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Article title

Assessing the Value and Impact of Demand Side Response using Whole-System Approach

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Abstract

This paper describes the whole-system based model called WeSIM to quantify the benefits of demand flexibility (DSR). WeSIM is a holistic and comprehensive electricity system analysis model which simultaneously optimises the long-term investment decisions against real-time operation decisions taking into account the flexibility provided by demand. The optimization considers the impact of DSR across all power subsystems, i.e. generation, transmission and distribution systems, in a coordinated fashion. This allows the model to capture the potential conflicts and synergies between different applications of DSR in supporting particularly intermittency management at the national level, improving capacity margin, and minimizing the cost of electrification. The impact and value of DSR driven by whole-system approach are compared against the impact and value of DSO or TSO-centric (silo approaches) DSR applications and the importance of control coordination between DSO and TSO for optimal DSR is discussed and highlighted.

Keywords

Demand Side Response, optimisation, whole-system approach

Introduction

Demand Side Response (DSR) is envisaged to be one of the pivotal technologies for improving the operational feasibility, efficiency, and economic performance of our future low-carbon electricity systems. These systems are likely to be characterized by generation mixes with a high share of variable and less flexible low-carbon technologies such as renewables (wind, solar, marine), nuclear, and Carbon Capture and Storage (CCS). Furthermore, in order to reduce further carbon emissions, at the certain extent, the use of gas for heating and hydrocarbon fuel for cars will be substituted by low-carbon energy such as electricity from renewable sources for electric vehicles, and heat pumps. Due to the load profiles, this electrification will, in turn, increase the peak demand of the system [1]. Therefore, real-time management of electricity loads, which traditionally are passive, is increasingly important as it can reduce the system (both generation and network) capacity required and enable higher utilization of lower cost resources.

Although the majority of DSR appliances / devices are connected at low voltage, the impact of large deployment of DSR is not only limited to the local networks but it can also influence the operation and capacity requirement of the national system and the cross-border power exchange between regions. This requires complex modelling of the whole system. Due to its complexity of modelling the whole system, simplified approaches are generally used to evaluate the impact and the value of this technology limited only on individual applications.

For example, the key benefits of demand side management in the UK electricity system were discussed in [2]. The benefits include: reduction of generation capacity requirement, improved utilisation of transmission grid and distribution network assets and operational efficiency, as well as enhancing the balancing capability between demand and supply in systems with intermittent renewables. Authors in [3] and [4] investigated the value of DSR delivering reserve services in joint energy/reserve markets. Short [5] demonstrated the concept and applicability of DSR in the provision of frequency response and provided a coarse estimate of its potential economic values. The applicability of DSR to provide frequency response was simulated and tested in [6]. The benefit of DSR for the economic and environmental performance of the electricity system has also been estimated in [7], by simulating annual system operation while taking into account reserve and response requirements.

Aggregating the benefits of DSR which are assessed in silos may overstate the value of DSR itself as the potential conflict across different DSR applications is neglected; for example, the use of DSR for peak-load reduction in a local distribution network by shifting demand from the local peak time to local off-peak time will actually increase the national peak demand if the peak time of national load coincides with the time where the local load recovery occurs. Another potential conflict may arise if the local peak load reduction increases the peak loading of transmission circuits / interconnectors which triggers demand for new transmission capacity. These potential conflicts have to be managed carefully to get the maximum benefits of DSR.

In this paper, the benefits of DSR in reducing the capacity of power system infrastructure and stabilizing the electricity prices have been investigated using Whole-electricity System Investment Model (WeSIM). WeSIM is a holistic and complex electricity system analysis model which concurrently optimizes the long-term investment decisions and real-time operation decisions taking into account the flexibility provided by DSR, across generation, transmission and distribution systems, in integrated coordinated fashion. Thus, the model can capture the potential conflicts and synergies across different applications of DSR in supporting intermittency management at the national level and asset management of the local distribution network.

The impact and value of DSR driven by whole-system approach are studied against different future system backgrounds postulated by the Transition Pathways project. The results of the whole-system approach are compared against the impact and value of DSO or TSO-centric (silo approaches) DSR applications and the importance of control coordination between DSO and TSO for optimal DSR is discussed and highlighted in Section 3: Case Studies together with the discussion on the system backgrounds used in the studies. Prior to this paper, it was unclear whether DSR should be controlled by DSO or TSO and whether some coordination between the TSO and DSO will be required and how the benefits from different control objectives can be compared and analysed. Preceding the discussion on the results, the methodology used for this quantitative analysis is described in Section 2. Finally, a set of conclusions is discussed at the end of this paper.

Methodology

The benefits of DSR can be derived by analysing the difference of the system performance between the system planned and operated with and without DSR. The analysis can encompass, amongst other, cost, emissions, and reliability performance. These are three non-complex indices commonly used to measure the economic efficiency, sustainability, and reliability of the system in question. In order to establish a consistent approach, in all cases (with and without DSR) the system should be optimized using the whole-system approach.

The whole-system approach looks into the effect of the strategic policies and deployment of technologies in question (e.g. DSR) on the system investment and operation. In order to do so, the operational problems should be captured with sufficient details across different operating conditions. This requires modelling of the real-time second-by-second balancing problems across sufficiently long time span capturing the short-term (hourly) to long-term (seasonal) dynamic characteristics of the system. Furthermore, the modelling should also capture different assets in the energy system: large-scale to distributed small-scale generation systems, transmission network (national and interconnections), and local distribution systems. This is important as DSR affects not only the local distribution network requirements but also the the capacity needed by national generation and transmission systems.

In order to capture the system conditions that may drive investment, the model requires hourly (or half-hourly) data of energy demand and profiles of renewable energy across one year period. All data for renewables and demand are time and space synchronised. Furthermore, some extreme conditions, e.g. coincidence between the extreme cold weathers and calm wind during winter evening period that can drive the system capacity requirements have been constructed within the input data. Consequently, the results will tend to be conservative. Considering that the study aims to stimulate high-level understanding of the impact of DSR and not to be used for planning in a specific system, we consider this approach is rational and can be accepted in order to reduce the computation cost.

The whole-system approach used in this paper simultaneously minimises the cost of investments into new generation, storage, interconnection, transmission, and distribution assets while optimising all resources to improve the efficiency of the short-term operation of the entire system on an hourly basis taking into account demand flexibility. System adequacy and security requirements together with emission constraints are considered within the same framework. The model further includes a detailed representation of electricity demand, and considers the capability of demand response technologies, using the inputs supplied by our detailed bottom-up demand models.

Problem formulation

The whole-system approach is formulated as a large-scale mixed-integer- linear-programming problem described in [8]. A slight modification is applied to the objective function to enable the analysis and comparison of different DSR's control objectives, i.e. whole-system, TSO and DSO centric approaches. The objective function φ (1) can be formulated as a problem to minimize the overall system cost consisting of annuitized capital cost of generation, network and storage assets and the annual system operating cost. The objective function φ (1) can be formulated as follow:

$$\begin{aligned} Minimise\ \varphi = & \sum_{i=1}^{S} \pi_{\hat{s}_i} . \hat{s}_i \\ & + K_{TSO}\left(\sum_{i=1}^{G} \pi_{\hat{\mu}_i} . \hat{\mu}_i + \sum_{i=1}^{F} \pi_{\hat{f}_i} . \hat{f}_i \right. \\ & \left. + \sum_{t=1}^{T}\sum_{i=1}^{G} C_{g_i}^{\ t}(\pi_{g_i}, g_i^t, \pi_{nl_i}, \pi_{st_i}, \mu_i^t)\right) + K_{DSO}\left(\sum_{i=1}^{DN} \pi_{\widehat{dn}_i} . \widehat{dn}_i\right) \end{aligned} \tag{1}$$

For simplicity, the superscript t indicating the time specific variable and subscript i indicating the asset/location specific are omitted in the following description. The investment cost includes (annuitized) capital cost of storage ($\hat{s}$) and new generating ($\hat{\mu}$) units, the reinforcement cost of transmission, interconnection capacity ($\hat{f}$), and distribution networks ($\widehat{dn}$). Investment cost of various assets ($\pi_{\hat{\mu}}, \pi_{\hat{s}}, \pi_{\hat{f}}, \pi_{\widehat{dn}}$) is annuitized using the appropriate hurdle rate and the estimated economic life of the asset.

System operating cost is the total annual generation cost that includes: (i) variable cost as a function of electricity output (π_g, g), (ii) no-load cost as a function of a number of synchronized units (π_{nl}, μ) committed each hour, (iii) generation start-up cost(π_{st}, μ). These operating cost categories have been modelled using the methodology presented in [8] taking into account the effect of carbon prices.

In order to simulate different control strategies for DSR, i.e. whole-system, TSO and DSO centric approaches, two variables K_{TSO} and K_{DSO} are used. For the whole-system approach, both K_{TSO} and K_{DSO} are set to 1 so the costs across different assets and operation costs are balanced. For the TSO centric approach, K_{TSO} is set to 1 but K_{DSO} is set to a small value (e.g. 0.001 p.u.) as the TSO will prioritise their interest in reducing the system cost at transmission levels before distribution network assets. Conversely, for the DSO centric approach, K_{DSO} is set to 1 but K_{TSO} is set to a small value as it is assumed that DSO will prioritise in reducing the cost of transmission network assets before generation/transmission assets and operating costs. It is important to note that TSO and DSO centric approaches emerge due to vertical unbundling between transmission and distribution network businesses as practised in a number of countries such as, among others, Chile and the UK. By comparing the results obtained from three different control strategies, i.e. whole-system, TSO, and DSO centric approaches, the performance of these three solutions can be compared and analysed.

The optimisation problem is subject to a set of equality and inequality constraints as described in [8] in order to ensure technical feasibility of the solution and respect the imposed limits. The whole-system planning problem is solved using FICO Xpress optimization tool [9]. It is important to highlight that in contrast to [8], which investigated the role and value of storage, this paper focuses on the role and value of DSR.

The methodology enables the impact of multi DSR applications on the system to be quantified. This includes the use of DSR for: (i) improving the efficiency of system operation by following the availability of low-marginal-cost generators such as renewables and providing ancillary services to reduce the balancing costs; (ii) peak demand reduction, which reduces the system capacity requirement in all subsystems (generation, transmission, distribution). Flexibility parameters associated with various forms of DSR are obtained using detailed bottom-up modelling of different types of flexible demand, as described in [10] and [11] for EVs and heat pumps (HPs).

One benefit of DSR applications that would like to be captured in this study is the use of DSR in reducing the reinforcement cost of distribution networks. The reinforcement can be driven by increased demand or distributed generation. In order to achieve this objective within the limitation of the model, distribution network cost analysis [12,13] needs to be carried out prior to the WeSIM study. This involves a large number of studies using AC power flow calculation where peak demand or capacity of DG is varied on different network configurations and the required reinforcements, either driven by thermal limit or voltage, and their related costs are identified. The outcome is a distribution network cost function based on the peak demand or peak reverse flows. This simplification may not able to capture the whole complexity of managing assets and constraints at the distribution network and therefore the results should be considered as high-level estimates.

Case studies

System Description

In order to demonstrate the role and benefits of DSR, three projected Great Britain (GB) demand and generation scenarios developed in the Transition Pathways project are used. The Transition Pathways project has developed and analysed a set of transition pathways to a highly electric, low-carbon UK energy system [14] driven by the UK Government’s target of reducing UK carbon emissions by 80% by 2050 [15]. The research was funded by the UK Engineering and Physical Sciences Research Council and the electricity utility E.ON UK and involved a consortium of researchers from UK universities. The consortium has identified three key transition pathways scenarios, namely “Market Rules” (MR), “Central Coordination” (CC), and “Thousand Flowers” (TF). The characteristics of each scenario can be described briefly as follows:

- Market Rules: this envisions the broad continuation of the current market-led governance pattern. In this scenario, the government determines the high level objectives of the system and sets up the broad institutional structures, in an approach based on minimal possible interference in market arrangements.
- Central Co-ordination: this envisions greater direct governmental involvement in the governance of energy systems and the pursuit of low-carbon energy, applying some of the principles of transition management.
- Thousand Flowers: this envisions a sharper focus on more local, bottom-up diverse solutions (‘let a thousand flowers bloom’),driven by innovative local authorities and citizens groups, such as the Transition Towns movement, to develop local microgrids and energy service companies.

The studies are carried out on a simplified GB model. Given that the GB transmission network is characterized by significant North-South power flows, for the purpose of this study the GB system is represented using 5 key regions and their boundaries: 1) Scotland, 2) North England and Wales (EW-N), 3) Middle England and Wales (EW-M), 4) South England and Wales (EW-S), and 5) London (embedded within the South England and Wales region). The topology of this system is depicted in Fig. 1.

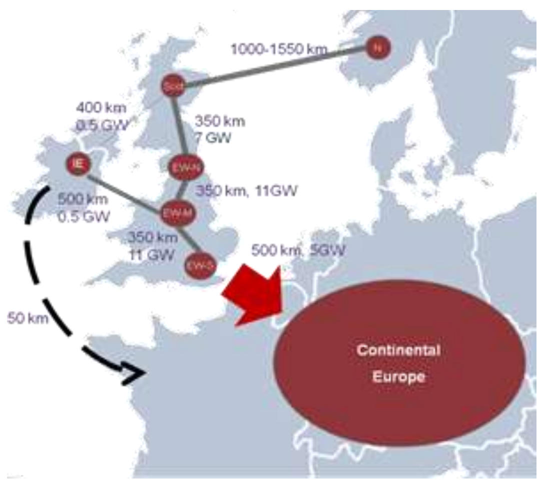

Fig. 1. Topology of the interconnected GB system used in the study

The two neighbouring systems, Ireland (IE) and Continental Europe are represented as separate areas, with an option to link Ireland directly to mainland Europe. Network lengths in Fig. 1 reflect the equivalent distances which take into account the additional local network investment that interconnection may require. Network capacities indicated in the figure refer to the capacities expected to be in place by 2020. No direct link was assumed to be in place between Ireland and continental Europe in 2020, but the model was allowed to build new capacity between the two systems if economically justified.

Both economic and reliability considerations are involved in transmission network and interconnection design [16]. In each of the regions distribution networks are represented by a mix of statistically representative distribution networks.

Impact of electrification on future electricity peak demand

In all aforementioned three transition pathways the consortium assumed a highly electric future, in which there will be a significant penetration of both electric heating and electric vehicles by 2050. The impact of the Pathways' scenarios on peak electricity demand is assessed taking into account hourly demand profiles different mixes and types of electricity loads. More information regarding the modelling of different types of demand (electric vehicles, smart appliances, and heat driven electricity demand) can be found in [17]. The results in Fig. 2 show the increased electricity peak demand in future in each pathway.

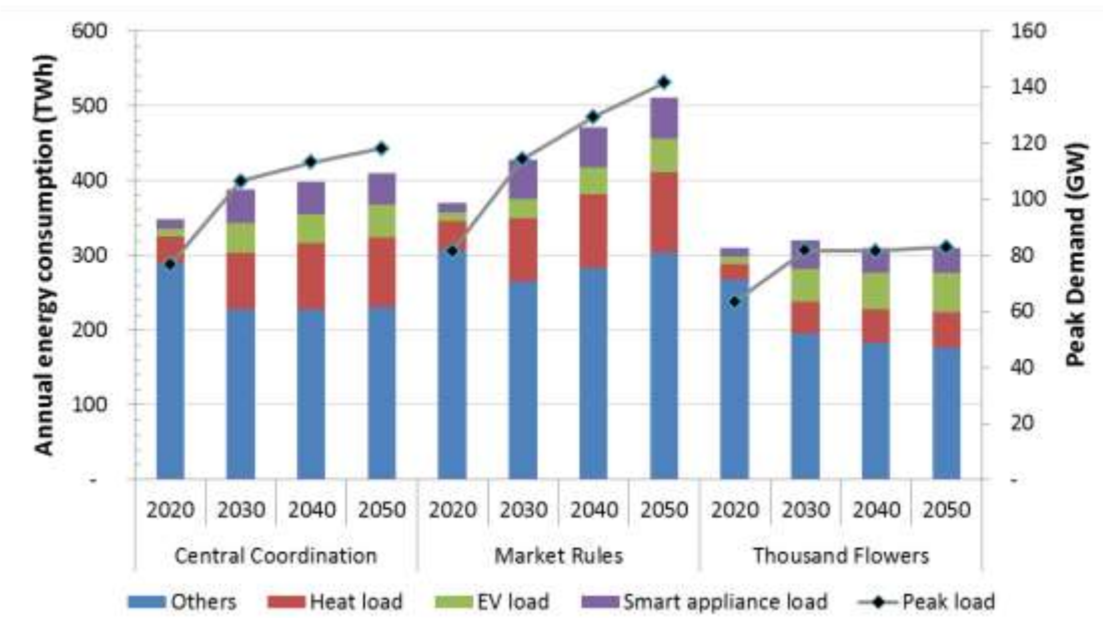

Fig. 2. Annual electricity demand and peak demand for different pathways which demonstrate the asymmetrical increase in the annual energy consumption and peak demand from 2020 to 2050

The increased peak demand in the first two pathways (i.e. Central Coordination and Market Rules) is relatively high. The peak demand increases from around 80 GW in 2020 to around 120 GW and 140 GW in Central Coordination and Market Rules respectively while the increased peak demand in the third pathway is much lesser as the level of electrification in the third pathway is not as high as the electrification in the first two pathways. Electrification can lead to more peaky demand due to its consumption profile [17]. Charging electric vehicles in the evening directly after working hours and switching on HVAC system during peak demand hours in the evening (typical Northern Europe situations) will contribute to increased peak demand, while the increased energy usage is not high.

In order to maintain the security and ability of the system to meet demand, the increase in peak demand has to be met by increased firm capacity of power generation and networks. Firm capacity is defined as the capacity with a constant high availability factor during peak demand conditions. Variable / intermittent generation such as wind and PV are not included in this category since their availability is not constant depending on the temporal weather conditions. Using the given demand backgrounds, WeSIM enforces the security of the system by adding the capacity of generation, transmission, and distribution in a cost efficient manner.

The benefits of DSR in reducing system capacity

While the generation mixes given by the Transition Pathway scenarios are not optimised by the model, the capacity of peaking plant given by the scenarios may be insufficient and therefore, it may require additional capacity which is determined by the model. In order to maintain cost effectively the security during infrequent peak demand conditions, it is suitable to use peaking capacity such as OCGT. Fig. 3 shows the generation mixes for each pathway with and without DSR. The installed capacity of OCGT increases in line with the increase of renewable capacity which consequently affects the capacity of baseload/mid-merit generators from traditional fossil fuel plants.

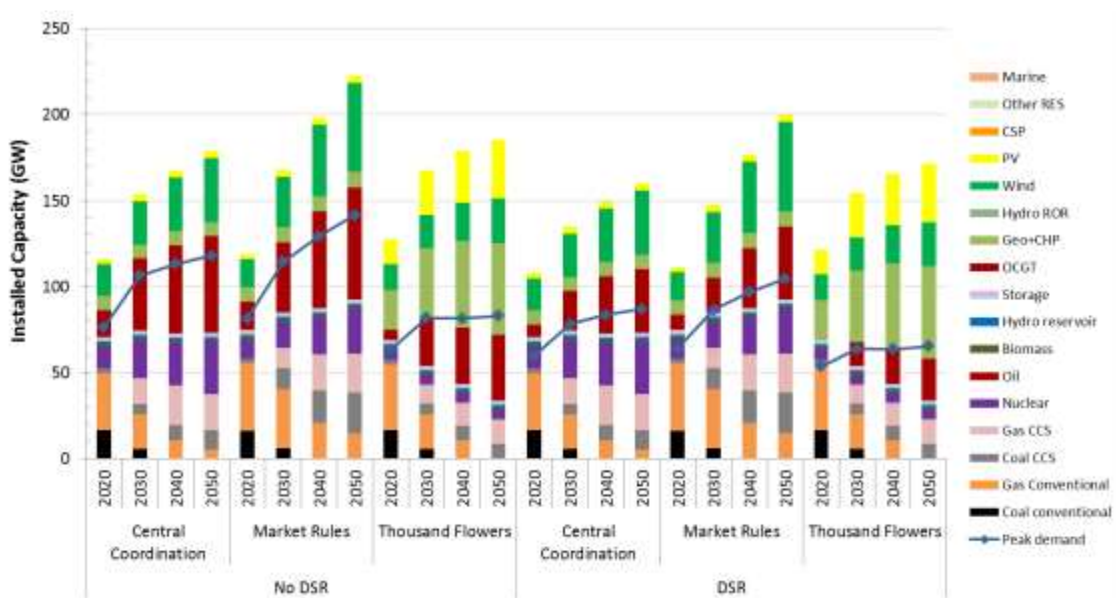

Fig. 3 Impact of DSR on the generation capacity requirement for different pathways

With DSR, the peak demand can be reduced significantly; for example the peak demand in 2050 in Market Rules is reduced from 140 GW to around 105 GW. DSR also reduces the peak demand in other pathways. The reduction of peak demand automatically reduces demand for peaking capacity and therefore less OCGT capacity is needed in the pathways with DSR as shown in Fig. 3. Furthermore, DSR may also reduce the capacity of low-carbon technology while meeting the carbon targets as it enables higher utilisation of low-carbon power generation. This effect is not shown in these results as the generation baseline capacities are dictated by the Pathways where cost is not the only parameter to determine the generation mixes. By minimising the capacity, this reduces the cost of the pathways and increases utilisation of the assets. The reduction of peak demand leads to the reduction of required generation capacity and network capacity in general.

The benefits of DSR in optimising dispatch and increasing utilisation of low carbon generation

The flexibility provided by DSR in shifting the load to the period where the low cost resources can be used optimally has impact on the annual electricity production for different generation technologies. The changes in the annual generation output due to DSR for different pathways are presented in Fig. 4. In 2020, the results show a shift between the output from gas and oil fired plant (CCGT and OCGT) to coal fired plant. This is due to relatively low carbon prices used for 2020 and the marginal fuel cost of coal fired power stations is assumed cheaper than the marginal cost of gas/oil fired plants. It is important to note that the cost minimisation in WeSIM does not directly minimise carbon emissions but through carbon prices embedded in the operating cost of generators. In the year 2030 onward, there is a shift between the output of gas-fired plants, both CCGT and OCGT, to low carbon generation (biomass, wind, PV, CCS and nuclear). The energy storage activity is also less due to DSR and therefore it can be concluded that energy losses due to storage are also smaller.

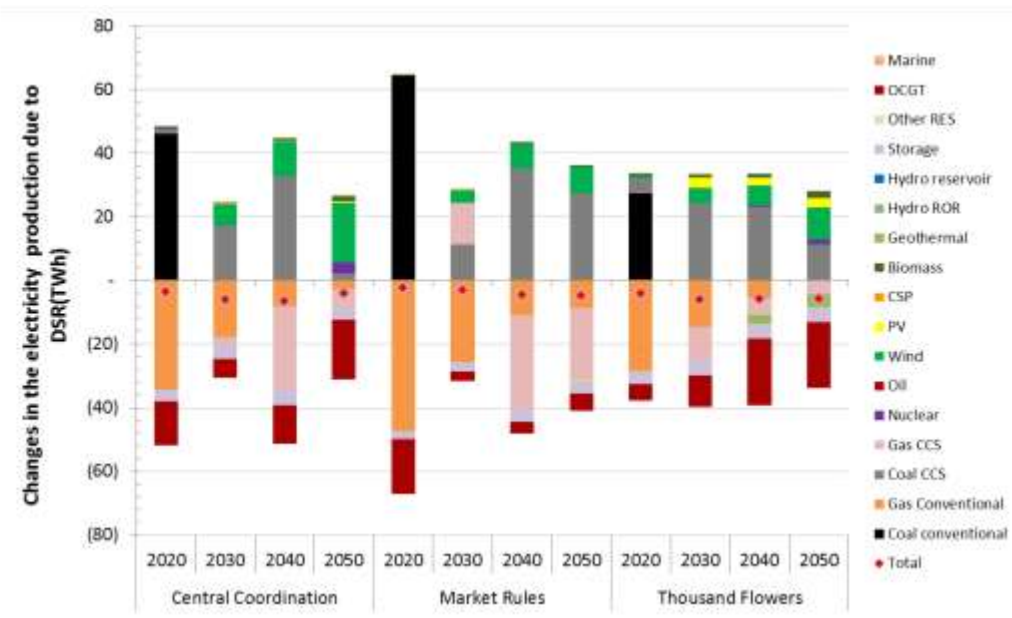

Fig. 4 Changes in the electricity production from different generation technologies due to DSR

Consequently, the changes in generation dispatch will also affect the operational cost of the pathways. As DSR can provide not only the flexibility in shifting the load from peak load conditions to off-peak load conditions but also can provide ancillary services in the forms of reserves and frequency regulation, DSR also improves the overall operational efficiency of the generation systems in the pathways. Consequently, this has economic benefits and value.

Economic value of DSR in different pathways

As discussed previously, DSR applications affect development and operational of other 3 main system components (generation, transmission, and distribution networks) and therefore the tangible economic value of the DSR can be derived by calculating the savings i.e. the reduction of investment and operation cost of generation, transmission and distribution that can be achieved by DSR. Fig. 5 shows the gross economic benefits of DSR in different pathways and by observing the results, it can be concluded that DSR will play important role in all considered different pathways. It is important to note that the cost of DSR is not included in this analysis.

In general, DSR reduces the investment cost of distribution, generation, and transmission although there are cases where the cost of transmission and interconnection (cross-border capacity from GB to mainland Europe) increases slightly due to DSR. It is important to note that the impact of DSR on the transmission/interconnection is locational specific, for example, the reduction of local load in the exporting area may reduce demand for distribution network reinforcement but at the expense of increased transmission requirements. In general, even with a slight increase in transmission/interconnection cost, the cost reduction in other system components is much larger.

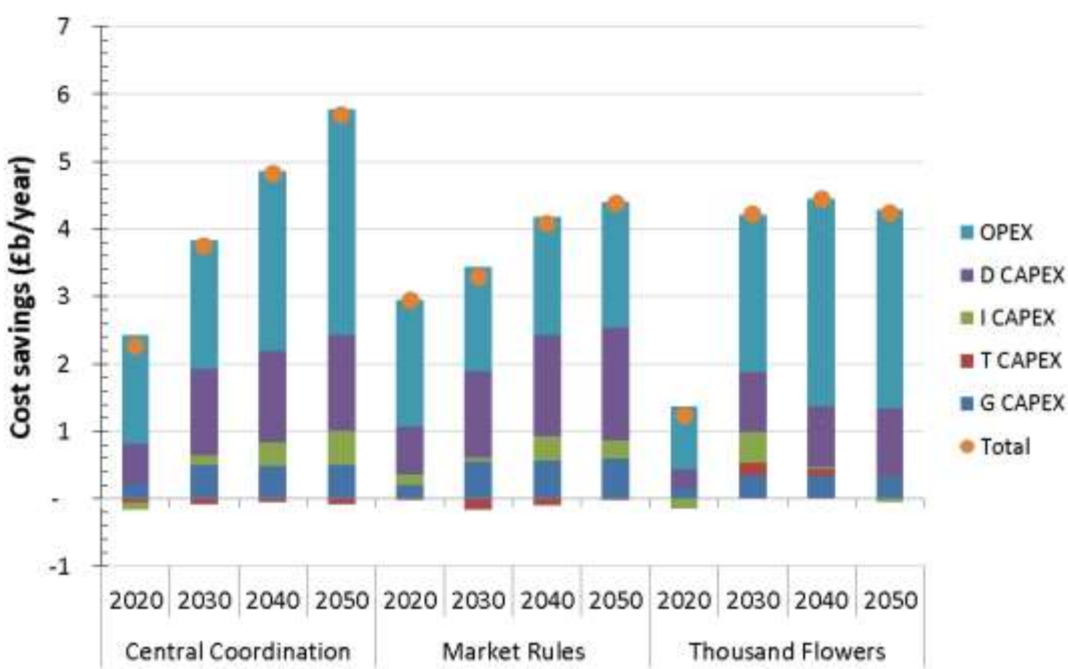

Fig. 5 Cost savings attributed to whole-system DSR applications in different pathways

In addition to savings in investment, the results also show a significant reduction in the operational expenditure (OPEX) as DSR allows better utilisation of lower marginal cost resources including renewables. The total cost savings reach £4.2 - £5.6 billion per year in 2050 in different pathways with the maximum benefits occur in Central Coordination. The benefits represent around 10% savings from the total annual cost of generation, and transmission; a similar amount to welfare gains reported in [18] estimated as results of the privatisation of the British Central Electricity Generating Board. However, it is important to bear in mind that the studies were carried out assuming full DSR flexibility with the objective of quantifying the maximum benefits that DSR could achieve. It can be expected that the value will be less depending on the level of DSR that can be available and how optimal the DSR can be deployed and operated.

The results also show an increasing trend of the savings from DSR, this is particularly driven by the benefits of DSR in mitigating the effects and cost of electrification and optimising the use of lower marginal cost resources; which may need to be curtailed or restricted if there is no flexibility from DSR. The savings in OPEX are dominant in these studies, followed by the reduction in distribution network cost and then generation and transmission/interconnection capital expenditure. This can be expected as the energy cost contributes to 40%-60% in the energy bill followed by network costs, tax, etc.

Role of DSR in reducing carbon emissions

Since DSR affects the generation dispatch and enables higher utilisation of low marginal cost generation, it is expected that it will have an impact on the carbon emission performance of the system as well. The results of calculating the carbon emission in the different pathways with and without DSR are presented in Fig. 6.

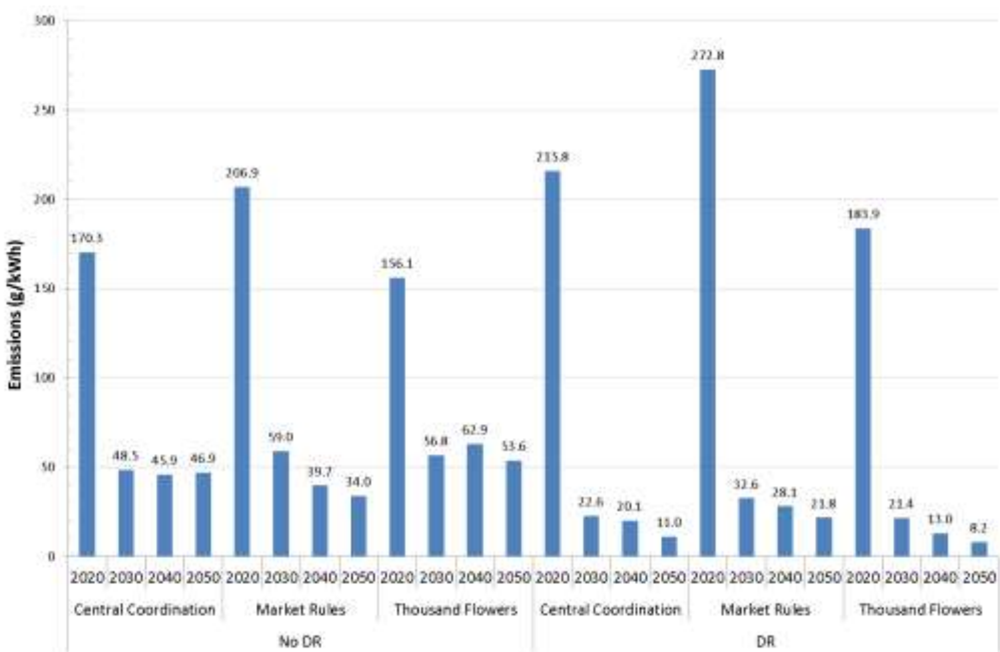

Fig. 6 Impact of DSR on carbon emissions in different pathways

The emissions in 2020 are generally higher in systems with DSR as the output of coal fired plant increases. Being a low marginal cost plant, as the carbon prices in 2020 are not sufficiently high to reduce the merit order of coal plant, the coal fired plant is utilised more in the system with DSR. This pushes an increase in carbon emissions.

As the carbon prices continue to increase in 2030 onward, coal is shifted to a higher place in the merit order dispatch and used as peaking capacity with low utilisation factors. Increased carbon prices increase the cost of high-content-carbon generators and make it unattractive to use. This leads to lower carbon emissions. As DSR also enables higher utilisation of RES and other low-carbon technology power generation, the emissions of the system are also reduced.

Economic performance of whole-system versus TSO and DSO centric based DSR applications

In order to simulate the DSO centric approach, the cost minimisation of distribution network reinforcement in WeSIM's objective function was prioritised. This means that DSR would be deployed first to reduce the reinforcement cost in the distribution network before it could be used for other purposes. Conversely, in the TSO centric approach, the cost of distribution network does not have any weight in the objective function and therefore the model will minimise the system cost from TSO's point of view ignoring distribution network cost. While in the whole system approach, all costs are considered in the objective function so the optimal balance across all investment and operation decisions can be achieved. Fig. 7 shows the benefits of DSR using the whole-system, TSO centric and DSO centric approach in different pathways in 2050.

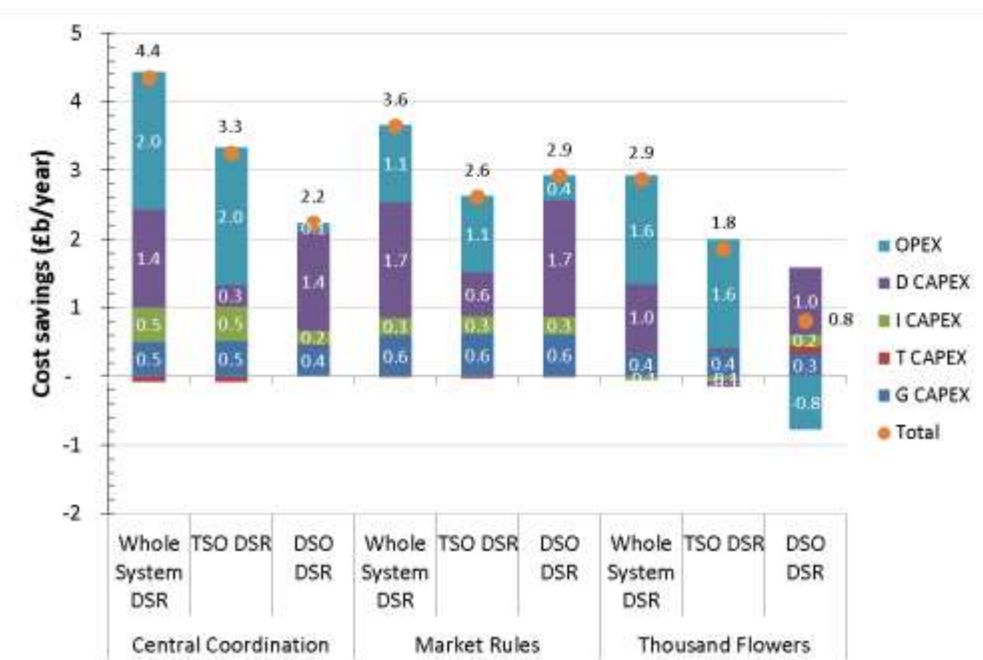

Fig. 7 Comparison between the savings attributed to whole system, TSO and DSO centric based DSR applications in different pathways in 2050

The results demonstrate that the DSO centric approach will prioritise the minimisation of distribution network cost and therefore it yields the highest savings in distribution network cost however at the expense of less optimal cost reduction in other sectors. Similarly, the TSO centric approach will prioritise the cost of system but ignoring the cost of distribution. This yields savings in OPEX, generation and transmission but at the expense of a suboptimal reduction in distribution network costs.

While the whole-system based DSR application is able to extract the maximum potential of multi DSR applications by synergising different applications of DSR and therefore, it is able to produce the maximum savings. This trend occurs in all pathways while the performance of TSO and DSO centric DSR varies in different pathways. For example, DSO centric DSR can save more in Market Rules than the TSO centric approach, but the opposite occurs in Central Coordination and Thousand Flowers. This is related to the peak demand in Market Rules in 2050, which is the highest one and therefore, the reduction of distribution network cost in Market Rules is the largest cost savings component.

Discussions

It is important to highlight that there is a large amount of uncertainty and paucity of data; amongst others, data regarding the future costs and the level of DSR available in the future. In addition to the uncertainty in the cost of distributed smart grid assets, including uncertainty in the cost and utilisation of investments in infrastructure, in the transactional costs of managing DSR customers, and in the potential costs of awareness raising and incentivising widespread uptake of DSR. Moreover, there are also potentially significant non-financial barriers. These include creating and implementing adequate policy frameworks for DSR, as well as the need for a much more mature supply chain than currently exists, both of which could require many years to progress. These non-financial barriers to the uptake of DSR will somehow add the real cost of enabling DSR.

The modelling and analysis in this paper do not attempt to incorporate the cost of enabling DSR with all its financial uncertainties; instead, it tries to evaluate the maximum potential benefit assuming DSR can be made available to the system. The tangible economic benefits of DSR quantified in the study may provide a high-level guidance on the maximum cost of DSR that can be justified. If the cost of enabling DSR, driven by not only the infrastructure but also the potential costs of incentivising customers exceeds the benefits, the cost will not be justifiable. Further studies will be required to estimate the real cost of DSR and to identify options to reduce its integration cost.

Conclusions

This paper describes the whole-system based model called WeSIM to quantify the benefits of demand flexibility (DSR) for different system transition pathways from 2020 to 2050. In contrast to the approaches which evaluate the benefits of various DSR applications in silos, WeSIM optimises the applications of DSR for reducing the system capacity (generation, transmission, and distribution) and operating costs simultaneously by balancing the long-term investment-related decisions against short-term operation decisions taking into account the flexibility provided by demand. The results of our studies using the three different pathways scenarios indicate that DSR can provide significant savings across all pathways. By 2020, the gross benefits are in the range of £1.2 – 2.9 billion per year while the value increases up to £5.6 billion per year by 2050. It is important to highlight that due to the uncertainties in many parts of the input data used by the model, the results of the study should be treated with caution as high level estimates which can be used as information for further studies.

The paper also demonstrates that the maximum potential of multi DSR applications can be achieved using the whole-system based DSR application. The benefits from the whole-system are considerably higher in comparison to TSO or DSO centric DSR applications. In order to realise this potential, coordinated control across DSO and TSO is a necessity. Further research in this area will be needed to solve this issue.

Acknowledgements

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