Imperial College London

Description of conflicts and synergies of MADE concept for distribution and transmission systems

MADE Briefing Note

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1. Introduction

Decarbonisation of the electricity system will require significant and continued investment in low-carbon energy sources and electrification of the heat and transport sectors. With diminishing output and shorter operating hours of conventional large-scale fossil fuel generators, there is a growing need and opportunity for distributed energy resources to contribute to the provision of system balancing and security services and support a cost-effective transition to a lower carbon energy system. Emerging smart technologies will open new opportunities for millions of users to participate actively in trading of electricity and various ancillary services through alternative mechanisms such as dynamic pricing, local energy markets, security markets, and peer-to-peer trading.

Links between various energy vectors, and in particular electricity and heat, will become stronger and much more dynamic than in the present predominantly natural gas-based heat supply. A higher degree of integration between electricity and other energy vectors, particularly heat and transport, presents novel and unique opportunities to make use of cross-vector flexibility to support the integration of low-carbon generation technologies and to significantly reduce the cost of decarbonisation. Previous analysis has also shown that various alternative heat decarbonisation pathways may be feasible, such as those based on heat networks, hydrogen, biogas, or electrified heating, each with their own cost implications and a rich set of interactions between energy vectors, opening opportunities to utilise the flexibility across multiple vectors.[1]

Quantitative evidence from recent studies strongly suggests that tapping into residential flexibility sources could unlock significant value for the system to support the decarbonisation of energy supply.[2] Nevertheless, there are significant challenges associated with efficient implementation of highly distributed flexible solutions at scale, as well as a clear need for more evidence from demonstrators and trials. Addressing this need is at the core of MADE project, which is looking to develop novel control concepts for efficient management of smart EV charging, smart hybrid heat pumps and other distributed energy resources. The outcome of the project is expected to provide insights into what types of solutions are needed to unlock the significant potential of demand-side flexibility.

This briefing note evaluates the potential conflicts and synergies associated with the provision of flexibility through decentralised sources in order to both support local network management and contribute to efficient operation and design of the national low-carbon electricity system. Decentralised flexibility could be provided by various means of customer-side resources such as smart transport and heating or distributed battery storage. Coordinated control approaches for these distributed smart resources represent the focus of MADE project trials.

The objective of MADE is to carry out a field trial with flexible domestic energy assets, including the necessary interventions, data monitoring and collection in order to study the impact of time-of-use tariffs and coordinated asset control on the overall household demand shape across different seasons. Of particular interest is the management of household peak demand, which represents a key driver for sizing the local distribution grid and investment in distribution network components. One of the main aims is to understand the potential interactions between

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1 Imperial College London, "Analysis of alternative UK heat decarbonisation pathways", report for the CCC, 2018.

2 OVO Energy & Imperial College: "Blueprint for a post-carbon society: How residential flexibility is key to decarbonising power, heat and transport", 2018.

smart EV charging, heat pump control, residential battery storage and rooftop solar PV generation.

Engagement of end consumers could be achieved through centralised or decentralised market approaches. While decentralisation would put consumers in the centre of decision-making processes regarding future system operation and development, an uncoordinated approach to decentralised dynamic pricing could lead to significant loss of demand diversity and demand response concentration, potentially leading to significant network congestion and supply shortages. Several illustrative quantitative studies presented in the document highlight the role and value of smart management of local flexible resources (e.g. through decentralised coordination), outlining the key challenges associated with balancing local, national and regional objectives to minimise the overall cost of decarbonising the future energy system.

2. Role and value of end-users' flexibility

While it is expected that the bulk of electricity in the future will be provided through large-scale investment in low-carbon technologies including renewables, and will flow from the transmission network towards the end users, the provision of flexibility and resilience will increasingly shift towards distributed flexibility sources provided by end consumers (Figure 1). Distributed generation, smart appliances, electric vehicles, heat pumps and energy storage technologies will transform passive consumers to active prosumers that may provide energy and flexibility services to both local and national systems.

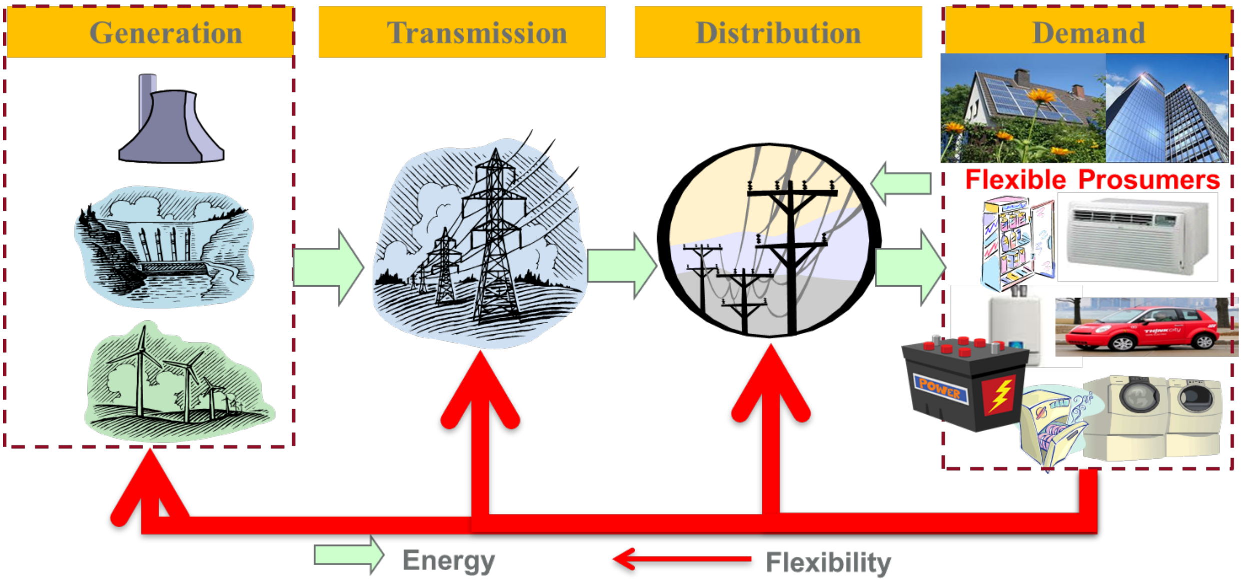

Figure 1. Energy flows from Grid to consumers while the flexibility flows from prosumers to the grid

By exploiting the flexibility of emerging distributed energy resources (DER), including demand-side response (DSR), flexible distributed generation, distributed energy storage technologies, etc., it will be possible to achieve very significant cost savings relative to a system that continues to rely on conventional generation to deliver flexibility and security of supply. This constitutes a paradigm shift from the traditional redundancy in an asset-based approach to the use of intelligence for providing resilience and security in future electricity systems.

In an assessment of the benefits of decentralised flexibility in the whole UK electricity system, our modelling results have demonstrated that alternative flexibility solutions can deliver cost savings between £3.8bn and £8bn per year, while meeting the future carbon intensity targets (100 gCO_2/kWh or 50 gCO_2/kWh), as shown in Figure 2.[3]

[3] The figure is taken from Imperial's 2015 report for the CCC ("Value of flexibility in a decarbonised grid and system externalities of low-carbon generation technologies").

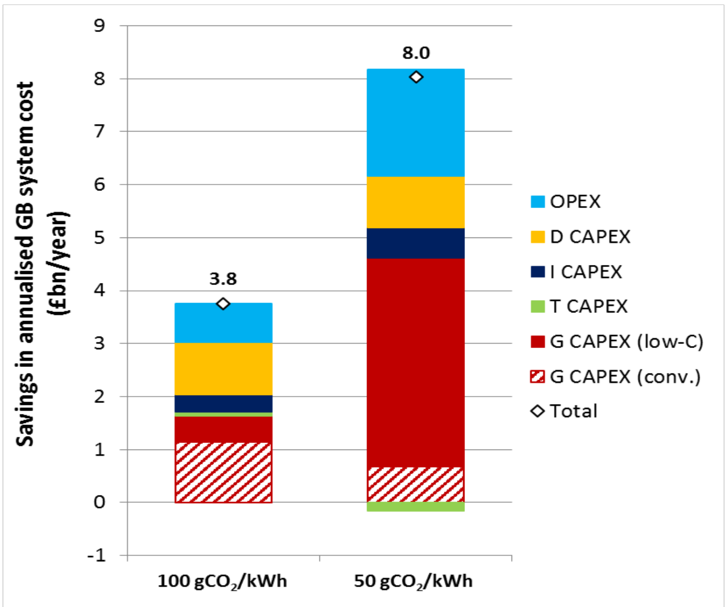

Figure 2. Gross system cost savings enabled by provision of decentralised flexibility across scenarios

As presented, the key components of gross cost savings delivered by decentralised flexibility resources include:

- Lower operating cost (OPEX) driven by avoided renewable generation curtailment, greater operating efficiency of conventional generation and more efficient provision of balancing services, respecting the reduction in system inertia.

- Reduction in network reinforcement, including Distribution (D CAPEX), Interconnection (I CAPEX) and Transmission (T CAPEX), enabled by reduced peak demand and enhanced utilisation of existing infrastructure;

- Reduced investment in low-carbon generation assets (G CAPEX, low-C) delivered through improved system operation and utilisation of renewable generation – note that these are the most dominant benefits of end-use flexibility due to high cost of low-carbon generation technologies, particularly carbon capture and storage (CCS) and nuclear.

- Reduced investment in conventional generation capacity (G CAPEX conv.) due to reduced system peak demand.

Given the very significant size of potential savings enabled by end-use flexibility, consumers should be allowed to modify their energy usage according to market forces. Our analysis suggests that in a future low-carbon electric system, the energy bill of a flexible consumer would be only 50% of the energy bill of an inflexible consumer, although they both would consume the same total amount of energy.[4] It is important to note that this will require integration of

[4] G. Strbac, D. Pudjianto, M. Aunedi, D. Papadaskalopoulos, P. Djapic, Yujian Ye, R. Moreira, H. Karimi, Ying Fan, "Cost-Effective Decarbonization in a Decentralized Market: The Benefits of Using Flexible Technologies and Resources", *IEEE Power & Energy Magazine*, vol. 17, pp. 25-36, March/April 2019.

wholesale and retail markets, with cost-effective, location-specific and time-varying prices of energy and ancillary services.

3. Managing synergies and conflicts between local and national system objectives

As demonstrated, the services delivered by flexible DER could bring very significant benefits to several sectors of the electricity industry, including distribution networks, transmission networks, and generation system operation and investment. However, energy supply, transmission, and distribution networks are operated by different entities with a level of coordination that is currently limited. Instead of using the DER-based services to maximise the whole-system benefits, individual entities tend to use these resources for maximising their own benefits, not considering the impact on other entities. Managing synergies and conflicts among the distribution network, transmission network, energy supply and EU-wide decarbonisation objectives when allocating DER flexibility will be critical for the optimal development of the system.

Interaction between DSO and ESO services provided through flexible DER will have both short-term and long-term perspectives. Both of these are discussed in more detail in this section.

3.1. Short-term interaction between flexible DSO and ESO services

Electricity price signals differentiated according to both location and time are generally seen as an efficient approach for coordinating a large volume of decentralised flexible resource. Traditional, centralised approaches for the coordination of flexible demand in electricity markets are subject to communication and computational scalability limitations, while raising privacy concerns from the consumers, who are generally reluctant to disclose private information and allow direct control by an external entity.

In view of these challenges, decentralised coordination approaches, based on dynamic pricing principles, have recently attracted significant interest, since these approaches drive demand response based on time-differentiated prices, without requiring centralised knowledge of the flexible loads' specific operating parameters.

However, a naïve application of dynamic pricing in combination with the envisaged automation in control of flexible loads may lead to a very significant loss of demand diversity and demand response concentration. At a high level, the demand shifting by flexible consumers can become highly concentrated during periods with lowest prices, potentially creating new demand peaks that could even exceed original levels of peak demand and thus causing network overloading and inefficient utilisation of electricity infrastructure. Such demand response concentration effects are illustrated in Figure 3, considering two examples with a) smart-charging of electric vehicles (EV) and b) wet appliances (WA) with delay functionality. In the first example, a 30% penetration of EV in the UK system is assumed and their flexibility is enabled through smart charging. In the second example all WA in the UK system are considered and their flexibility is reflected in the ability to delay their operating cycles by a maximum of 12 hours. The inflexible EV scenario assumes that EV start charging immediately after they are connected to the grid until they are fully charged, while the inflexible WA scenario assumes that their cycles cannot be delayed.

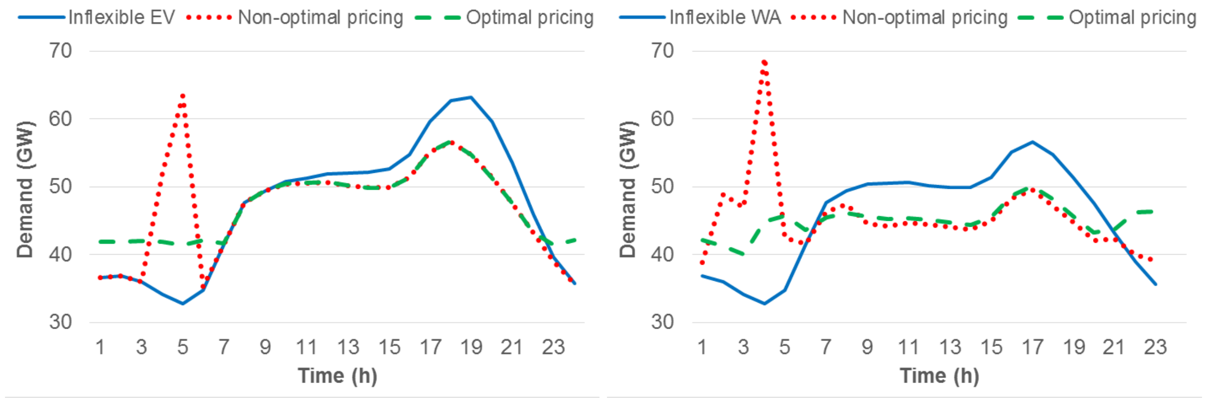

Figure 3. Performance of alternative strategies for the coordination of flexible EV (left) and WA (right)

Smart decentralised coordination strategies are therefore necessary in order to address the challenge of demand response concentration and utilise the full potential of flexible loads. In this context, alternative smart strategies have been assessed using a combination of measures (relative flexibility restrictions, penalising the extent of flexibility or randomizing the prices transmitted to flexible loads) in order to diversify their responses and discourage concentration of demand in the lowest-priced periods. Figure 3 illustrates the performance of these strategies in mitigating demand response concentration and shows that these approaches can avoid the issue of demand concentration and generating new peaks.[5]

3.2. Long-term interaction between flexible DSO and ESO services

It is evident that in order to achieve efficient outcomes from the whole-system perspective there will be a need for stronger coordination between system operators at both transmission and distribution levels. This coordination will enable the use of all available flexibility resources while managing synergies and conflicts across different networks. A whole-system approach will be required for both operation of the system and management of future networks at maximum efficiency. The modelling results in Figure 4 show that a whole-system-based network management approach may result in savings in system investment and operation cost that are approximately twice as high as the savings in the distribution-centric approach.

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[5] Details behind the modelling presented here can be found in:
D. Papadaskalopoulos, G. Strbac, "Decentralized Participation of Flexible Demand in Electricity Markets—Part I: Market Mechanism", *IEEE Transactions on Power Systems*, Vol. 28, pp. 3658-3666, November 2013.
D. Papadaskalopoulos, G. Strbac, P. Mancarella, M. Aunedi, V. Stanojevic, "Decentralized Participation of Flexible Demand in Electricity Markets—Part II: Application With Electric Vehicles and Heat Pump Systems", IEEE Transactions on Power Systems, Vol. 28, pp. 3667-3674, November 2013.

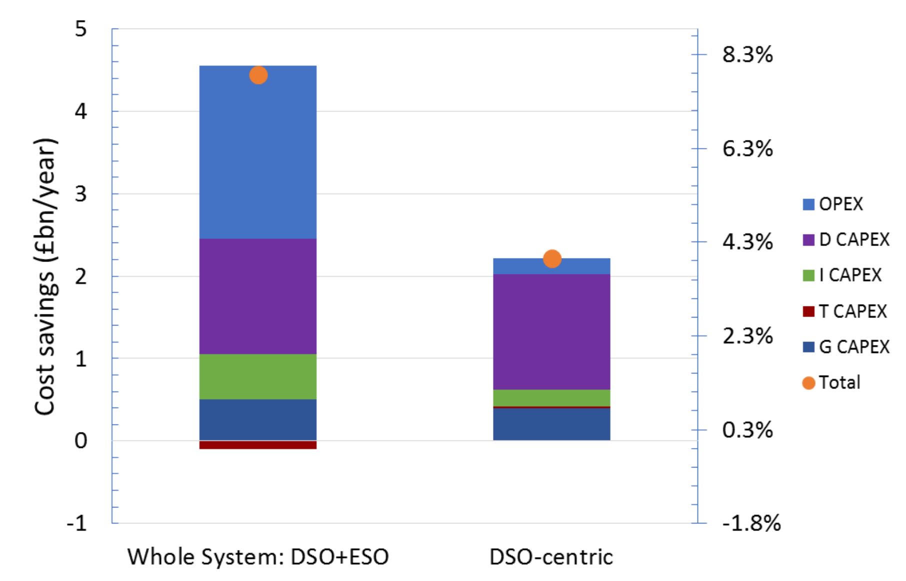

Figure 4. Potential benefits of improved transmission and distribution control interface. Right vertical axis shows cost savings relative to total system cost without added flexibility. DSO = Distribution System Operator, ESO = Electricity System Operator

In this case, the DSO-centric approach focuses on the use of DER for deferring distribution network investment by reducing peak demand, although this may not be optimal for transmission system operation and investment. In contrast, the whole-system approach would allow the DER to be used towards meeting both local and national infrastructure objectives by managing the synergies and conflicts between various DER applications. The whole-system approach is still able to deliver almost the same level of cost savings in distribution network cost as in the DSO-centric case, suggesting that only a minor compromise[6] on the distribution cost savings from using flexible DER can deliver significant additional savings in other segments of the power system. However, realising this additional potential requires close coordination between system operators, with clarity on their future roles and responsibilities, which would be achieved through a decentralised, fully cost-reflective market design.[7]

Figure 5 shows the total system cost differences between the solutions that optimise the utilisation of demand-side flexibility obtained by the whole-system and DSO-centric approaches assuming both inflexible and flexible generation systems (referring to the ramping, start-up and frequency regulation capabilities of conventional generators). In both cases, the whole-system solution is characterised by lower cost than the DSO-centric approach, which explains the net negative cost difference. The benefit of the whole-system solution is slightly larger in the inflexible system, highlighting the need to have a more intensive system coordination in the inflexible system.

In the case of inflexible system, the modelling demonstrates that the whole system would benefit from investment in distribution network reinforcement i.e. in upgrading high- and low-voltage distribution network assets (lines, cables and transformers). Such investment would

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6 The compromise refers to slightly higher cost of reinforcement of both LV and HV distribution networks.

7 G. Strbac, D. Pudjianto, M. Aunedi, D. Papadaskalopoulos, P. Djapic, Yujian Ye, R. Moreira, H. Karimi, Ying Fan, "Cost-Effective Decarbonization in a Decentralized Market: The Benefits of Using Flexible Technologies and Resources", *IEEE Power & Energy Magazine*, vol. 17, pp. 25-36, March/April 2019.

enable end-use flexibility to reduce the system operating cost and also reduce the corresponding generation CAPEX needed to reach the CO_2 target cost effectively. In this case, flexible consumers would be willing to pay for distribution network reinforcement, as the revenues from providing balancing services at the national level would be greater than the cost of distribution network reinforcement, which would reduce their energy bills.

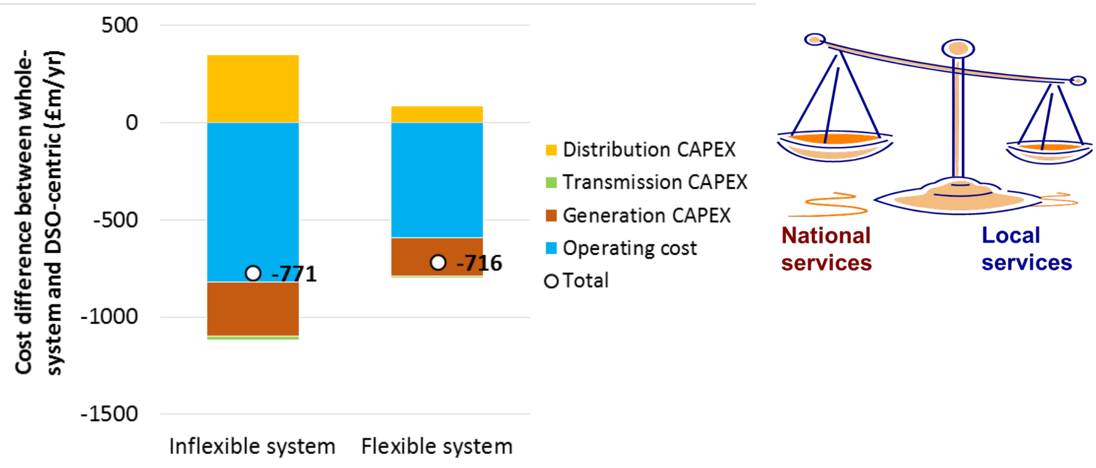

Figure 5. Impact of generation flexibility on the role and value of demand-side flexibility. Cost differences shown are between whole-system and DSO-centric approaches, for two flexibility levels of conventional generation fleet

On the other hand, in the presence of flexible generation and high level of interconnection with the EU that would provide national level balancing services, end-use flexibility resources should be primarily used to manage peaks and minimise reinforcement in distribution networks, while supporting balancing of demand and supply at the national level only when this activity would not conflict with local distribution network constraint management objectives.

From these studies, it can be concluded that it will be important to manage the synergies and conflicts between distribution networks, energy supply, and transmission networks when allocating DER flexibility. It will be essential to acknowledge the value of decentralised flexibility by incorporating it into electricity markets which provide cost-effective price signals, reflecting both national and local-level costs and benefits. Such decentralised flexibility resources with adequate access to national and local markets will enable consumers to make appropriate choices to facilitate cost-effective decarbonisation while reducing their energy bills.

3.3. Interaction between local flexibility, network infrastructure and national decarbonisation objectives

In a whole-system paradigm for investment and operation of the future low-carbon system it will be critical to utilise local flexible resources in order to strike the right balance between investment in the infrastructure and the investment required to meet the national carbon target. Figure 6 shows an example of this based on the earlier analysis carried out in the FREEDOM project[8]. The figure shows the whole-system benefits of using hybrid heat pumps (HHPs) quantified as total system cost savings against a counterfactual scenario with electric heat pumps (EHPs) in a future GB power system designed and operated to meet the carbon target

[8] https://www.westernpower.co.uk/projects/freedom

of 100 gCO_2/kWh at the lowest cost. To make the impact of HHP flexibility easier to distinguish, it was assumed that other flexibility technologies (DSR, energy storage etc.) are not available.

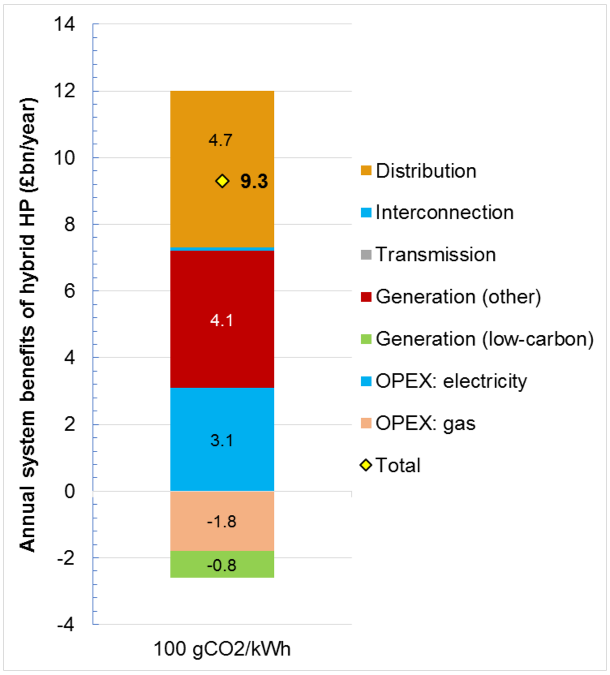

Figure 6. System-level benefits of hybrid heat pumps in the future GB power system with the carbon target of 100 gCO_2/kWh[9]

The components of system costs considered in this study included: (1) annualised capex of network reinforcement (distribution, interconnection, transmission); (2) annualised capex of generation investment distinguished between investment in traditional fossil-fuelled power plant and low-carbon power technologies including nuclear, CCS, and renewables (wind and PV); (3) operating cost of electricity including fuel, no-load, and startup costs of generators; and (4) operating cost of gas for heating. The cost of maintaining the existing gas network infrastructure, the cost of heating appliances and the cost of household conversion needed to accommodate EHPs or HHPs are excluded from this analysis.

The results show that the benefits of managing peaks by using gas rather than electricity to supply heat during system peak conditions are significantly larger than the increase in: (1) operating cost due to increased use of gas during peak demand conditions; and (2) additional investment cost in low carbon generation required to meet carbon target. These cost increases are more than offset by considerable savings in the cost of distribution network reinforcement, operating cost of electricity generation, and the overall generation investment cost (although the cost of low-carbon generation increases). The net cost savings quantified for this case were £9.3bn per year.

[9] Note that the benefits in this figure exceed those in Figure 2, given that this analysis additionally includes decarbonisation of heat and the flexibility provided by integrating electricity and heat sectors.

Cost savings are delivered by providing cross-energy vector flexibility enabling the switch between electric and gas heating to minimise the overall system cost; consequently, which results in substantial reduction in peak demand and hence requires much lower investment in network and peaking generation capacity required to meet the peak.

3.4. Illustrative case study: smart EV charging

Electric vehicles (EVs) are an essential element in decarbonising the road transport sector by replacing fossil fuel demand with low-carbon electricity. One of the key concerns for rapid electrification of road transport is the potential increase in peak demand that is disproportionately higher than the increase in energy.[10] However, EVs possess significant inherent energy storage capability, which opens up opportunities for utilising more efficient charging strategies, not only to optimise electricity generation and provide frequency regulation services more efficiently, but also to enhance the efficient usage of network capacity.

While flexible EV demand can be efficiently used to reduce peak loads and consequently improve network capacity utilisation and avoid increasing the local peak demand, it may also be desirable for flexible EV loads to respond to opportunities in the energy market and maximise their benefit by responding to time-varying energy prices. An example to illustrate the potential conflict between maximising the network and system operation benefits for the case of flexible EVs is given in Figure 7. The diagram on the left depicts optimised EV charging with the objective of reducing system peak. In the diagram on the right, however, the objective is to minimise system operation costs in a potential future situation where high wind generation output coincides with peak demand. In this supply-driven optimisation of EV charging, much of EV consumption is shifted towards the time around system peak to make full use of available wind energy.

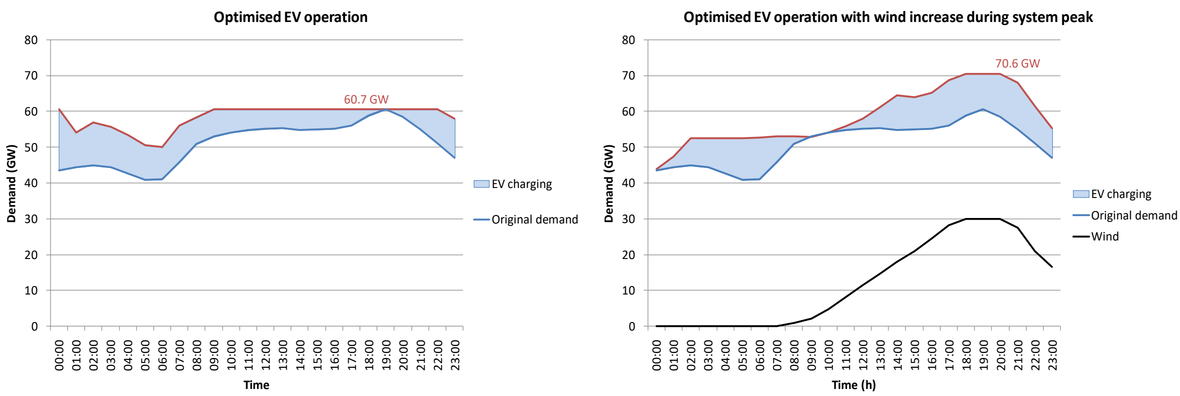

Figure 7. DSO-centric vs. ESO-centric EV charging management

If a large number of EVs are charged during peak hours, driven by supply price signals, the increased stress on the distribution networks could be significant. Imperial's earlier analysis showed that optimising EV charging purely to optimise energy supply may result in a much higher proportion of overloaded feeders (32% vs. 1%) and transformers (60% vs. 11%) than with the peak minimisation approach, which would also be reflected in appropriately higher network reinforcement costs. This simple example illustrates that independent operation of

10 Imperial's earlier assessments indicate that even with a 100% penetration of EVs in the UK's light vehicle fleet the increase in annual electricity demand would be 20%, while the corresponding increase in peak demand could be as high as 50% if EV charging is not managed.

the electricity market (based on “unconstrained” trading) without due consideration of distribution network limitations will potentially be suboptimal in terms of the overall efficiency (and therefore cost) of the whole electricity system. As discussed earlier in this section, a whole-system approach is needed to identify cost-optimal trade-off between using flexibility to meet local vs. national objectives.

4. Whole-system benefits of flexible DER

Substantial whole-system benefits of DER highlight the need to shift the system paradigm from isolated role of DNOs and ESO to "whole-system", in order to facilitate cost-effective transition to low-carbon energy future. This is further highlighted in this section using examples from Imperial's recent heat decarbonisation study carried out for the Committee on Climate Change[11].

Figure 8 shows the value of flexibility in different future heat decarbonisation pathways for the 30 Mt carbon target in the CCC study. Three heat decarbonisation pathways analysed in this study using the Integrated Whole-Energy System (IWES) model include: (i) Hydrogen, (ii) Electrification, and (iii) Hybrid pathways. The modelling considered 29 different cost categories, but for simplicity, the annual system costs are presented and grouped into five Capital expenditure (C) and two Operating cost (O) categories described as follows (these categories also explain the legend entries of Figure 8):

a. ***C: Electricity generation*** – annuitised capital cost of electricity generation that encompasses both low-carbon and non-low carbon generation.
b. ***C: Electricity networks*** – annuitised capital cost of the electricity network that consists of the cost of the distribution network, transmission network and interconnectors.
c. ***O: Electricity*** – annual operating cost of electricity that includes all the variable operating costs (e.g. fuel, O&M) as well as start-up, and fixed operating costs. Carbon prices are excluded from this analysis.
d. ***C: Electric heating + storage*** – annuitised capital cost of electric heating and energy storage in electric scenario includes the capital cost of the heat pump (domestic and industrial), resistive heating, electric storage, thermal energy storage, cost of end-use conversion (replacing gas-based heating to electric), cost of appliances and cost of decommissioning gas distribution due to electrification.
e. ***C: H2+CCS+P2G*** – annuitised capital cost of hydrogen and CCS infrastructure, including the cost of all hydrogen production technologies, cost of hydrogen and CCS networks, cost of hydrogen storage and carbon storage.
f. ***O: NG+H2+CCS*** – annual operating cost of the natural gas system that includes fuel cost of gas-based hydrogen production technologies, e.g. SMR and ATR, cost of hydrogen import, operating cost of hydrogen storage and the fuel cost of the natural gas (NG)-based boiler.
g. ***C: Non-electric heating*** – annuitised capital cost of non-electric heating includes the capital cost of natural gas (NG) and hydrogen-based boilers, cost of district heating infrastructure, conversion cost and the cost of maintaining the existing gas distribution network.

In the Hydrogen pathway, the heat demand is decarbonised using hydrogen as the primary source for heating while in the Electrification scenario the main heating source is based on electric heating (e.g. heat pumps and resistive heating). In the Hybrid scenario, the heat demand is supplied by both electric heating and gas boilers to meet high-temperature and peak of heat demand. One of the primary sources of flexibility involved in this study comes from the

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11 Imperial College London, "Analysis of Alternative UK Heat Decarbonisation Pathways", report for the Committee on Climate Change, August 2018, https://www.theccc.org.uk/wp-content/uploads/2018/06/Imperial-College-2018-Analysis-of-Alternative-UK-Heat-Decarbonisation-Pathways.pdf.

distribution level in the form of controllable loads (e.g. EVs, smart appliances) and various forms of energy storage including battery energy storage, thermal storage and the use of building thermal inertia to enable load shifting of heat demand (e.g. by preheating).

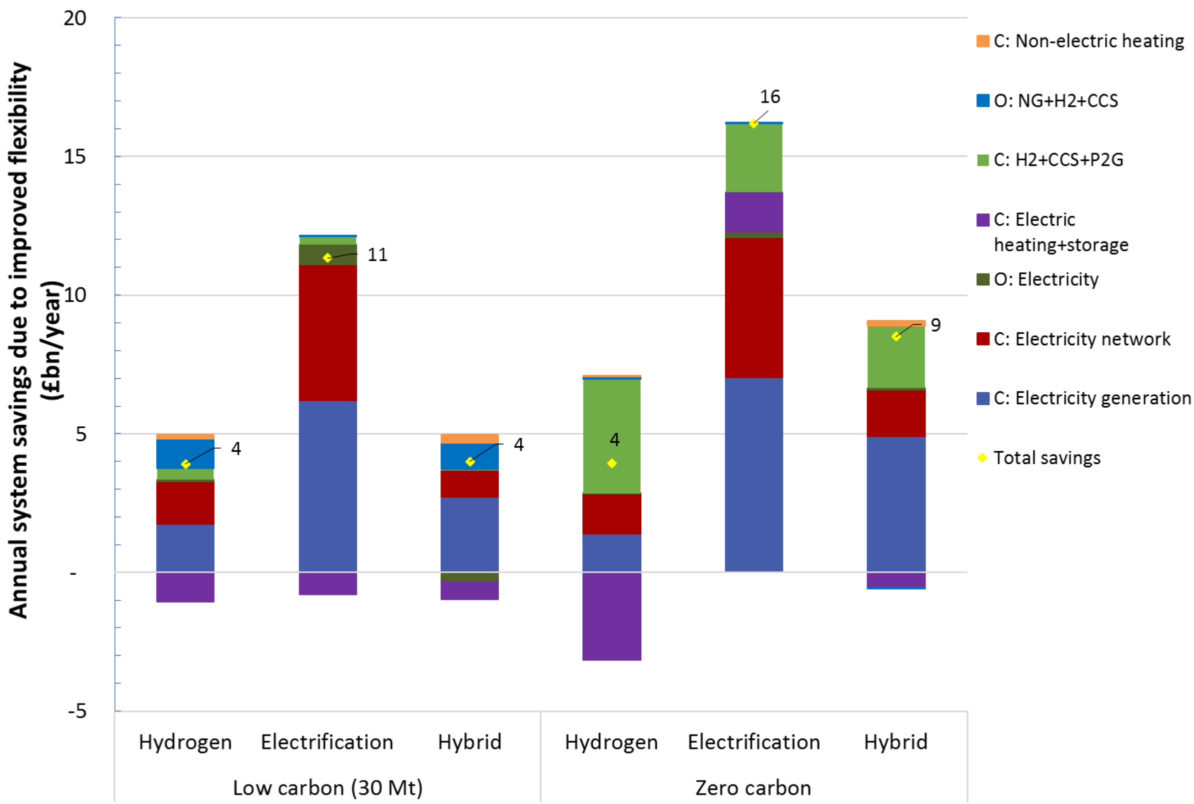

Figure 8. Value of flexibility in 2050 under different energy heat decarbonisation pathways

By comparing the cost of a flexible system with the cost of an inflexible system, the results demonstrate that by improving flexibility in the 30 $MtCO_2$/year scenario the total system costs can be reduced by between £4bn and £11bn per year. The results provide evidence that the benefits are not only related to savings in network assets (interconnection, transmission, and distribution) but also to savings in power generation capex, capex of other low-carbon technology infrastructure such as hydrogen, and operating cost of both electricity and gas sectors. For example, in the low-carbon (30 Mt) Electrification scenario, by having a system with high flexibility, the savings in electricity network (mostly at distribution level) are around £4.9bn/year, while the savings in the capex of electricity generation are even higher at £6.2bn/year. The flexibility also reduces the operating cost of the electricity system (by £718m/year) and the cost of hydrogen infrastructure to support the decarbonisation of the energy system. To achieve these savings, additional investment cost in flexibility (such as storage) will be justified; this is shown as negative savings in Figure 8. It is also worth highlighting that the benefits of flexibility will increase to more than £16bn/year (in the Electrification scenario) in the zero-carbon system.

While the current regulatory framework has acknowledged the innovation and efficiency in distribution network management to reduce the cost of the distribution system, the value of DSO in reducing the whole-system cost of low-carbon energy system needs to be explicitly recognised and rewarded. It is important to highlight that the savings in low-carbon generation capex can exceed the cost savings in networks, as shown in Figure 8.

The value of flexibility also varies across different heat decarbonisation strategies. The value is much higher in the Electrification scenario compared to the other two scenarios. Heat electrification will double the annual electricity demand and increase the peak demand from the current level of around 60 GW to more than 180 GW if there is no flexibility in supplying heat demand, which leads to high requirements for new electric infrastructure capacity to maintain the system security and supply reliability standards. Flexibility in supplying heat demand, e.g. by preheating and/or using heat storage can reduce the peak demand substantially. Requirements for new electricity infrastructure will be much less in the Hydrogen and Hybrid scenarios since their peak demand is covered using the gas infrastructure relieving the stress in the electricity system. This explains why the value of flexibility in the Electrification scenario is much higher than the value of flexibility in the other two heat decarbonisation pathways.

The ranges of cost savings obtained by optimising the use of flexibility using the whole-system approach for different system components (as shown in Figure 8) are summarised in Table 1.

Table 1. Value of whole-system benefits of flexibility services from distributed energy resources (ranges reflect results in different heat pathways)

	CAPEX savings		OPEX savings		
GB Value (£bn/year)	Generation	Electricity Network	Electricity system	Others	Total
Whole-system flexibility	1.4-7.0	0.9-5.0	(-0.3)-0.7	(-0.5)-3.9	3.9-16.2

The values are expressed in £bn/year and encompassed the benefits for the GB energy system. A negative value means that there is an additional cost to the system. The CAPEX savings of generation includes the savings from all generation technologies including nuclear, offshore and onshore wind, PV, gas plant with CCS, hydrogen-based power generation, hydro, combined heat and power. CAPEX savings of electricity network includes the savings from interconnection, transmission, and distribution costs. OPEX savings of electricity system contains the savings in the operating cost of the electricity system, and “Others” includes all other savings from Figure 8.

5. ESO-DSO coordination and control of flexible DER

The current model of contracting transmission services from DER does not allow a substantial operational (and planning) coordination between ESO and DSO as the involvement of the local network operator is considered minimal. ESO makes a direct contractual arrangement with DER or aggregators without strong coordination with DSO. This practice works well when the volume of DER service is considered small and does not affect the operation of the local network. However, increased capacity and participation of DER to provide ancillary services to transmission as well as rolling out of the active distribution network management requires a fundamental review of the current model because of the following reasons:

- In an active network, the utilisation of DER may be constrained due to the requirement to manage the local network. This implies that DSO may need to adjust their operating conditions to enable more access for DER to provide transmission services;

- There is a need to have the synergy of using the local DER for both transmission and distribution network services and to prevent conflicts caused by different objectives applied by different users of DER services.

In this context, a potential future model (in the right-hand diagram of Figure 9) envisages a stronger interaction between ESO-DSO and more active roles for DSO in enabling access for DER to ESO's ancillary services while at the same time using the services for managing distribution constraints.

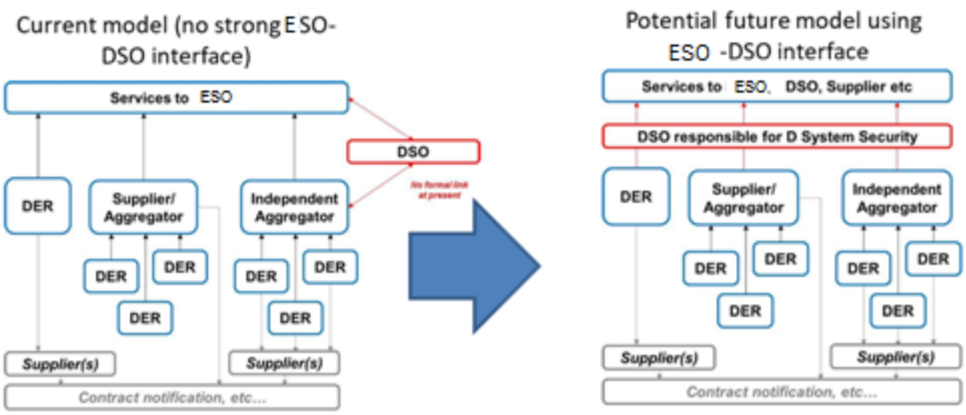

Figure 9. A potential future model of ESO-DSO interface[12]

In the future model, DSO may have a central role in providing the interface between ESO, DER and an independent aggregator. This framework allows DSO to maximise the value and system benefits of DER by enabling DER to provide both distribution and transmission services as well as facilitating DER to access energy market. DSO will also have a role in providing aggregated information to ESO on the volume of DER that can be accessed by ESO. This information is not static but dynamic following the changes in the DER availability and local system conditions. An outage at distribution may have a significant effect in reducing the volume of DER that can be accessed by transmission and DSO would be the best entity to capture this effect and provide such information to ESO.

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12 Source: ENA's report on the Commercial Principles for Contracted Flexibility which assumes that DSOs have a range of contracts with DER for distribution network management purposes.

Operational challenges arise as the use of DER by different operators (i.e. DSOs and GB ESO) may trigger conflicts between serving the local or national objectives. Operational planning coordination will be required to maximise the synergy of using the distributed resources to provide multiple services. In order to maximise the access of DER for transmission, DSO may need to operate differently within the statutory limits as the current practices may impose a constraint on the usage of DER and hinder full access of DER to provide transmission services. For example, it has been demonstrated that sub-optimal voltage management might constrain the use of the DG capacity for providing frequency response or reserve services, especially during the low-demand period due to voltage limits. Improving voltage management by optimising the tap setting of distribution transformers can help relieve the 'latent' capacity of the DG so it can be used entirely to provide ancillary services needed by the system when needed. The proliferation of Distributed Energy Resource Management Systems (DERMS) and Active Network Management (ANM) systems on DNO networks where all the network data, schedules and information are available, provides the infrastructure to effectively optimise the distribution network and provide services to ESO in a coordinated fashion.

In this context, the DSO will need to start optimising their distribution system management not only for DSO's objective but also to enable ESO to access DER resources cost-optimally while considering distribution network constraints. The use of DER to serve the overall system objectives (both transmission and distribution) will lead to the overall optimal solution for the whole system. The use of DER services to support transmission is being trialled in the UK (e.g. in the Power Potential project, which is trialling the use of distributed reactive power sources to support the South East region of the GB transmission system) but the benefits of the approach on the GB system have not been quantified yet. However, considering that the sources of flexibility to support the future electricity system will be shifted to distribution systems, further research and trials will be required to examine this approach more carefully.

6. Conclusions

Flexible technologies and resources are crucial for delivering cost-effective decarbonisation of electricity systems. Flexible DER such as demand-side response and energy storage are increasingly emerging at the local (distribution) network level, which stresses the need to develop decentralised control approaches to coordinate the actions of potentially many millions of prosumers. Dynamic pricing, local energy markets, and peer-to-peer trading will change the traditional power sector paradigm where electricity is procured by a small number of suppliers, and instead open up opportunities to a very large number of smaller players for trading locally, regionally, and internationally. Smart decentralised coordination of flexible DERs can avoid issues related to loss of demand diversity and provide a basis for cost-effective trading.

At present, the actions of flexible DER tend to focus more on local district or national level markets, while not directly facilitating cost-effective decarbonisation of the entire energy system. Appropriate policies and commercial frameworks should be developed in the future to reflect the impact of their decisions on wider-system costs, which will require integration of wholesale and retail markets, with location-specific and time-varying energy prices, fully reflecting the actual cost of providing both energy and ancillary services (time and location specific). A full coordination between local, regional, national and international level objectives will be necessary to maximise whole-system benefits of flexible resources, which is a major challenge for future market design.

The role and responsibility of DSO will need to evolve to efficiently ensure access for DER to provide transmission-level services, which will require the development of a commercial framework that adequately remunerates these services. The capability of DER to provide services to the ESO will vary dynamically according to the conditions in the local distribution network, and therefore real-time monitoring and active management of the network will be required.

Smart home-energy management system trialled in MADE could potentially support both the management of distribution-level constraints as well as transmission-level constraints. Given the growth in conflicting objectives with respect to using flexibility at transmission and distribution level, it will be important to demonstrate the ability of MADE smart control concept to deliver services both locally and nationally through close coordination between ESO and DSO-level control.

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