response

18. While this report considers the potential of DD in a demand side application, the SEDG has also been active in exploring the capabilities of modern wind turbines to support system operation through Frequency Response.

19. Although wind turbines behave differently to the incumbent synchronous generation technology, they can be used to provide additional services to the System Operator, including Frequency Response. This is based on a controlled exchange of the short term kinetic energy stored in rotational masses between the wind turbines and the system. This research has been carried out in collaboration with the GB Transmission Companies and major equipment manufacturers in the UK.

4. Further Research and Demonstration

1. Since publication of the Secretary of State's report on the potential for DD in 2007, discussions have continued with a range of stakeholders including technology developers, the NGET and the energy regulator Ofgem.

Academic Research

2. Whilst the results of the SEDG study have helped identify the potential benefits of DD and the importance of various drivers, the approach was limited by the use of generic, simplified models of refrigerators and the generation system. More detailed models are essential for investigations of the behaviour of a very large number of DD refrigerators in order to establish the aggregate persistence of Frequency Response Service delivery and the dynamics of the recovery of diversity in the context of the interaction with alternative generation systems. The SEDG work points out that more exact modelling of this interaction will be a key to valuing DD technology and a comprehensive analysis is planned to be conducted in the near future.

Demonstration: Carbon Emission Reduction Target Scheme

3. The Carbon Emission Reduction Target (CERT) legislation replaces the earlier 2001 and 2004 Energy Efficiency Obligations placed on electricity suppliers. Under CERT licensed electricity suppliers who supply at least 50,000 domestic customers are obliged to deliver their share (determined by Ofgem) of the total CERT target for the period 1st April 2008 to 31st March 2011 of 154 million lifetime tonnes of carbon dioxide. This is delivered through energy saving measures ('qualifying actions') agreed with Ofgem. Under this legislation suppliers can trial new products, that are reasonably expected to achieve a reduction in carbon emissions but where the actual reduction is not known, and receive carbon emission reductions based on their level of investment. These trials are known as 'demonstration actions'.

4. In November Ofgem approved an application by a major electricity supplier to carry out a 'demonstration action' using refrigerators fitted with DD. This project, will initially trial 300 refrigerators fitted with DD technology, moving if successful to 3,000 refrigerators. It will be the first major demonstration of the technology in the UK and will provide the opportunity to build upon and verify the findings of previous research. The project will commence in 2009 and has a planned duration of 18 months with full results expected in the autumn of 2010.

Related Research

5. The SEDG, with support from the Transmission Companies and major manufacturers, is actively involved in improving the frequency response capability of wind turbines of different technologies to provide effective Frequency Response Services. A significant amount of work has been carried out to better understand the dynamic behaviours of wind turbines and the optimisation of the associated control systems to ensure stable plant operation. The remaining work is focusing on building more sophisticated wind turbine generator models of different designs. This will allow the interaction between the wind turbines and other generating plant types in the electrical power system to be explored. There are, therefore, some significant conceptual similarities between using DD and wind turbines for frequency response, that these might be evaluated within a similar modelling framework.

Routes for Further Research

6. Government funding for low carbon energy technology innovation is primarily delivered through the Energy Technologies Institute and the Technology Strategy Board[11]. These bodies all recognise low carbon technologies as a priority and work closely together to ensure that funding activities are complementary and together effectively support a portfolio of technologies. The Energy Technologies Institute[12] is currently developing a new R&D and Demonstration programme covering Energy Networks.

7. The Innovation Funding Incentive (IFI) is administered by Ofgem and supports innovation in energy network technology. Operators of electricity networks are bale to draw on IFI funding for research and development into the technical development of networks.

8. The programmes delivered by these bodies together with other initiatives designed to assist in the commercial development of products and projects, provided through Business Link[13] could also provide opportunities for further research, development and demonstration of DD technologies.

National Grid – GB System Operator

9. We have worked closely with NGET in producing this report, who recognise that in the future the need for frequency response will increase as generation loss risk will be higher, due to larger unit rating for some generation plant and increasing levels of variable output wind generation. Against this background it will therefore be beneficial to extend the form of Frequency Response Services to allow contribution from DD.

10. NGET as the GB System Operator is therefore actively involved in exploring the potential of adopting DD technology for Frequency Response Service provision. The company has worked closely with industry, government and academia and has expressed the view that DD is a useful concept which if correctly developed, demonstrated and widely implemented could have the potential to contribute to future system frequency control.

11. NGET therefore believes that DD technology merits further research and development effort to ensure correct development and implementation of the service without compromising system security and quality of supply and so is willing to explore the possibility of offering service contracts for DD subject to it meeting the necessary technical performance requirements. The existing commercial and regulatory framework for procurement of such services would not in itself present a barrier to such an arrangement.

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[11] Further information on the Technology Strategy Board can be found at http://www.innovateuk.org/

[12] Further information on the Energy Technologies Institute can be found at http://www.energytechnologies.co.uk/

[13] Further information on a range of matters including business support tools and programmes can be found at http://www.businesslink.gov.uk/

12. NGET is also involved with the SEDG on projects that deal with future developments of grid codes on the supply side and research into frequency regulation by wind turbines.

5. Conclusions

1. While the initial SEDG study results are promising and indicate that DD incorporated into refrigerators[14] could provide system Balancing Services to the System Operator and reduce carbon emissions, it has also identified a number of issues that might be considered critical to the viability of DD and so suggest further research and demonstration will be needed before the technology can be fully understood and evaluated.

2. The Secretary of State therefore welcomes the proposed 'demonstration action' under the Ofgem administered CERT scheme, looks forward to seeing the outcomes from these trials in 2010 and expects the planned CERT demonstration action, along with positive interest and engagement from National Grid, will provide a firm foundation for gaining a much better understanding the technology and its potential.

3. Clearly there is now the opportunity to demonstrate whether DD is an attractive option for delivering carbon emissions reductions and providing Balancing Services to the GB System Operator, when compared with other options already available or which might become available in the future.

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[14] Domestic appliances other than refrigerators may also have potential to provide DD response. Work is also underway in SEDG to investigate the potential for wind turbines to provide frequency response services.

Appendix

Centre for Sustainable Electricity and Distributed Generation

Economic and Environmental Impact of Dynamic Demand

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Summary Report

1 Overall aim and scope of work

The key objective of this report is to quantify the order of magnitude value of Dynamic Demand (DD) concept, when used for providing Frequency Regulation services in GB power system under alternative future development scenarios. This value will be expressed through reduced system operation cost and lower carbon emissions.

Several key drivers of the value of DD were identified and their composite impact was quantified through a number of case studies. The impact of the penetration of DD technology was investigated, as well as the sensitivity to the contribution that refrigerators may be able to offer to the Frequency Regulation services. This work also investigates the impact of levels of penetration of wind power on the value of DD, since the variability of wind output puts additional burden on generators providing response and reserve. Furthermore, the increase of the share of less flexible capacity in the system (such as nuclear) is expected to impact the benefits from DD and a study was undertaken to inform this. The impact of a set of measures aimed at increasing demand-side energy efficiency combined with large penetration of wind and less flexible generation on the value of DD is also investigated.

2 Overview of frequency regulation

System frequency is a continuously changing variable that is determined and controlled by the careful balance between system demand and generation. If demand is greater than generation, the frequency falls below 50 Hz while if generation is greater than demand, the frequency rises above 50 Hz. As the demand is continuously changing so the frequency varies by small amounts but larger frequency changes occur when there are significant imbalances of power, such as a loss of large generating plant. In order to maintain a secure and stable system operation, the balance between demand and generation must be continually maintained such that the system frequency is retained within narrow limits around 50 Hz[1].

Automatic frequency regulation services are required for the management of frequency immediately after a sudden loss of generation. These services are provided by synchronised generators specially selected to operate in frequency sensitive mode (while running part loaded) and by load reductions from some industrial customers. These Frequency Response services[2] maintain the system frequency profile over

[1] Under normal operating conditions, the system frequency should not change for more than ±0.2 Hz around nominal value, while for sudden loss of generation greater than 1000 MW and less than or equal to 1320 MW, the system frequency should not fall below 49.2 Hz and should be restored to 49.5 Hz within 1 minute.

[2] There are two types of Response Services: Primary Response is used to contain the frequency drop while Secondary Response is utilised to allow the containment unit to return to its pre-disturbance conditions once the system frequency is restored to the operational limits. Some large demand

time scale from seconds to several tens of minutes. Beyond these timescales, the system operator would call upon Reserves that are used to re-establish the original level of Frequency Response services in the system, so that any subsequent loss of generation can be dealt with. These Reserve requirements are met by (slower) part-loaded plant and by non-synchronised plant, which can start generating quickly upon receiving an instruction from the system operator (Standing Reserve Service). Finally, the original levels of Reserves will be re-establish by scheduling another generator to replace the lost plant (Replacement Reserves)[3], and this process would normally be completed within several hours (driven by the time needed to start up a coal-fired unit or a CCGT). Both market and system operator would be involved in this activity.

Provision of Response Services (that are the focus of this analysis) is associated with running part loaded plant, with the consequence of reduced efficiency of plant operation. This leads to additional fuel consumption with corresponding cost and CO_2 implications. Fuel-cost based estimate of the total value of frequency Response Services in the central scenario is at about £120m per annum. However, the actual market-value of the Response Services in GB system has recently increased and is approaching £200m per annum.

In the context of the Government Renewable Energy Strategy, it is important to recognise that in a system with significant contribution from variable and difficult-to-predict wind generation and the presence of less flexible nuclear plant, may challenge the ability of the system to absorb wind power[4], particularly during high wind and low demand conditions. The reason is the need to increase the amount of Response and Reserve services to deal with uncertainty in wind output. Hence, the application of Dynamic Demand technology may provide some benefits by enhancing the system capabilities to absorb more renewable energy.

Investigations are carried out within SEDG on quantifying the value of Frequency Response services that appropriately controlled wind turbines might be able to offer at very low cost. Given that the volume of wind generation to be connected to the GB system may potentially approach 30 GW, this may be material. This is another example of potential new providers of these services, but this time on the supply side.

3 Potential role of Dynamic Demand

The work investigates the potential role of frequency-responsive load, referred to as “dynamic demand”, in providing Frequency Response services. Examples of such

consumers provide the service via the operation of low frequency relays when there has been a sudden and significant mismatch between demand and generation causing the system frequency to fall rapidly and sufficiently low to trigger the low frequency relays.

[3] This will depend on the exact time in the daily load cycle when the unit was lost

[4] This may be related to both “technical” limitations and commercial consequences associated with different levels of flexibility that would be made available. It is important to bear in mind however that this analysis does not explicitly consider other, alternative providers of operational services that may emerge when the demand and value of these services increase, particularly on the demand side, and the effect of the feedback that market signals would stimulate.

appliances that might be considered as DD are refrigerators, freezers, air conditioners, water heaters, some pumps, ovens and heating systems [Short, 2007]. However, we specifically investigate the suitability of domestic refrigerators because of their large number, widespread distribution and suggested potential importance. The control algorithm of DD is designed to dynamically modify the refrigerator duty cycle length in response to changes in system frequency, whilst maintaining the operating temperature in individual refrigerators within the prescribed limits (hence not affecting food quality).

4 The Mechanism of DD

By changing (reducing) the length of the duty cycle of refrigerators in response to sudden frequency drop caused by loss of generation, the refrigerators contribute to frequency stabilisation through reducing their aggregate load seen by the system. During that time refrigerators deliver some of their stored energy to support the system, and their average temperature slightly increases as a result[5]. After certain time, the temperature increase will cause the disconnected refrigerators to progressively reconnect (in order to maintain the temperature within the prescribed limits) and they will require a certain amount of energy to gradually restore their duty cycle length to the original, pre-disturbance, level.

Dynamics of delivering energy to the system can be controlled in relation to changes in system frequency. The ability of refrigerators to sustain the rate of delivering energy (the energy stored in the refrigerators) will be critical for the value of DD when providing Frequency Response services[6].The entire process of load reduction and load recovery could be optimised to complement the dynamic parameters of the generation system.

When choosing a control algorithm for DD, a trade-off needs to be made between re-establishing diversity of the entire population of refrigerators quickly and the rate at which the additional energy needs to be provided to refrigerators during the recovery period. In this study a basic control algorithm was adopted, however more advanced algorithms should be investigated in the future.

5 The Added Value

The objective of DD is to reduce Frequency Response requirements from thermal generators in the system, thus enabling them to operate at higher fuel efficiencies. The savings in fuel cost represent the economic value added by DD. In addition to that, it is expected that in systems with high penetrations of wind energy the flexibility released through the application of DD could also improve the system's

[5] It is important to recognise that although the average temperature across all refrigerators slightly increases, the actual temperature in any given appliance does not exceed the prescribed limits.

[6] In a highly inflexible generation system, for instance, where frequency response needs to be maintained for a longer time, e.g. 1 hour, the refrigerators would not be able to provide any response contribution.

ability to absorb variable wind output. The resulting economical and environmental benefits further augment the value of DD.

6 Approach and Assumptions

Two models were developed within this work to assess the value of DD: Dynamic Response Model and Value Assessment Model. This is represented in the figure below. The Dynamic Response Model simulates frequency fluctuations in time as a result of imbalance between demand and generation. Based on its outputs, the Value Assessment Model quantifies savings in fuel cost, increased wind energy absorbed and the corresponding carbon emissions avoided as a result of DD. A more detailed description of both models and the corresponding outputs is appended to this report.

6.1 Dynamic Response Model

The Dynamic Response Model incorporates key dynamic parameters of generators and refrigerators, modelling in time the energy exchange between refrigerators and generators during load reduction and load recovery periods. The model was calibrated to replicate the behaviour of the actual UK power system, where the generation system was modelled based on dynamic characteristics of generic units. The contribution of refrigerators to the volume of frequency response delivered is then provided as a key input into the Value Assessment Model.

Assessing the aggregate behaviour of refrigerators involved thermal modelling of a very large number of individual appliances, and simulating their individual operation following a system disturbance. The model is able to simulate an entire population of refrigerators, which permitted detailed monitoring of the load reduction and recovery processes on an aggregate level. Particular contribution of this work is in the robust statistical modelling of the population of a large number of appliances.

The simple thermal model of a refrigerator used in this study includes generic heat losses and a duty cycle depending on room temperature. Dynamic parameters of the model were obtained from the appliance industry, and the model was calibrated to reproduce the expected operation of the refrigerators.

A basic proportional control algorithm was used for adjusting the duty cycle lengths of refrigerators in response to frequency changes, while maintaining the temperatures within the acceptable limits. The choice of the algorithm will determine the exchange of energy between refrigerators and the system, and will impact the speed of diversity restoration and the potential impact of reserve requirements to be provided by generators. Hence, it will be appropriate to enhance the control strategy for the actual system in question.

The dynamic model provides fundamental input to the Value Assessment Model in the form of an average response contribution per individual appliance. It assumes that this contribution can be sustained for the required time until the energy in the reserve generation plant can be delivered to the system. In order to evaluate the spread of refrigerator response contributions that would result from different control strategies, we carried out a sensitivity assessment around the contribution obtained using the basic algorithm for a reference generation system. Hence, this would reflect algorithm and system uncertainties regarding the ability to sustain the contribution. Therefore, this could be smaller or larger than the central value of 20 W per refrigerator that we obtained for the basic model in the reference generation system.

6.2 Value Assessment Model

The second model carries out an annual assessment of generation system operation. It optimally allocates generation resources among energy, reserve and response service provisions, given the contribution to response services which the refrigerators can provide. The model incorporates different generation technologies and their capabilities, daily and seasonal changes in demand and different levels of wind penetration.

The key feature of this model (although simplified) is the ability to capture the interaction between response, reserve and energy provision from generators, taking into account their cost characteristics and dynamic capabilities. Considering response services in isolation from reserve and energy would provide unrealistic results. In terms of the range of various balancing services, the present model supports only a single generic response service and single generic reserve service.

The conventional generation system was represented using generic units of different technologies – CCGT, coal and nuclear. The data associated with generator physical parameters, cost, efficiency and emission characteristics were obtained from previous studies[7].

The resulting outputs, i.e. performance indicators assessed include the reduced fuel consumption associated with improvements in efficiency, amount of wind energy saved and corresponding CO_2 benefits of DD.

7 Main findings

The results from the economic assessment of DD indicate that the savings in system operation cost achieved across all refrigerators range from £0.7 to £5.6 per year for different system development scenarios. When capitalised over an assumed 10-year lifecycle with a discount rate of 10 percent, these values would be equivalent to an

[7] See e.g. [Bopp & Strbac, 2004]

upfront sum of £4.4-34.1. The results confirm that the value of DD is driven by wind penetration levels, total installed capacity of less flexible units and demand levels.

The impact of DD on the annual reduction of CO_2 emissions was found to be in the range between 17 and 44 kg CO_2 per appliance[8]. Attaching an economic value to the emission reduction, for instance £16/tCO_2, an additional value of £0.3-0.7 per appliance per year (i.e. £1.7-4.3 of capitalised value using above assumptions) is attained.

The value assessment results are summarised in the table below. The table indicates the maximum and minimum values obtained for fuel cost savings and carbon emission reductions across different scenarios.

	CCGT-dominated system	Coal-dominated system
Highest value of DD per appliance (corresponding scenario)	**£5.55 p.a.** (Nuclear + Energy eff. + 30 GW wind)	**£1.12 p.a.** (Nuclear + 20 GW wind)
Lowest value of DD per appliance (corresponding scenario)	**£2.16 p.a.** (Baseline + no wind)	**£0.72 p.a.** (Energy eff. + no wind)
Highest CO_2 emission reduction per appliance (scenario)	**43.6 kg CO_2 p.a.** (Nuclear + Energy eff. + 30 GW wind)	**29.9 kg CO_2 p.a.** (Nuclear + 20 GW wind)
Lowest CO_2 emission reduction per appliance (scenario)	**17.0 kg CO_2 p.a.** (Baseline + no wind)	**19.6 kg CO_2 p.a.** (Energy eff. + no wind)

Global trends reveal that savings in fuel cost and CO_2 emissions increase with larger share of less flexible (nuclear) capacity, higher wind penetration and lower demand levels. In a CCGT-dominated system the highest value of DD per appliance is more than double than the fuel cost and CO_2 savings in a baseline scenario. In a coal-dominated system the trends are similar, but specific values are different. This is a consequence of a complex interaction between fuel price differences between CCGT and coal technologies, but also influenced by dynamic properties and efficiency characteristics. The results of the study indicate that there is a potential benefit for the system from using DD, arising from savings in fuel cost and emission reductions across all scenarios analysed, however this needs to be verified by more detailed research.

8 Future Work

Whilst the results of this study have helped identify the order of magnitude benefits of DD, there are remaining questions in a number of areas, as discussed below.

Modelling of balancing services is limited to only two generic service types in this study, and it might be beneficial to expand this and include the entire range of service categories from primary response to replacement reserve. In particular, this also needs to include High Frequency Response, not considered here.

[8] For 40 million appliances, the total annual carbon reduction obtained in this study would be equivalent to the emissions of a base-load CCGT plant of capacity between 230 and 600 MW, operating for one year at 85% load factor.

Furthermore, more advanced control strategies should be investigated in order to optimise the algorithm performance in realistic system conditions. The algorithm will impact the dynamics of the load reduction and load recovery processes. A trade-off has to be made at this point between the additional load during recovery period that needs to be supplied by the generation system, and the speed of re-establishing diversity of the refrigerators' operating patterns.

It is critical to bear in mind that our evaluations assumed that the refrigerators can deliver the required levels of frequency response service that can persist for sufficient amount of time (say 30 minutes). Furthermore, we need to understand further the time required for all refrigerators to recover their initial temperatures (diversity) and the additional power required for this to be achieved. This is clearly of fundamental importance for the value of DD and further research in this area is essential.

The modelling approach assumed full diversity was established prior to a disturbance event. In reality however, because of continuous frequency changes of smaller degree, the operating pattern of the refrigerators and their actual contribution could be affected by preceding frequency oscillations. The operation of refrigerators may also be influenced by consumers' patterns of use, so that DD contribution may be lower in periods of frequent door opening of the refrigerators. Understanding these effects requires additional research. Future work may also include an analysis of the implications of trends of changes in refrigerator design driven by energy efficiency or other factors.

Future analysis will need to encompass a wider range of fuel prices. Also, using more detailed cost characteristics may be required to assess the robustness of DD value under various input assumptions.

SEDG has been carrying out significant research work on the integration of wind power in the GB system. This work includes consideration of ancillary services that this new generation technologies can offer to improve the stability performance of the system. It also incorporates an analysis of the contribution that appropriately controlled wind turbines might be able to make to frequency regulation, as a complementary technology to DD.

Appendix 1: Dynamic Response Modelling

The aim of this section of the report is to determine the reduction in the amount of response requirement, provided by synchronised conventional generation, when dynamic demand refrigerators are installed onto the power system. This figure is determined considering different system loading conditions, different generation outages and penetrations of DD refrigerators. The requirement in all cases is that the amount of response procured by the system, acting in conjunction with DD appliances, is able to maintain the system frequency within 0.5 Hz for a nominal generation loss from 400 to 1000 MW, and 0.8 Hz of nominal under a sudden loss of generation above 1000 MW. Under the worst case loss, the power system frequency should drop by exactly 0.8 Hz, otherwise either too little (which could lead to system collapse) or too much (unnecessarily expensive) reserve had been scheduled.

In order to determine the reduction in the amount of required response to maintain frequency within the acceptable limits, when DD refrigerators are connected to the power system, it is necessary to understand and quantify the overall behaviour and the interactions between the existing power system and the appliances. There is a two-way interaction between the power system and DD refrigerators. This is because changes in system frequency will alter the total refrigerator load on the system and in turn changes in system load affect the system frequency. Therefore, a unified modelling approach is required. The unified approach consists of two main parts:

- Power System Frequency Response model
- Refrigeration Model (covering potentially millions of appliances)

These two simulation parts are then run together in order to determine the reduction in the amount of response that should be scheduled. Once this reduction has been quantified under different scenarios, the potential cost and carbon savings are determined using the methodology presented in Appendix 2.

Dynamic Frequency Response Model

The basis for the power system frequency response model used in this work is well known and is shown below. The model includes governor speed regulation and time constants corresponding to the action of the governor steam valve and turbine. These features are important because a real power plant is unable to respond immediately to changes in demand.

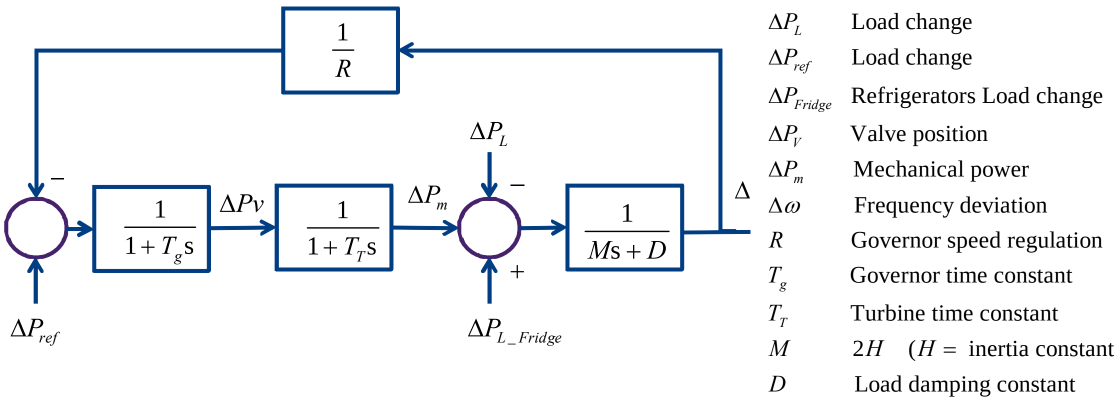

Figure A1-1. Power system frequency response model

In this system model, the response of the power system due to a plant failure can be simulated by adding a step increase in ΔP_L equal to the plant loss. The model then shows the change in system frequency (from the nominal 50 Hz) as $\Delta\omega$. An example result from this model when a sudden loss of generation occurs is shown in Figure A1-2 for loss sizes of 1 GW and 1.32 GW. As can be seen, the system frequency drops and is contained at -0.8 Hz, i.e. -0.5 Hz (corresponding to an actual system frequency of 49.2 Hz, i.e. 49.5 Hz), as required by the System Operator's operating practices. The lowest frequency is obtained after 10-15 s and then the system recovers over the next 50 s, with the frequency stabilising at -0.34 Hz, i.e. -0.12 Hz.

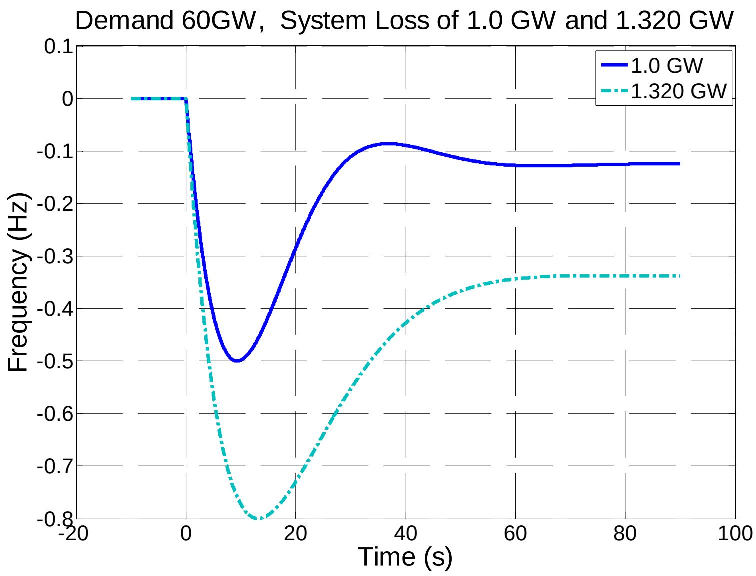

Figure A1-2. System frequency response with 1 GW loss of generation when demand is 60 GW

The parameters for this model were chosen to match the behaviour of the present UK power system and agree with the models and figures detailed by the National Grid (System Operator). The model depicted in Figure A1-1 is capable of predicting the behaviour of the power system when DD refrigerators are connected to the system, as these simply present a change in load which is presented to the model as ΔP_{L_Fridge}.

Refrigerator Models

The domestic refrigerators generally maintain the refrigerator temperature between two set points. When the internal temperature rises to the set point value of T_{max}, the compressor is started and the refrigerator begins to cool. When the refrigerator's internal temperature reaches the minimum required temperature set point of T_{min}, the compressor is stopped. This duty cycle then repeats. This standard non-DD refrigeration cycle is shown in Figure A1-3. As can be seen, the compressor duty cycle (i.e. the time during which the refrigerator is using energy) is around 20 to 30%. When the compressor is on, the temperature drops and when it is off the refrigerator cabinet temperature rises. This refrigeration model is based on Newton's Law of cooling.

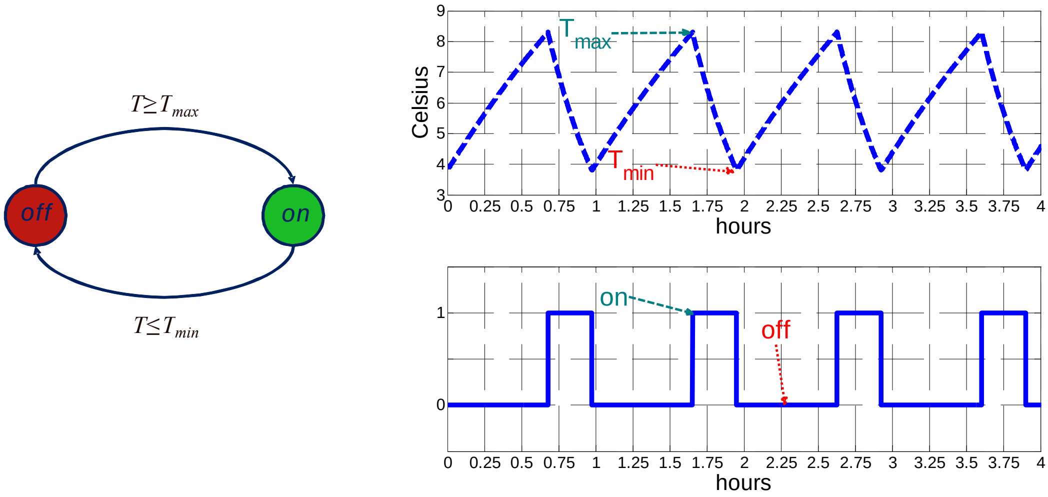

Figure A1-3. Standard refrigerator cycles (left – state representation, right – refrigerator temperature and compressor state).

Dynamic Demand Controller

The inclusion of DD control to a normal domestic refrigerator changes the behaviour by altering its duty cycle length in response to frequency changes. There are many possible methods of achieving this, and many different algorithms that could be used. However, the requirement for the refrigerator to be able to contribute positively to dynamic demand is that the average energy consumption per appliance should reduce when the system frequency reduces.

In this work, a basic algorithm has been investigated, where the duty cycle length is changed in direct proportion to the change in system frequency. Figure A1-4 shows the behaviour of a DD-enabled refrigerator when the system frequency changes. At the 2 hour point, the grid frequency changes from exactly 50 Hz to 49.5 Hz. As can be seen, the refrigerator duty cycle is adjusted i.e. decreased as a consequence of frequency drop.

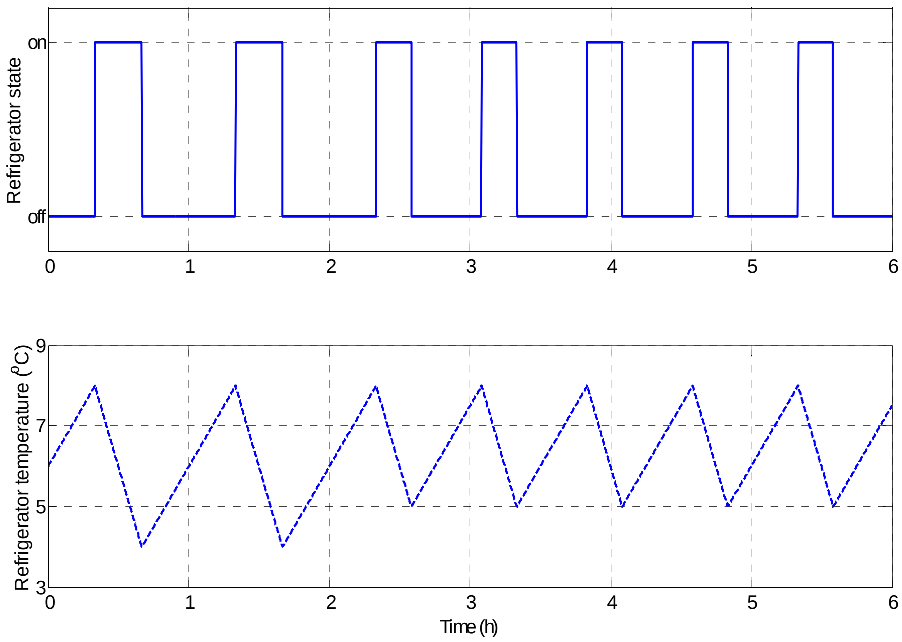

Figure A1-4. DD Refrigerator behaviour with a step change of system frequency

It is important to note that the model is able to capture the net statistical effect of a large number of simulated appliances (typically ranging from thousands to millions), and perform detailed monitoring of energy exchange between refrigerators and generators during a disturbance event.

System Response Requirements under Different Scenarios

The amount of response required by the system is normally specified in terms of the amount of demand connected to the system at a given time and the maximum generation loss that system must be able to withstand. This information is provided by the System Operator (SO) in the form of response requirement curves.

The combined power system and refrigeration models were used to generate new system response requirement curves for different penetrations of dynamic demand refrigerators. These curves represent the additional response required from conventional generation considering the contribution of the refrigerators. This was done by running the simulation model of Figure A1-1 in conjunction with the DD-controlled refrigerator models to schedule enough response under different penetrations of DD refrigerators for generation losses of 1320 MW and 1800 MW. In each case, the scheduled response which allowed the system to arrest the frequency drop at a minimum of 49.2 Hz was found.

Figure A1-5 shows the response requirement curves for the system as a function of demand, for different penetrations of DD refrigerators. The line for 0% penetration corresponds to no DD installation and is thus the response requirement curves as specified for the system at the moment by the SO. As can be seen, the response requirements reduce with greater installation of dynamic demand refrigerators. Note that this figure corresponds to the amount of system response required for a single loss of generation of 1320 MW.

Figure A1-5. Response requirements for system loss of 1320 MW with varying DD refrigerator penetration

Future generating plant, such as new nuclear builds, will probably contain generating sets with greater capacity than 1320 MW. It is likely that the largests sets, and thus the largest single failure will be 1800 MW. Figure A1-6 shows the response curves for a system which must withstand a loss of 1800 MW.

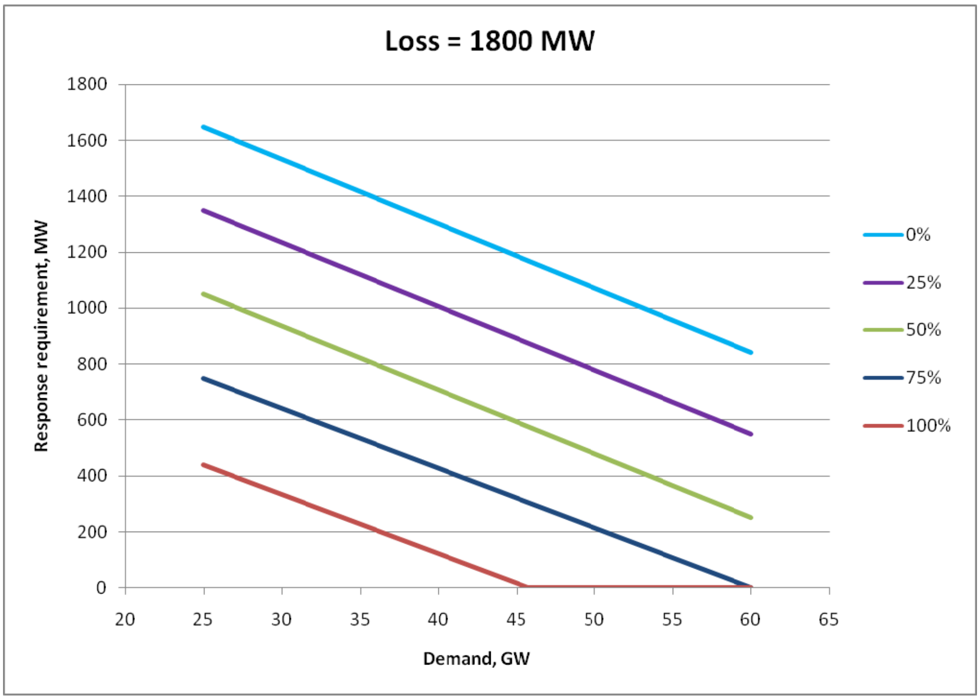

Figure A1-6. Response requirements for system loss of 1800 MW with varying DD refrigerator penetration

Both of the above figures imply that DD might considerably reduce the system-level (primary) response requirement from synchronised generators. In case of a 1320 MW loss, a full oenetration of of 40 million DD refrigirators would result in upto from 784 MW to 1164 MW. However, these values are related to the different generation scenarios studied (with generic generator models) and the assumptions used for the ability of DD to sustain the delivery of the response and to have sufficiently fast recovery of diversity, which are yet to be established through further modelling.

Table A1-1 summarises the contribution to system response, calculated per appliance (assuming a 150 W appliance), for different scenarios of demand level, size of generation loss and penetration of refrigeration with DD controller. These values were used to define the contribution per single refrigerator to be included in the Value Assessment Model to evaluate the benefits of DD. Since this contribution changes with system conditions such as the size of the largest unit and the demand level, additional sensitivity studies to the contribution of an individual appliance will be performed to take into account these differences.

It is critical to bear in mind that these evaluations assumed that the required levels of the delivery of response can persist for sufficient amount of time (say 30 minutes) and that all refrigerators will recover instantly their temperature (while not taking any additional power to achieve this). This is clearly overly optimistic, and hence the figures in the table should be seen very much as upper limits.

Table A1-1. Power potentially relieved by refrigerators while delivering frequency response

		Power relieved for response in W/appliance				
	In fed Loss (MW)	1320			1800	
	System Demand (GW)	25	40	60	25	60
DD Penetration (%)	100	19	21	18	29	24
	75	19	25	20	29	27
	50	19	28	23	28	27
	25	20	29	26	28	28

Appendix 2: Value Assessment of Dynamic Demand

System Response and Reserve Requirements in the UK

An overriding factor of the operation of power systems is the need to maintain system security, i.e. to supply customers with electricity, while meeting the quality of supply requirements at all times. Constancy of power system frequency is a key measure of the quality of power supply, which is continuous and defined by its frequency and voltage. Traditionally security at the system level is associated with the ability of the system to follow changes in demand.

System security involves operation and design practices, including appropriate levels of reserve and flexibility, necessary to keep the system operating under a range of conditions including: credible plant outage; predictable and uncertain variations in demand and availability of primary generation resources including wind.

With the increasing penetrations of intermittent generation, mainly wind, the system will need additional reserve and response capabilities to react to the uncertainty and variability of wind power outputs. This is illustrated in Figure A2-1, which shows how the system response requirement curves suitable for the current system change with installation of substantial quantities of wind power.

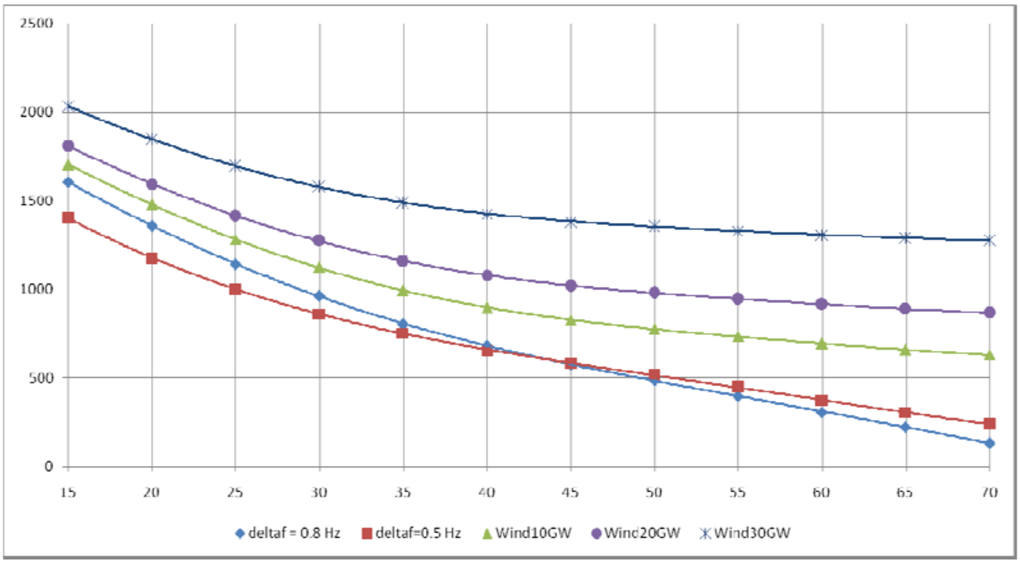

Figure A2-1. Increase in system response requirements for different levels of wind penetration

One important aspect of system security is the ability to balance supply and demand over various time scales. This is performed using a mix of services defined by the Grid Code (such as frequency response and reactive support), and a spectrum of commercial services (such as standing reserve).

Frequency response services

System frequency is a continuously changing variable that is determined and controlled by the balance between supply and demand. If demand is greater than generation, the frequency falls below 50 Hz while if generation is greater than demand, the frequency rises above 50 Hz. The balance between demand and generation must be automatically and continually maintained in order to meet the performance targets of the system frequency set in narrow limits around 50 Hz.

The electricity supply regulation requires the system frequency to be maintained at ±1% of the nominal system frequency (50 Hz), except in abnormal or exceptional circumstances. The system operator is incentivised to procure efficiently the adequate amounts of various ancillary services to meet this requirement. Regarding the Response Services, SO needs to ensure that the system can withstand the largest credible generator outage, the size of which is currently 1320 MW. Larger, simultaneous outages of generators would be covered potentially by short term demand disconnections.

The frequency containment operational policy currently adopted by the SO is based on the following requirements:

- Under normal operating conditions frequency needs to be maintained within ±0.2 Hz of the nominal system frequency;
- For a sudden generation loss or demand changes up to 300 MW the maximum frequency changes will be limited to ±0.2 Hz of the nominal system frequency;
- For a sudden generation loss or demand changes within the interval from 300 MW to 1000 MW the maximum frequency changes will be limited to ±0.5 Hz of the nominal system frequency;
- For a sudden generation loss within the interval of 1000 MW to 1320 MW the maximum frequency changes will be limited to –0.8 Hz with frequency restored to 49.5 Hz within 1 minute.

For any loss larger than 1320 MW the event will be treated as an emergency condition and automatic low frequency load shedding will start at 48.8 Hz. In the event of reaching frequencies above 52.2 Hz or below 47 Hz independent protection action is permitted to protect generators.

To meet the requirements described above the system operator needs to manage frequency continuously. SO utilises a range of ancillary services that operate over different time scales in order to manage system frequency effectively.

In short term, over the operational time scales from a second over to an hour and a day, adequate response and reserve needs to be procured from generators and demand, to maintain system operation in the event of a sudden generation outage. In the long term, from months to years, it is important that sufficient plant margin is present.

To handle the short terms response and reserve needs, the system operator needs to ensure that the system is able to meet forecasted demand plus a margin above this, to deal with the uncertainty in demand and generation in the system. This means that the system needs to procure response services for the short term frequency control and operational reserve for restoration of response capabilities in the system to deal with further potential outages and therefore achieve an acceptable level of security of supply.

Response requirements change with the time scales and are detailed below:

> **Primary Response** is defined as the automatic increase in output or decrease in demand, in response to a fall in frequency that occurs in the period 0 to 10 seconds from the time of the frequency fall and is sustained for a further 20 seconds. Primary response has the purpose of arresting the frequency fall, following a loss of generation, until secondary response becomes available. The primary response requirement is defined as the response 10 seconds after the loss of generation that would result in a frequency drop of –0.5 Hz for a significant or -0.8 Hz for an abnormal event.
>
> **Secondary Response** is defined as the automatic increase in output or decrease in demand in response to frequency fall that is fully available 30 seconds from the time of the frequency fall, and is sustained at least for further 30 minutes. The objective of secondary response is to contain and partially recover the frequency after the fall has been arrested.
>
> **High Frequency Response** is defined as the automatic decrease in output in response to a frequency rise that occurs in the period 0 to 10 seconds immediately after frequency rise and is sustainable thereafter. High frequency response has the purpose to arrest and contain the rise in frequency following a loss in demand.

Reserve services

Reserve is used to take over from frequency response services, to re-establish the level of response capability following a short term generation outage. These requirements are met by part loaded synchronised plants, providing spinning reserve, and by non-synchronised generators, storage and demand reduction providing standing reserve[9].

The combination of spinning and standing reserve forms the operational reserve required to cover the changes in generation (conventional and wind) and demand that take place before real time. The requirement for reserve is related to the statistics of credible generator outages, along with demand and wind forecast errors. The volume of reserve held is driven by the combined forecasting error associated with wind power, demand and available generation. Effectively the amount of reserve procured represents the level of operational risk that is being accepted and varies by time of the day, type of day and time of the year.

Spinning reserve, which has low utilisation cost, generally covers more frequent and smaller imbalances. Standing reserve has a lower holding cost than spinning reserve, but has higher utilisation cost so it is likely to be deployed to help with less frequent but larger imbalances. The cost characteristic of the different forms of generators will be relevant for determining an appropriate allocation between amounts of spinning and standing reserve.

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[9] Spinning reserve corresponds to the unused capacity of part-loaded plants scheduled and is required to be delivered in time scales of 5 to 10 minutes. Standing reserve is provided by non-synchronised plants along with demand side and storage, and is required to be delivered within time scales of less than 20 minutes.

The model developed for this study considers the interaction between response, reserve and energy provision from generators, taking into account their cost characteristics and dynamic capabilities. In terms of the range of various balancing services, however, the present model supports only a single generic response service and single generic reserve service.

Dynamic Demand application for Frequency Management

Providing response and reserve services from synchronised generation requires the units to run part loaded. This leads to efficiency losses in plant operation and a consequent increase in operation cost and the CO_2 emissions, to supply the same level of demand when compared to a scenario where no reserve is held by the plant.

Dynamic Demand (DD) can provide an alternative source of primary response. DD concept means that using low-cost microcontrollers makes it possible to design electrical appliances, which can automatically alter the timing of their electricity demand requirements in relation to frequency variation. When acting together, these appliances can react very quickly by reducing demand as a response to a frequency drop, more rapidly than a traditional synchronised generator could increase its output.

There are many electrical appliances (such as refrigerators) which are not time-critical, in that they need energy but there is some flexibility regarding *when* that energy is actually delivered. Early research [Short, 2007] suggests that these appliances, taken together, provide the potential for a large DD contribution which could act to reduce imbalances on the electricity grid – potentially providing a more carbon efficient solution than traditional response provision options. If developed successfully, DD has the potential to reduce the costs of managing frequency (particularly with the predicted growth in variable-output renewable generation), and at the same time reduce carbon emissions.

In summary, the potential benefits of dynamic demand include:

- Increase of system flexibility, particularly in a system with significant penetration of wind combined with nuclear power;
- Reduction in the system operation cost particularly for high penetrations of intermittent generation;
- Reduction of CO_2 emissions from power generation.

The extent to which DD could replace response capability held on partly-loaded generation will depend on many factors and the following sections present the methodology used to quantify the benefits of DD, identify the drivers for these benefits and present results obtained.

Methodology for Quantification of the Benefits of Dynamic Demand

This section outlines the methodology developed to quantify the benefits of Dynamic Demand. The methodology includes quantifying reserve and response requirements in terms of uncertainty of demand and wind output. Different options for response and reserve provision are evaluated considering economic and environmental benefits.

The methodology is based on a detailed simulation of the operation of the system. This simulation is performed for every half hour of one year. The optimal economic operation of the system is calculated taking into consideration daily and seasonal demand variations and variations in wind output over the year. In this manner, the underlying costs associated with operating the system are evaluated for different future development scenarios.

To properly simulate system operation, and include the changes in the relevant parameters, the methodology includes the following considerations:

- Modified system response requirements were generated through the adjustment of the system primary response requirements to incorporate the uncertainty of wind. The statistical characteristics of realistic wind data were incorporated into calculations of new system response requirements which capture the additional uncertainty introduced by wind generation. This procedure was repeated for different wind penetration scenarios. The new response requirements ensure that the risk of violating frequency limits remains unchanged.
- The current response requirements assume 1320 MW as the largest credible generation loss. In order to consider scenarios of system development with a possible generation loss of up to 1800 MW, while keeping frequency within the existing limits for abnormal events, new response curves were determined assuming that the new plants will have similar inertia to the existing ones.
- Reserve requirements are defined taking into account wind and demand forecast errors and generation outages within operational reserve time scales. This was incorporated into calculations of the additional reserves (the forecast lead time used is 4 hours, corresponding to the expected time required to start a new plant). This process was carried out for different wind penetration scenarios. The reserve requirements ensure that wind uncertainty is taken into account without changing the operational risk accepted by the system operator.
- CO_2 emissions from fossil fuel-based electricity generation are modelled considering International Panel on Climate Changes (IPCC) emission factors for different fuels. The emission factors establish a proportional relationship between primary energy used for generating electricity and the CO_2 emissions caused by the process. They also imply that CO_2 emissions per unit of electricity output depend on the efficiency of the technology, meaning that emissions per megawatt-hour of electricity generated increase when power plants are part loaded.
- Weekly and seasonal changes in demand are considered by running yearly studies using eight characteristic demand days, representing weekdays and weekends for all four seasons.

- The variation of wind generation over the year is taken into account by using an appropriately constructed wind time series based on typical UK values, and simulating wind outputs for different future wind penetration levels.

The allocation between spinning and standing reserve is optimised to minimise expected imbalance costs for different evolution paths of the generation system.

Simulation of System Operation

An annual generation scheduling algorithm was developed for this project, suitable for simulating annual system operation considering the contribution from DD. The algorithm's key features include:

- Commitment and dispatch of generation units, while minimising operation costs, considering: generation start up; incremental production costs and cost of holding standing reserve in stand-by plants (generic data were used here based on earlier studies[10]).
- Consideration of generators' technical limits and capability to change the output (generic data were again used):
  - Generation technical limits;
  - Ramp rates;
  - Minimum up and down times;
- Demand balance constraint based on the criterion that the generation schedule needs to meet net demand at all times, where net demand is the difference between demand and wind generation;
- Deterministic requirements constraining the minimum levels of:
  - Primary response: provided both by part loaded conventional generation plants and DD;
  - Spinning reserve: provided by part loaded plants and set according to the optimal allocation obtained externally;
  - Standing reserve: provided by stand by plants and set to provide the difference between total reserve required and the spinning reserve allocated;
- The algorithm models the interaction between provision of response and spinning reserve by the same unit. The capacity available for spinning reserve is taken into account when setting the generator's available response capacity.

The system operation is simulated for one year with half-hourly time resolution. The results obtained for each scenario represent the minimum operation cost to supply net demand and hold pre-defined levels of response and reserve. Additionally the model provides information on the CO_2 emissions[11] and wind curtailment for all scenarios.

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[10] See e.g. "Value of fault ride through capability of wind generation in the UK", SEDG, 2004

[11] According to assumptions used in the basic generation mix, the emission factor at full output for a coal power plant is 925 kg CO_2/MWh, while for a CCGT plant this is 394 kg CO_2/MWh

Evaluation of the Benefits of Dynamic Demand

This section is concerned with evaluating the benefits of DD for providing primary response as part of the overall response needs, in terms of savings in fuel cost and CO_2 emissions. The value of DD is quantified applying the methodology described in the previous section to a set of scenarios representing future power system development alternatives.

The value of DD is quantified per refrigerator, by finding the avoided fuel cost and CO_2 emissions when comparing a scenario without DD with the same scenario with DD. This value can be capitalised using present worth analysis over an assumed refrigerator life cycle of 10 years, to estimate the present value of the benefits achieved.

System Development Scenarios

The baseline scenario is intended to represent the size and structure of today's power system in a simplified manner. It is based on the following considerations:

- Representative generation system with similar flexibility to the current (or near future) UK generation mix. This system is composed of 6 GW of nuclear plants, 20 GW of coal plants and 50 GW of Combined Cycle Gas Turbine (CCGT) plants;
- Fuel prices are assumed as follows: 75 p/therm (gas), £90/t (coal).
- Demand profile is defined using typical days.

Efficiency and emission characteristics of gas and coal units are assumed in a way which captures the efficiency losses and emissions increase when generators operate in a part-loaded regime. The characteristics used in the model are shown in Figure A2-2 and Figure A2-3.

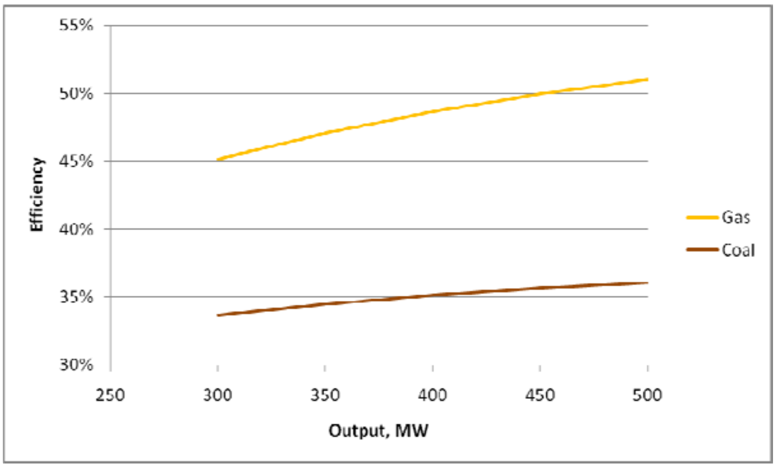

Figure A2-2. Efficiency characteristics of gas and coal units

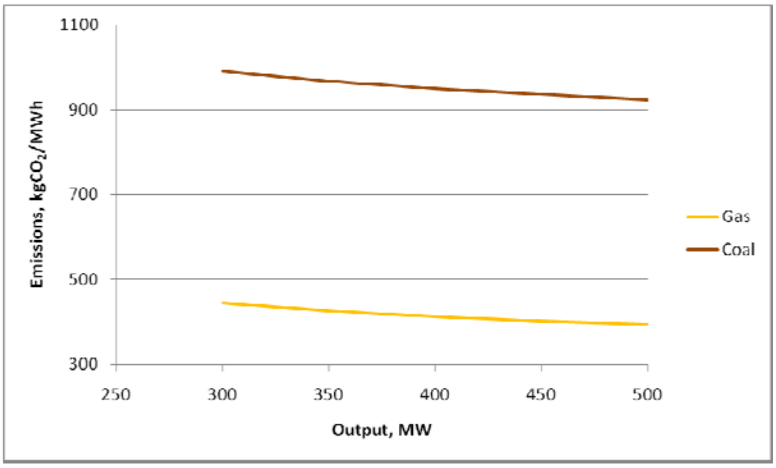

Figure A2-3. Emissions characteristics of gas and coal units

On top of the baseline scenario, the benefits from using DD are also evaluated for alternative evolution paths, in order to investigate how different development scenarios affect the value of DD:

- Nuclear capacity of 10 GW;
- Predominance of CCGT or coal in the conventional generation mix[12];
- Introduction of energy efficiency measures (resulting in decrease of demand);
- High penetration of wind generation capacity (up to 30 GW).

All of the alternative scenarios are simulated with and without DD, to evaluate the savings in cost and emissions.

The scenario where increased nuclear is combined with energy efficiency measures and a 30 GW wind penetration broadly reflects the Renewable Energy Strategy as published in [BERR, 2008].

Results

The methodology described earlier was used to carry out a large number of case studies, with the objective to identify and quantify the key drivers behind the value of DD in system operation. This value will greatly depend on the input assumptions.

The value of Dynamic Demand, expressed in monetary terms as fuel cost savings achieved within one year's operation, is first evaluated for the base case without wind generation. In this manner the reference values are obtained for subsequent comparisons. Total savings are determined as the difference between total system operation cost in cases with and without DD. Savings per appliance are then simply calculated by dividing the total savings with the number of refrigerators.

Figure A2-4 shows how annual cost savings per appliance differ with various DD penetration levels, as well as with contributions of individual refrigerators within the

[12] The difference between CCGT-dominated and coal-dominated systems is in the technology that provides response services.

response control mechanism. One can notice that for small DD penetrations the increase in refrigerator contribution from 10 to 30 W generates a substantial increase in savings value. On the other hand, a saturation effect can be observed for higher penetrations, where the increase of contribution from 20 to 30 W does not produce any significant savings. The values of annual benefit per appliance are in the range of approximately £1.5-5.

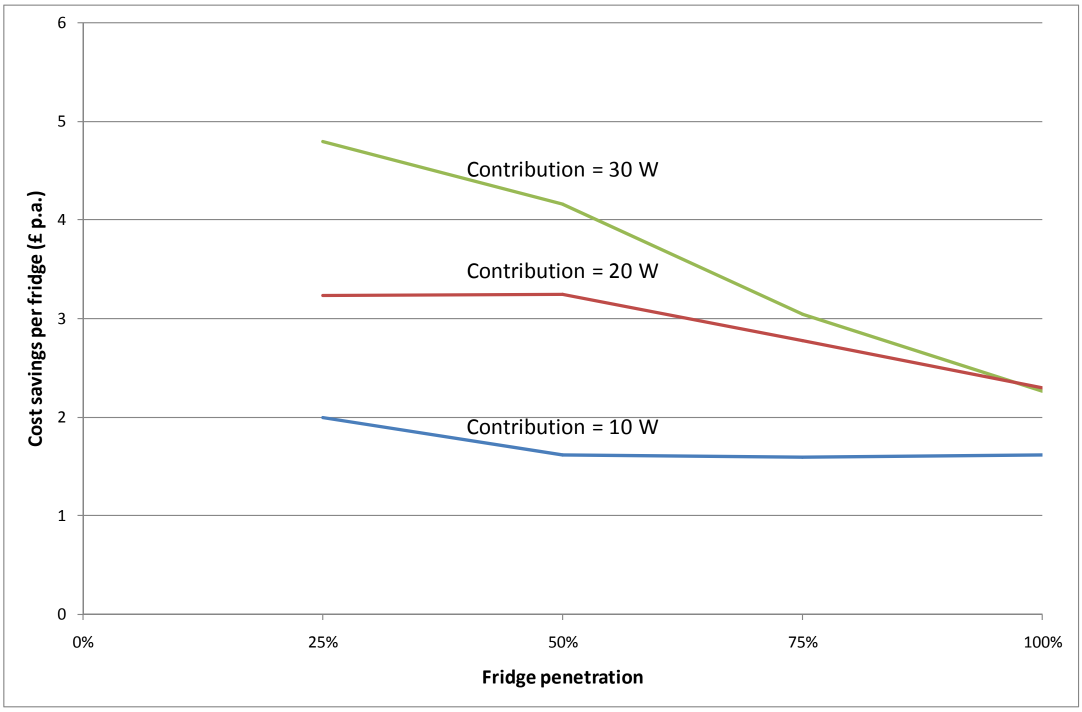

Figure A2-4. Annual cost savings per appliance for different DD penetrations and contributions (baseline generation mix without wind)

Based on the results of the dynamic output model the value of 20 W was chosen as a reference value that was used in all subsequent calculations.

It is clear that the value of DD strongly depends on the cost characteristics and structure of the conventional generation system. In order to investigate how the DD penetration affects this value, two extreme cases were analysed; one was dominated by CCGT units, and the other by coal units in terms of providing response. The two extreme cases constructed in this way should provide an estimate of the range of values for the value of DD in a system that consists of a mix of the two technologies.

In Figure A2-5, an indication is given on how the value of providing frequency response per appliance changes with different DD penetration levels in the two extreme hypothetical cases, with the installed wind capacity of 20 GW. It is clear that the value of annual cost savings per appliance is almost constant for different penetration levels and hence only the penetration of 100% is considered in subsequent simulations.

One can also notice that the value shown in Figure A2-5 (for 20 W contribution) is different from the two extreme cases, since in the base case there is an interaction between coal and CCGT units providing energy, reserve and response with different costs. For small penetration levels, DD displaces the response (and indirectly reserve) occasionally provided by coal plants, enabling them to generate more electricity, replacing the more expensive CCGT units. With higher penetrations, however, the response from coal units becomes almost completely displaced, and the only cost benefits are caused by reducing the part-loading of CCGT units. On the other hand, when one technology strongly dominates the system, only the part-loading reduction is reflected in the benefits.

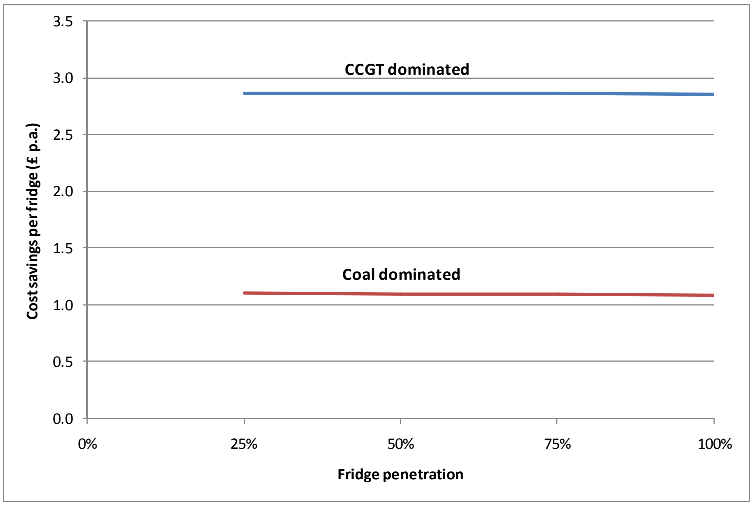

Figure A2-5. Annual cost savings per appliance for different DD penetrations and conventional generation technologies, with wind installed capacity of 20 GW

With previous considerations in mind, the value of savings achieved by using Dynamic Demand was estimated for different development scenarios and across a range of wind penetration levels. The results are shown in Figure A2-6, for both CCGT-dominated and coal-dominated systems, with the latter ones represented by dashed lines in colours matching the equivalent scenarios of the CCGT-dominated system.

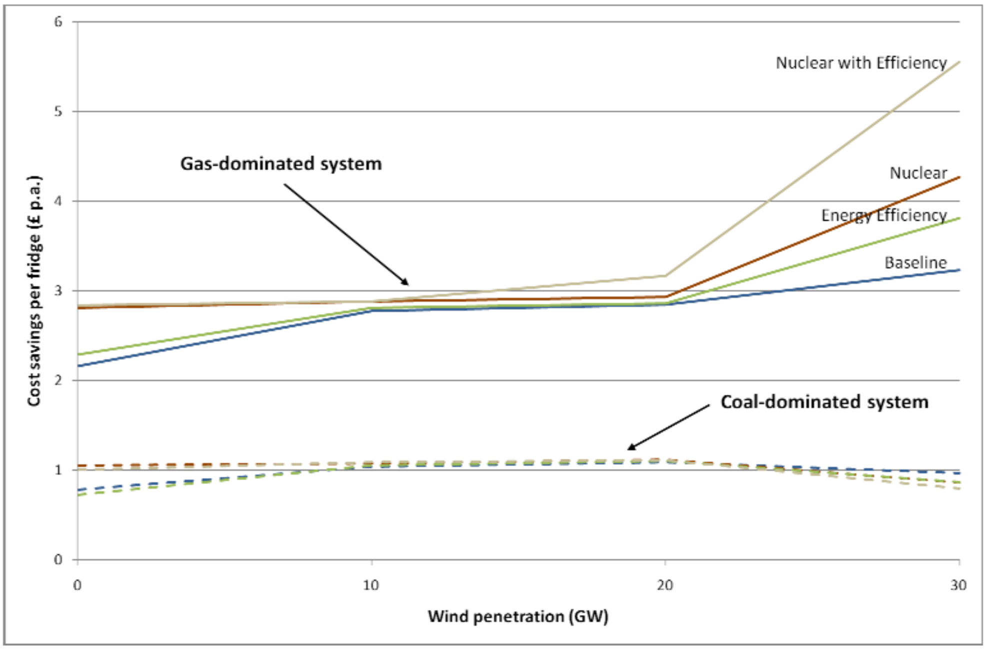

Figure A2-6. Annual cost savings per appliance for different wind penetration levels and development scenarios

It is obvious that savings are significantly lower in case of a coal-dominated system, with very little variation around £1 value across various scenarios and wind penetrations. In the CCGT-dominated system on the other hand, this value increases with wind penetration, and also shows considerable variations across different scenarios. This allows for identifying the impact of different drivers for the value of DD. The value generally increases with wind penetration, starting from the value above £2 in cases without additional nuclear capacity, i.e. from slightly below £3 when nuclear power is expanded. On the other end of the scale, for extremely high wind penetrations, this value can exceed £5, depending on the development strategy of the power system. Compared to the baseline case, energy efficiency measures increase the value of DD for very high wind penetrations, while additional nuclear capacity increases the value of DD for both low and high penetrations of wind. Furthermore, the combination of energy efficiency and additional nuclear power generates the greatest benefit from DD when there is a lot of wind in the system.

Larger wind penetrations in a CCGT-dominated system boost the value of DD because DD relax very high response and reserve requirements that have to be met by significant part-loading of generation units. This is possible because of a relatively high flexibility of gas units to change their output. In that situation, the DD response contribution greatly reduces the efficiency losses in CCGT units, otherwise used for providing all response and reserve. Contrary to that, when coal is dominant technology, due to its limited flexibility, more units are needed to maintain the same level of response and reserve. Combined with lower overall cost of coal units and a more flat efficiency characteristic, this helps explain the lower value of DD in case of coal-dominated system.

Apart from the cost savings from using DD, its engagement would also cause the reduction of CO_2 emissions from conventional power plants. Similarly to the impact on cost savings, the effect of DD on emission reductions for different wind penetrations and development scenarios is quantified in Figure A2-7. The shape of the characteristics is almost the same as in Figure A2-6, which is expected considering that cost savings arise from avoided fuel consumption, which are in direct proportion to the avoided emissions. The only difference is the relation between emission savings between CCGT and coal-dominated systems, and this is a consequence of larger emission factors for coal than gas.

For low and intermediate wind penetrations the emission reduction in a coal-dominated system exceeds that of a CCGT-dominated system, with typical values ranging from 20 to 30 kg CO_2. Conversely, when wind penetrations exceed 20 GW, emission reduction in a coal-dominated system falls below savings from a CCGT-dominated system. This is again a consequence of plant ramping rates, i.e. their ability to accommodate large quantities of variable wind output without DD contribution, and this is much more pronounced in case of CCGT than for coal.

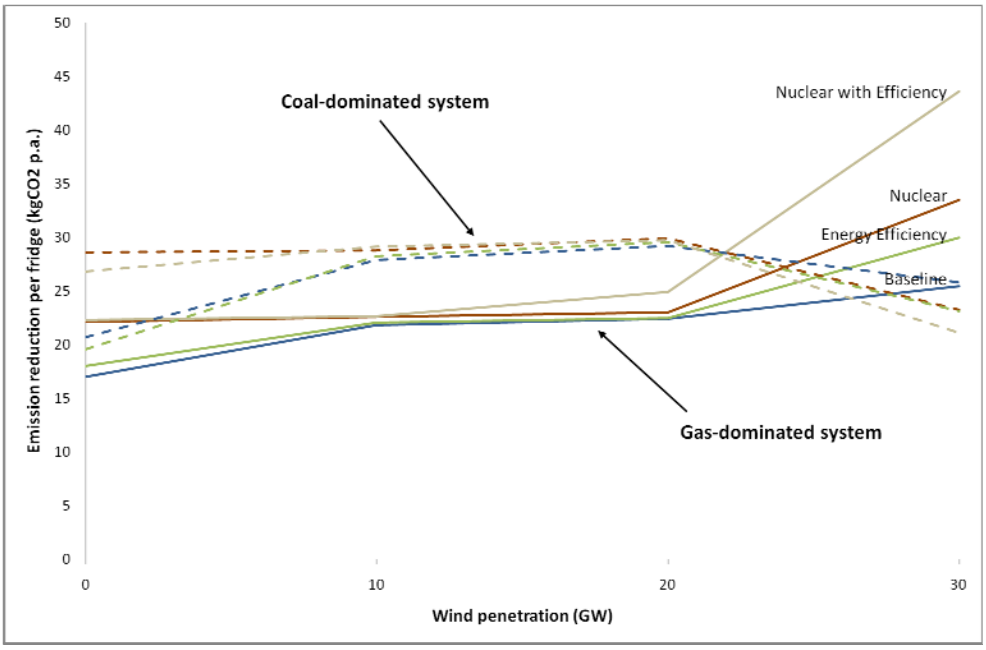

Figure A2-7. Annual CO_2 emission reduction per appliance for different wind penetration levels and development scenarios

The Impact of DD on Wind Curtailment

For very high penetration of wind capacity, the system might not be able to absorb the entire wind output, especially in combination with low demand periods or high amounts of less flexible capacity (e.g. nuclear). This is because a certain number of flexible units need to be online in order to provide the necessary response and reserves.

The ability of the system to absorb wind output will depend on the characteristics of the conventional generators, in particular the ratio between minimum and maximum output, and the ability of units to change output (ramping rates).

One of the results of the annual generation scheduling model is the amount of wind energy that had to be curtailed because of system’s inability to use it in certain periods. The results reveal that significant wind curtailment starts occurring only at a very high wind penetration level, i.e. for 30 GW of wind.

The curtailment levels are much higher for the coal-dominated generation system (or less flexible generation system of any technology), and can reach 26.5% of total wind output in the worst case simulated in the model. This is a consequence of coal units having lower ramping rates, which limit the reserve contribution from an individual unit. For that reason, more coal units need to be committed to provide sufficient reserve, which leaves less room to absorb wind. Gas units are much less constrained in that sense, and the corresponding curtailment levels are lower.

In a low demand scenario with significant contribution of less flexible (nuclear) generation, contributes to a considerable increase in curtailed wind energy.

The characteristics of the technologies also affect how the introduction of DD reduces wind curtailment due to lower response requirements from conventional generation. Because of low ramping rates that restrict reserve contribution of coal units, the response provided by DD does not improve the system's ability to absorb wind on a significant scale. On the other hand, when gas units are considered, introducing DD actually releases a considerable amount of capacity previously used for providing response, which can then be used to provide reserve. This will result in fewer units being committed, leaving more room to accommodate wind in the system. As a consequence, the reduction of wind curtailment with gas units will be substantial, although the initial value is already lower.

Summary of Findings

The annual value of cost savings achieved by DD obtained by the model using the assumptions described above, ranges between £2.2 and £5.6 for a system dominated by CCGT units, i.e. between £0.7 and £1.1 for a coal-dominated system. For a full penetration of 40 million DD refrigerators, the total value of fuel savings would range between £28.8m and £222m per annum, based on the above values of saving associated an individual appliance.

If a lifecycle of 10 years is assumed for a typical refrigerator, and a discount rate of say 10%, the above values would translate into a capitalised value of DD per refrigerator of £13.3-34.1 (CCGT-dominated), i.e. £4.4-6.8 (coal-dominated)[13]. This provides a range of values to be compared to an estimated installation cost of DD controllers.

[13] The discounted present value (or the capitalised value) of the income stream from cost savings is found using the following formula:

$$DPV = C \cdot \sum_{t=1}^{N} \frac{1}{(1+i)^t} = C \cdot \frac{1-(1+i)^{-n}}{i}$$

where *N* is the length of the lifecycle, *C* is the constant annual income, and *i* is the interest rate. For example, for a 10-year lifecycle, annual income of £1 and interest rate of 10%, the resulting discounted present value is £6.14. Also, for an annual income of *C* pounds, the capitalised value equals 6.14*C*.

Both for CCGT and coal-dominated systems the lowest value was obtained in a system without wind, while the highest value was obtained in a CCGT-dominated system with additional nuclear capacity, lower demand level due to energy efficiency measures, and extremely high wind penetration (30 GW). This is the scenario that reflects the expected system developments following the Renewable Energy Strategy (RES) as described in the consultation document [BERR, 2008].

At the same time, the impact of DD on the reduction of CO_2 emissions was found to be in the range between 17 and 44 kg CO_2, using the same assumptions. If translated into emissions generated by a base-load CCGT unit operating with 85% load factor, this would be equivalent to emissions of a plant of capacity between 230 and 600 MW.

If it is possible to attach a certain economic value to the emission reduction, such as e.g. £16/tCO_2, this would additionally imply a value of £0.3-0.7 per refrigerator per year, i.e. £1.7-4.3 when capitalised over an assumed 10-year lifecycle using 10% discount rate. For a full penetration of 40 million DD refrigerators, the total annual value of carbon emission reduction (assuming £16/tCO_2) would range between £10.9m and £28.9m per annum.

Table A2-1 provides the summary of values obtained.

Table A2-1. Summary of results for value of Dynamic Demand

	CCGT-dominated system	**Coal-dominated system**
Highest value of DD per appliance (corresponding scenario)	**£5.55 p.a.** (Nuclear + Energy eff. + 30 GW wind)	**£1.12 p.a.** (Nuclear + 20 GW wind)
Lowest value of DD per appliance (corresponding scenario)	**£2.16 p.a.** (Baseline + no wind)	**£0.72 p.a.** (Energy eff. + no wind)
Highest CO_2 emission reduction per appliance (scenario)	**43.6 kg CO_2 p.a.** (Nuclear + Energy eff. + 30 GW wind)	**29.9 kg CO_2 p.a.** (Nuclear + 20 GW wind)
Lowest CO_2 emission reduction per appliance (scenario)	**17.0 kg CO_2 p.a.** (Baseline + no wind)	**19.6 kg CO_2 p.a.** (Energy eff. + no wind)

Drivers for the value of Dynamic Demand

Based on the results presented so far, the value of DD depends on several critical drivers related to the characteristics of the power system where DD is applied. They are as follows:

Wind penetration. Larger wind capacity generally increases the value of DD (with some exceptions in a coal-dominated system with extremely high wind penetrations). This is understandable, since DD reduces the response contribution from conventional generators, which in turn enables them to be less part-loaded, i.e. operate with higher efficiency. Higher wind penetrations imply higher overall response requirements, meaning that plants need to be offloaded even further, and this makes the benefit from using DD larger.

System demand level. Lower demand levels, achieved e.g. as a consequence of energy efficiency measures, require more frequency response due to lower inertia of the system. This has the tendency to drive the value of DD higher, since it decreases the response contribution from conventional generators from a higher level than in the normal demand case.

Nuclear power expansion. It is expected that nuclear generation may be less flexible and consequently the value of DD tends to be higher

Structure of conventional generation mix. This affects the value of DD in several levels. First, the overall cost of the dominating technology has an obvious impact on the amount of fuel cost savings achieved by DD, so that the savings are smaller in systems with cheaper generation, and with units with lower efficiency losses due to part-loading. Also, the rate at which the generators are able to change their output (ramping rates) affects this value, in the way that the amount of reserve they are providing is more limited by the ramp rates than by providing frequency response. Therefore, the value of DD is smaller in such cases compared to the generators with higher ramp rates.

Additional Key Factors Affecting DD Response Contribution

The dynamic system model has indicated the basic properties of the refrigerators' behaviour while providing DD-based frequency response. It is however important to consider other phenomena that might affect the system value of DD response.

First, it is necessary to ensure that DD is capable of sustaining its response contribution, i.e. maintaining its operation at decreased output, for sufficient time for the system reserve to become available (typically in the order of 30 minutes). If the contribution delivered to the system in the initial minutes following a disturbance cannot be maintained for long enough, the effective response contribution will be lower, which is expected to reduce the value provided by DD.

Another important occurrence is the energy recovery effect taking place when the refrigerators start reconnecting as the reserve begins restoring the frequency towards 50 Hz. This effect stresses the basic difference in response provision between DD and conventional generation. While delivering frequency response, the average temperature of the refrigerators inevitably rises, and this needs to be compensated by the system in the form of additional cooling energy when conditions normalise. The amount of energy required to restore the operating temperature is generally less than the energy released during response provision. The exact amount will depend on the conditions of the system, but it would typically be around 60% of supplied energy.

With additional energy, the recovery effect also requires extra capacity provided as a part of reserve requirements. The increase in necessary reserve capacity will generally put additional burden on the system and add to system costs, thus lowering the value of DD. Some preliminary studies were carried out to investigate the magnitude of this effect, and the results indicate 5-20% reduction of the DD value, where more reduction occurs in systems without wind energy due to lower starting reserve requirements. This issue requires further exploration.

A key to the value of DD is the speed of re-establishing diversity of the refrigerators' operating patterns, immediately after they provided frequency response. This report assumed (optimistically) that in about 30 minutes the diversity of the entire population of refrigerators would be fully re-established. Clearly, this requires further detailed investigation.

All of the above effects tend to decrease DD response contribution. The values obtained from dynamic system simulations (Table A2-1) are in the range between 20 and 30 watts for large generation loss sizes. Because of the other assumptions made, regarding the ability of DD to sustain the delivery of primary response and re-establishment of full diversity,, a lower boundary of 20 W was taken as reference value, and a sensitivity analysis was performed around it.

The issues highlighted above require further research, and will serve as guidelines in further investigation of the topic.

Issues arising from this study

The results of the model developed in order to evaluate the benefits of using Dynamic Demand indicate that it might have the potential to generate cost savings and emission reductions. The value of DD appears to be at its maximum when the system consists of relatively expensive and flexible units (such as CCGT) and a substantial amount of inflexible must-run capacity (such as nuclear), combined with low system demand and high wind penetration.

Therefore, Dynamic Demand seems to be a technology that could support a low carbon future where the power system will have to accommodate both high quantities of variable output from renewables (i.e. wind) and possibly a considerable amount of inflexible must-run generation (nuclear or carbon capture and storage technologies). It also has a potential to reduce the curtailment of wind output due to the limitation of conventional generation system, i.e. to improve the ability of the system to absorb wind capacity.

Further research should investigate the relationship between DD-based response and the resulting reserve requirements necessary to compensate the energy relieved by the refrigerators during frequency drops, in order to recover their operating temperature. This work will also include evaluation of alternative technologies, particularly wind turbines.

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