Role and value of flexibility in facilitating cost-effective energy system decarbonisation

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Abstract

Decarbonisation of the electricity system requires 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 other emerging technologies to provide flexibility in the context of grid support, balancing, security services, and investment options to support a cost-effective transition to a lower-carbon energy system. This article summarises the key findings from a range of studies investigating the potential benefits and challenges associated with the future low-carbon energy system. The key challenges associated with balancing local, national and regional objectives to minimise the overall cost of decarbonising the future energy system are also discussed. Furthermore, the paper highlights the importance of cross-energy vector flexibility, and coordination across electricity, heat, and gas systems which is critical for shaping the future low-carbon energy systems. Although most of the case studies presented in this article are based on the UK, and to some extent the EU decarbonisation pathways, the overall conclusions regarding the value of flexibility are relevant for the global energy transition.

1. Introduction

Future energy systems are expected to undergo a fundamental transformation over the next couple of decades in response to increasingly ambitious energy sector decarbonisation targets [1]. Environmental issues, such as climate change and local air pollution, represent a major driver for a rapid increase in the share of renewable energy expected in future energy systems. For instance, the International Energy Agency (IEA) envisages that many countries may reach 100% renewable energy supply by 2050 [2]. Wind and solar-based technologies are the most promising options to produce energy from renewable sources due to their widespread availability, efficiency, and progressively decreasing cost. However, these sources are also associated with challenges due to their intermittency and output variability given their dependency on weather conditions [3].

Renewable sources, particularly wind and solar, have seen their cost reduce substantially over the past decade, as shown by the International Renewable Energy Agency (IRENA) [4]. The cost of electricity from wind farms and solar photovoltaics (PV) in 2020 has decreased to a level that is comparable to fossil fuel-fired power plants, i.e. to 0.049 kWh⁻¹ and 0.055 kWh⁻¹, respectively. Improvements in technology and manufacturing processes, regional manufacturing and a competitive market are the main reasons that have contributed to decreasing costs of these technologies. The considerable cost reduction of wind generation has been achieved by increasing rotor diameters and the capacities of individual turbines, while the cost reduction in solar PV was mainly through the development of crystalline cells. Driven by the reduced cost of renewables, the U.S. National Renewable Energy Laboratory (NREL) has projected that the U.S. share of renewable energy generation in 2050 will increase between 30% and 90% [3]. Some of the challenges of integrating such high volumes of variable renewables will include greater voltage and frequency fluctuations.
Different approaches, such as developing novel power electronic solutions or control strategies, have been proposed for regulating grid frequency [5]. For instance, fast frequency response of some wind turbines (e.g., type 4 wind turbine generators with full converter [6]) can impact the frequency of an area [7]. Moreover, a frequency control strategy can be devised considering the kinetic and mechanical power of wind turbine to provide frequency regulation support [8].

Another approach that could contribute to carbon neutrality is to employ net negative emission technologies, such as capturing the CO$_2$ from biomass-fired electricity generation with carbon capture and storage (BECCS) or through direct air capture (DAC) technologies [9]. At present, DAC is an expensive technology, however, some projections forecast its cost to drop below 60/tCO$_2$ in 2040 [10]. On the demand side, the proportion of electricity demand used for charging electric vehicles (EVs) in Europe is forecasted to grow from less than 0.05% in 2010 to almost 10% in 2050 [11], as part of the target to reduce EU’s greenhouse gas emissions by 80%–95% by 2050 [12]. At present, the energy required for heating and cooling residential and commercial buildings in Europe is mostly supplied through fossil fuel-based technologies, resulting in significant carbon emissions. For instance, in the EU, almost half of the total energy consumption is for cooling and heating systems, with 82% of that amount delivered through fossil fuels, which is obviously in contrast with the climate change objectives of the Paris agreement. To mitigate the environmental footprint, electrification of cooling and heating sectors is considered by many countries, which will also lead to a considerable increase in electricity demand [13].

There is a substantial body of literature exploring the technical feasibility and economic viability of 100% renewable pathways for decarbonising electricity generation. A comprehensive overview of relevant publications is provided in [14]. Heard et al express concerns regarding the feasibility of achieving a 100% renewable electricity system, stating that most of the relevant studies do not meet the criteria of consistency with energy demand forecasts, reliability and resilience, transmission and distribution network requirements and the provision of essential ancillary services [15]. On the other hand, Brown et al respond to these concerns by identifying existing low-cost solutions from available literature that make high-renewable systems technically feasible and economically viable [16]. In addition to the technical feasibility of 100% renewable power systems, heavy reliance on exploitation of hydroelectricity and biomass also raises concerns regarding environmental sustainability and social justice. Oyewo et al present a number of issues associated with the development of a very large hydroelectricity project proposed in Congo, including its exaggerated benefits, marginalised environmental concerns, underestimated risks for weak local economies, as well as financial risks, cost overruns and schedule spills that are typical of building very large dams [17]. The authors argue that Sub-Saharan Africa can be more economically powered by a mix of solar PV and wind energy supported by batteries. Bogdanov et al make the case for a technically feasible and economically viable evolutionary change towards a 100% renewable electricity system globally by 2050, arguing that low cost of renewables and energy storage (ES) will displace fossil fuel-based electricity, with solar PV becoming the dominant source of electricity, albeit subject to country-specific variations [1]. Jacobson et al develop Green New Deal energy roadmaps for 143 countries that represent a 100% transition of energy supply to wind-water-solar energy, efficiency, and ES by 2050 [18]. The roadmaps are shown to require less energy, cost less, and create more jobs than a business-as-usual approach. Benefits of designing a 100% renewable electricity sector by 2050 across a larger area (such as the whole of Europe) with stronger interconnection links rather than at a smaller-scale regional level are presented by Child et al in [19], although the benefits of a 100% renewable transition over the current levelised cost of electricity are shown to exist regardless of the geographical scale considered.

As part of the EU’s efforts to decarbonise energy, distributed generation has been gaining attention, in particular through utility-scale wind and solar systems that are directly connected to the distribution system, reducing transmission losses and air pollution [20]. The increasing share of distributed renewable energy sources (RES) will require enhanced grid flexibility to ensure cost-efficient integration, such as through smart grid solutions [21]. The future electricity network is therefore expected to be more decentralised and complex in comparison with the current situation. Traditional control systems and technologies are not well suited to support the shift from centralised to decentralised electricity network paradigm. To address that, NREL has implemented the ‘Autonomous Energy Grid’ in its laboratory to ensure that decentralised future grids can efficiently manage bi-directional energy flows and uncertainties associated with distributed renewable energy systems. ‘Autonomous Energy Grid’ consisted of group of microgrids with a variety of communication and control solutions that could adjust demand, generation, and local energy pricing [22]. New sources of flexibility will be required to support this paradigm, such as developing ES systems that can be employed to store the excess output of renewable energy generators and release it during periods of peak demand [23]. With ever-growing share of renewable energy resources, ES systems are expected to play a crucial role in balancing energy supply and demand, especially given the rapidly reducing cost of ES systems (especially battery storage) seen over the past decade. It is predicted that the global installed storage capacity
Figure 1. An illustrative example of a more challenging balancing requirement driven by future renewable electricity production and demand patterns which indicates a higher requirement for operational flexibility in the future.

will increase to more than 14 TWh by 2026 [24]. Also, electricity and gas networks can be coordinated to benefit from the network’s capability to store renewable or natural gas. Another integrating solution is the production of hydrogen through electrolysis, which can also be used to store excess energy from renewable generation [25].

Demand response is another source of flexibility in energy systems that enables managing the variations in demand in order to increase the efficiency of energy supply. Traditionally, only supply-side resources have been assumed to provide flexibility in energy system planning. Going forward, however, demand response should be considered in system design and operation given the variability and intermittency of renewable energy resources and their effect on the reliability of the system. Furthermore, demand response could also lead to cost savings by reducing peak demand, which will also reduce network and generation capacity required to meet that peak. NREL examined the value of demand response in Florida while considering a high penetration of solar PV systems, and concluded that demand response could operate similarly to a gigawatt of battery capacity, delivering cost savings of between $76 m to $259 m for different PV penetrations [26]. Ali, et al discuss the significant role of demand response in supporting the 100% renewable system in Australia, specifically through load shifting of electric water heaters [27].

While there are many possible configurations of energy supply and demand that deliver carbon emission reductions, any future low-carbon energy system is likely to be characterised by: (i) a much higher penetration of low-carbon generation with a significant increase in variable renewable sources and increase in load due to electrification of transport and segments of heating sectors; (ii) growth in the capacity of distribution-connected flexibility resource; (iii) an increased ‘flexibility’ requirement to ensure the system can efficiently maintain secure and stable operation; (iv) opportunities to deploy ES facilities at both transmission and distribution levels; and (v) expansion in the provision and use of demand-side response (DSR) across all sectors of the economy.

Delivering on the desired energy decarbonisation targets will require investment in a portfolio of low-carbon technologies, and an increase in the provision of flexibility services to enable the cost-effective integration of the new system [28, 29]. Delivering the required level of flexibility requires the development and deployment of innovative technologies and the emergence of new business models and service offerings.

Figure 1 shows an illustrative snapshot of the hourly net demand profile (i.e. system demand minus intermittent generation) for a typical winter week using a future Great Britain (GB) scenario [30]. A key observation is that the net demand becomes more volatile and often peakier with shorter durations of peak demand in the future than today. This leads to a need for a very steep ramping requirement in power—i.e. an increase as well as a decrease in power generation or demand from dispatchable resources (demand or generation) in the system.

In this case, the steepest ramp requirement is found when the morning demand pick-up coincides with a large reduction in the output of renewable generation. For safe operation of the system, a large number of dispatchable generators need to be synchronised to be able to meet this ramping requirement to maintain demand-supply balance in the system.

Figure 1 also shows that the minimum net demand levels which occur during a low demand period coincide with the high renewable output. The minimum net demand approaches zero, indicating that the
Figure 2. Potential wind generation curtailment in the UK as a function of installed wind capacity if the existing approach to balancing is maintained (for comparison, the current UK system peak demand is about 62 GW).

Figure 3. Degradation in fossil-fuelled capacity factors in the UK systems in the low-flexible system) counteract by flexible technologies. Capacity factors are expressed for aggregate fossil fuel generation capacity.

entire system demand is supplied by renewables during such periods. However, such conditions create a challenge in power system operation since renewables such as wind and solar PV do not contribute to the system inertia and are not the primary providers of frequency response or regulation.

Therefore, there are fundamental effects responsible for the additional system costs that are associated with low-carbon energy systems, i.e.:

1. Reduced efficiency of system balancing. The need for balancing services at high penetration of variable renewable generation will increase significantly above historical levels. The anticipated lack of flexible fossil-fuelled generating units may reduce the ability of the system to accommodate variable renewable and base-loaded nuclear generation and lead to the curtailment of renewable output. As demonstrated in figure 2, increased levels of penetration of wind generation (shown here for the case of the UK) may lead to significant curtailment if system balancing is provided by the present fossil-fuel generation characterised by limited flexibility. Increased curtailment of renewables could also compromise meeting carbon reduction targets and significantly increase overall system cost. Hence, the future lower-carbon energy system will benefit from flexibility technologies. Note that this example represents an extreme case of high wind capacity being added onto the system in a non-optimised manner, without any improvement in the flexibility of system operation.

2. Degradation in the utilisation of generation infrastructure. Intermittent renewable generation displaces the energy produced by conventional fossil-fuelled plants; but its ability to displace the capacity of the
conventional plant is substantially limited without flexible technologies, leading to increase in generation capacity margins and reduced utilisation of conventional generation (figure 3).

Furthermore, the electrification of segments of the heat and transport sector represents a major challenge as the increase in peak demand may be disproportionally higher than the corresponding increase in energy. The surge in peak demand will also potentially require very significant reinforcement of the generation and network infrastructures. The combination of a lower system load factor and need for higher capital investment in infrastructure would increase the total electricity system costs of supplying the additional electrified heat and transport sector demand.

2. Flexibility technologies and services

System flexibility, i.e. the ability to adjust generation or consumption in the presence of system constraints to maintain a secure system operation for reliable service to consumers, will be the key enabler of this transformation to a cost-effective low-carbon electricity system. There are several flexibility resource options available, including highly flexible thermal generation, ES, DSR and cross-border interconnection to other systems [31–33].

System flexibility has two-time dimensions: (i) operational dimension—i.e. the use of resources, both energy and ancillary services, to ensure efficient and secure system operation [34, 35]; and (ii) capacity dimension—i.e. maintaining the long-term capacity requirement of the system [36, 37].

The two dimensions of flexibility are complementary—for example, ES supports maintaining demand-supply balance during system operation, and it can also reduce system peak demand lowering the need for generation and network capacity in the long-term.

Technologies that can provide system flexibility can be classified into four main categories, i.e.:

- Flexible generation: advances in conventional generation technologies are enabling them to provide enhanced flexibility to the system. This is due to their ability to start more quickly, operate at lower levels of power output (minimum stable generation), and achieve faster changes in output [38].
- Cross-border interconnection: interconnectors to other systems enable large-scale sharing of energy, ancillary service and back-up resources [39].
- Demand Side Response (DSR): DSR schemes can re-distribute consumption and engage demand-side resources for system balancing to enhance system flexibility without compromising the service quality delivered to end customers [40–42]. These schemes have significant potential to provide different types of flexibility services across multiple time frames and system sectors, from providing primary frequency response to facilitating network congestion management.
- Energy storage: ES technologies have the ability to act as both demand and generation sources. These can contribute substantially to services such as system balancing, various ancillary services and network management [39, 43].

Flexibility is also seen as critical by Child et al, who find that a 100% RE system appears achievable and cost-competitive for Europe by 2050 provided that there is a substantial increase in interconnection and ES capacity and the use of flexible renewable generators such as hydro and biomass [19]. Another option that can be acceptable to support system balancing is allowing renewable output curtailment, as long as the curtailed volume is kept low [44].

In addition to the above-mentioned flexibility providing technologies, there is significant potential for the power sector to access the flexibility embedded in other energy sectors, particularly the heat [45] and gas [46, 47] sectors (e.g. flexible gas compressors).

Additional flexibility can be categorized into the following:

- arbitrage services that allow load management and participation of ES in the day-ahead energy market;
- balancing services to ensure the supply-demand balance in real-time; this includes frequency regulation services which can be grouped into primary, secondary, and tertiary frequency regulation services depending on its activation time;
- contribution to meeting peak demand to reduce the need for peaking plant;
- network support by enabling better network congestion management which consequently reduces the need for network reinforcement;
- flexibility supports meeting carbon targets while minimising the need of low-carbon generation;
- option value which provides flexibility to deal with uncertainty.
3. Value of flexibility

There are several alternative options for delivering the necessary flexibility in a decarbonised energy system. 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 4) [48]. Distributed generation, smart appliances, EVs, and ES technologies will transform passive consumers into active prosumers that may provide both energy and flexibility services to both local and national systems.

By exploiting the flexibility of emerging distributed energy resources (DER), including DSR, flexible distributed generation, distributed ES 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 intelligent control in providing resilience and security in future electricity systems.

To a greater or lesser extent, by exploiting new sources of flexibility, there is the potential to realise significant cost savings associated with:

- Avoidance of energy curtailment from low-carbon generation sources: a lack of operational flexibility limits the system's ability to accommodate output from intermittent renewable technologies, particularly during periods when low demand conditions coincide with high output from wind and solar sources. The presence of system flexibility sources such as ES facilities DSR or interconnectors can absorb/export surplus generation in the system, thus avoiding energy curtailment and associated costs [49, 50]. Although flexibility is critical for avoiding excessive and inefficient curtailment of variable renewable output from technologies such as solar and wind, it is important to note that when it comes to renewable output curtailment there is a trade-off between reducing the curtailment level beyond a certain point by e.g. enhancing flexibility and the total system cost [44], suggesting that moderate levels of curtailment can be tolerated in cost-efficient, highly renewable systems.

- Efficient provision of operating reserve and response related balancing services: the provision of the operating reserve to the system by flexibility technologies (i.e. storage, DSR and interconnection) increases the ability of the system to absorb low-carbon electricity. It reduces the need to maintain the thermal plants at a minimum stable generation with associated impacts on carbon emissions and operating costs due to efficiency losses.

- Potential savings in generation capacity: new service providers may reduce overall generation capacity on the system due to:
  - Reduced need for low-carbon capacity in the system: reductions in energy curtailment will result in increased utilisation hence lower the capacity of low-carbon generation to meet the decarbonisation targets.
  - Peak reduction: electrification of heat and transport will increase peak electricity demand very significantly. However, system flexibility in the form of ES or DSR can reduce system peak by redistributing demand from high demand to low demand periods. This reduces the amount of required generation capacity in the system (particularly the peaking plant capacity).
  - Reduced need for back-up capacity: ES, DSR and interconnection, can reduce the need for back-up generation capacity required to support the intermittent generation.
Figure 5. System cost savings due to alternative flexibility provision across future UK energy development scenarios with different carbon targets [30].

- Deferral or avoidance of network reinforcement/addition: in addition to the network capacity savings driven by lower generation capacity requirements (as described above), additional network capacity savings are possible by deploying flexibility to manage network constraints and reassessing the need for network reinforcement in conjunction with innovative network planning and operation standards.

The results of our modelling analysis [30] demonstrate that alternative system flexibility solutions for meeting the UK 2030 carbon intensity target (100 gCO₂ kWh⁻¹) can save up to £4.7 bn yr⁻¹. The savings are obtained from the reduction in system capacity requirement (low-carbon generation, conventional generation, transmission, interconnection, distribution assets) and lower operating cost (due to energy curtailment avoidance, CO₂ cost savings, and reduced fuel usage) as shown in figure 5 [30] for different scenarios.

The results also show that the savings due to increased system flexibility are higher in scenarios with large penetration of intermittent generation (High Wind or High PV scenarios). This is because the volume of additional system flexibility becomes more pronounced in such systems compared to a system that also contains non-intermittent low-carbon, nuclear and CCS, generation (e.g. the Balanced scenario). The increased levels of flexibility services, from ES and/or DSR, enables more efficient management of demand-supply balance by time-shifting the surplus intermittent generation or demand. This avoids curtailment of solar and/or wind energy as well as reducing the need for their generation capacity resulting in higher savings in operational expenditure (Opex) and capital expenditure (capex) respectively.

Moreover, a more ambitious carbon reduction target (50 g CO₂ kWh⁻¹) would see a further increase the value of flexibility (up to £7.8 bn yr⁻¹) in this case as the system would need to accommodate more low-carbon generation.

3.1. Flexibility enables higher penetration of variable low-carbon generation

Studies carried out in [51] using the carbon target as illustrated in figure 6 demonstrated that flexibility is the key enabler to reduce the generation capacity requirement of both low-carbon generation and peaking capacity. Multi-year energy system optimisation was used to determine the required least-cost generation system in GB, without Northern Ireland, to meet the carbon targets. Figures 7 and 8 show the optimal generation capacity of the GB electricity system that meets the carbon target without and with additional flexibility. High and low flexibility of gas-fired Combined Cycle Gas Turbine (CCGT) [Gas(HF), Gas(LF)] and nuclear plants [Nuclear(HF), Nuclear(LF)] were considered. A high flexible plant has more capability to provide frequency response and has less dynamic operating constraints.

With additional flexibility, the system requires 14 GW less of the nuclear plant and 46 GW less of open cycle gas turbines (OCGTs) since the peak demand can be reduced through load shifting and the output of renewables can be best utilised, reducing the need for firm low-carbon capacity to meet the carbon target.

Whether nuclear and CCS should be a part of the least-cost low-carbon generation portfolio will depend on the assumed cost of nuclear and other low-carbon options including renewables. There are uncertainties over the role of nuclear and CCS in the future low-carbon energy system, due to a relatively high cost compared to wind and solar as well as long development times. Additional challenges in the case of CCS technology are its low maturity and incompatibility with a zero-carbon target unless it is coupled with a low-carbon fuel. For instance, Child, et al argue that a 100% renewable system is not only feasible for Scotland in 2050 but also economically and socially superior to the one with baseload nuclear capacity [52].
3.2. Cross-border sharing flexibility
With a large increase in flexibility requirements in the future de-carbonised electricity systems, there is a need to explore all available flexibility sources, including cross-border flexibility resource.

Currently, interconnectors to the GB electricity system offer some flexibility on both sides of the interconnectors based on energy arbitrage. However, system balancing services are not shared across the border with the connected systems. This was mainly due to a lower need for flexibility requirements in the
past and the absence of a mechanism for GB to participate in the exchange of cross-border flexibility services. Recently, a pilot project (Trans-European Replacement Reserve Exchange, TERRE) has been initiated for a cross-national exchange of operating reserve between GB, France, Spain, Portugal, Italy, Switzerland and Greece.

The cross-border sharing of flexibility, particularly of ancillary services, brings additional complexity in system operation as the utilisation of diverse national flexibility resources (available at both transmission and distribution connected) will need to be optimised alongside the cross-border flexibility resource. This will also need another layer of coordination between GB system operators and cross-border system operators. Therefore, system operators will need to be prepared to utilise this resource, and the required coordination functions should be defined in their new roles and responsibilities.

The benefit of sharing balancing services with other systems through interconnectors is shown in figure 9 for two targets of CO$_2$ intensities in 2030 (100 g CO$_2$ kWh$^{-1}$ and 50 g CO$_2$ kWh$^{-1}$).

Figure 9 indicates significant benefits for the GB system from accessing cross-border flexibility. These benefits are driven by savings in low-carbon generation capacity [G-CAPEX(low-C)] and system operating costs (OPEX) while meeting the 2030 carbon intensity target for the power sector. The net savings are higher for a tighter decarbonisation target case. These are driven by the avoidance of energy curtailment produced by renewables, allowing CO$_2$ targets to be met with a relatively lower installed capacity of low-carbon technologies and back-up capacity (i.e. savings in generation capex) at the cost of increased interconnection capacity to enable sharing of balancing capability and exchange energy across borders.

Benefits of inter-regional integration of electricity systems have been recognised in the literature. For instance, Breyer et al demonstrate the economic benefits of integrating decentralised regional power systems on a continental level, while suggesting there are only limited benefits of connecting major regions through a global-scale electricity interconnection [53]. A similar study carried out for Americas [54] looked at a cost-optimised 100% renewable energy system in 2030, finding significant benefits in integrating regional systems through optimised transmission grids, but limited benefits (1.6%—4.0% cost reduction) for a Pan-American energy system integrating North and South America.

3.3. Cost-efficient deployment of renewables

In [55], the benefits of strengthening Pan-European grids on the cost-efficient deployment of renewables were reported. The studies were using the 2030 future system backgrounds, and two cases were analysed: (i) the case where RES were deployed based on the National Renewable Energy Action Plans (NREAPs) from each EU Member States and (ii) the case where RES were deployed on the locations with the highest capacity factors. As a result, the capacity of wind and PV in the second case is 146 GW less than in the first case. The cost savings shown in figure 10 are substantial, €33 bn yr$^{-1}$ coming from the reduction of capex for RES. To obtain these savings, there is an additional transmission investment which increases the cost of the EU transmission grid by €2.3 bn yr$^{-1}$ and operating cost of generation (€0.4 bn yr$^{-1}$).

3.4. Value of energy storage

Figure 11 illustrates the value of storage (y-axis), which increases over time (2015–2050) based on the studies of the GB scenarios. The (marginal/average) value decreases along with the increased capacity of storage in the system as the value of the first installed capacity is higher than the value of subsequent ones.
Figure 10. Benefits of interconnectors for facilitating the cost-efficient deployment of renewables at the most resourceful locations across Europe [22].

Figure 11. Value of energy storage as a function of total installed capacity across different system conditions (2015, 2030, and 2050).

The studies also show the increased storage capacity requirement proposed by the planning model. For example, with the cost of storage around £1.2 k kW\(^{-1}\), the proposed installed capacity is 2 GW in 2015, 15 GW in 2030, and 25 GW in 2050. This increased capacity is driven by the increased benefits of flexibility in future low carbon systems.

3.5. Benefits of flexibility from end-use assets

Two examples of the benefits related to flexible end-use assets are discussed in this section. Figure 12 shows how the application of controlled charging of EVs can reduce the emissions associated with the electricity supplied to the vehicles in the 2030 UK system for a 15% penetration of EVs. The analysis was based on actual driving patterns characteristic for the UK light vehicle fleet. It is important to stress that in this example, the application of smart charging did not compromise the ability of EV users to make their original journeys. The implications of three different control modes on carbon emissions have been examined. First, the business-as-usual (‘BaU’) case assumes EVs will be directly charged at the end of the journeys and EV does not provide any system services. Second, a ‘smart charging’ mode of EVs refers to the ability to shift EV charging demand while the vehicle is stationary without feeding power back into the grid. Reduction in carbon emissions through smart charging of EVs (which is driven by improved load factors of low-carbon generation and reduced renewable generation curtailment. Third, a fully smart vehicle-to-grid (‘V2G’) concept would enable EVs to provide primary frequency response by injecting power back into the grid in case of a plant outage. This solution would make the carbon emissions driven by very flexible EVs negative, given improved efficiency due to a reduced requirement for conventional fossil-fuelled generators to provide frequency regulation services, which also reduces the curtailment of renewable generation. This modelling demonstrates that consumers providing V2G services to the system should get an additional reward for
Figure 12. Impact of different EV operating modes on carbon emissions. Flexible EV operating modes reduce carbon emissions.

Figure 13. Annual cost savings per household attributed to the smart operation of hybrid heat pumps. Savings are expressed in 2018 prices.

flexibility (i.e. get paid for smart charging their EVs while providing system balancing services), as the resulting carbon reduction would also mean that the overall system-wide carbon target can be reached with less low-carbon generation capacity than in the BaU case.

Other studies have also identified V2G as an important enabler for cost-efficient integration of variable renewables. Child, et al demonstrate the role and value of high penetration of V2G in facilitating the 100% renewable energy scenario for the Aland islands in 2030 [56]. Child et al further illustrate the potential for flexibility enhancement in the 100% renewable energy system in Aland islands through synergies between power, transport and gas systems enabled by V2G and P2G [57]. In a similar fashion, Taljegard et al indicate that combined planning of power and transport sectors based on the V2G option can replace investments in long-term storage and stimulate an increase in VRE share [58].

Another example, shown in figure 13 illustrates the consumer benefits of smart control of domestic hybrid heat pumps (HHPs) that are optimally (smart) controlled to maximise the benefits of delivering system-balancing and network services, while not compromising consumer comfort. In this example, it is assumed that 50% of domestic consumers have adopted smart control of their HHPs.

Although the value of flexibility in the current system is relatively modest, with an accelerated uptake of renewable generation and electrification of transport and heat sectors in the 2030–2050 time-horizons, smart control of end-use appliances could generate very significant reductions in consumer bills, while still delivering the same comfort levels to end-users.

This clearly demonstrates the need for enabling consumer engagement, as their choices will have a very significant impact on overall system costs and their energy bills. While it is likely that benefits per consumer would reduce in the case of full adoption of smart HHP control, the requirements for flexibility in the future, on the other hand, will grow substantially so the consumers would still see considerable benefits even at relatively high penetrations of smart HHPs.
3.6. Impact of interactions between flexibility products on the accrued value

Currently, a wide range of flexibility system balancing services is procured by the system operator. The procurement of these services differs in terms of technical requirements, validation processes, contract type and procurement platform, increasing complexity and reducing transparency. Another key issue is the limitation in offering bundled services as these different services are procured at different times in isolation without full consideration of their mutual interactions, particularly from the provider’s perspective.

The procurement of services should take account interactions or trade-offs between services. Under the current arrangements, the volumes of various operating reserve services are procured separately and do not comprehensively take account of the interactions (e.g. temporal, technical and cost interactions) between the procured products. For example, as both primary and enhanced frequency response (PFR and EFR) share the same goal to limit the system frequency nadir above the standard, these two services should, in fact, be procured together based on their mutual interactions to minimise their overall cost. With a rise in the amount of flexibility requirement, the optimisation of the portfolio of various flexibility services required by the system becomes more important.

Furthermore, some forms of flexibility sources create additional demand for flexibility at other times which need to be included in the decision process while procuring flexibility. For example, DSR based provision of ancillary services generally redistributes demand across different times. This means that a reduction in demand at a point in time aimed at providing reserve services, will be followed by an increase in demand during a subsequent period—e.g. use of Thermostatic Loads to provide frequency response will increase the need for secondary reserve, which should be accounted for. Otherwise, the value of this flexibility source would be overestimated, as depicted in figure 14.

Understanding the characteristics of the flexible demand and quantifying the flexibility they can potentially offer to the system is vital to establishing its economic value of DSR. To offer flexibility, controlled devices (or appliances) must have access to some form of storage when rescheduling their operation (e.g. thermal, chemical or mechanical energy, or storage of intermediate products). Load reduction periods are followed or preceded by load recovery, which is a function of the type of interrupted process and the type of storage. This, in turn, requires bottom-up modelling of each individual demand-side technology to simulate actual service functions while exploiting their flexibility without compromising the service that it delivers.

3.7. Benefits of enhanced flexibility of CCGT

This section investigates the value of flexible generation. Main characteristics of flexibility under investigation are defined in table 1.

Commitment time (CT) describes the time that a thermal plant takes from turning on to reach the minimum stable generation output. The start-up decision of a thermal plant with shorter commitment time can be made nearer to real-time operation, which significantly reduces the uncertainty faced by the system operator. Minimum stable generation (MSG) is defined as the lowest level of output that a thermal plant can
Table 1. Flexibility features of CCGT.

| Feature                              | Base case | Enhanced flexibility |
|--------------------------------------|-----------|----------------------|
| Commitment time (CT)                 | 4 h       | 2 h                  |
| Minimum stable generation (MSG)      | 50%       | 20%                  |
| Idle state (idle)                    | No        | With                 |
| Max response capability (response)   | 17%       | 40%                  |
| Ramp up/down speed (ramp rate)       | 32%/10 min| 50%/10 min           |

Figure 15. Potential Value of enhanced flexibility of conventional gas plant in systems with different penetration levels of wind.

...contINUously operate at. Lower MSG not only increases the capacity of ancillary services provided by CCGT plants but also reduces the minimum electricity production needed for the plant to provide system services. Maximum response capability (response) defines the maximum amount of frequency response the plant can provide, which is an important feature for the future low inertia power system. Idle state (idle) is a hold point in the plant start-up procedure. This capability allows a thermal plant to provide operating reserve and inertia services without any energy delivered. Ramp up/down speed (ramp rate) describes the speed at which the thermal plant can change its output between the minimum and maximum load levels. Higher ramp rate allows the more operating reserve to be delivered in a short period.

As shown in figure 15, the increased penetration of wind generation drives up the value of enhanced flexibility, in line with the increasing need for ancillary services. In particular, one of the key drivers for the high value of some flexibility features is the system inertia reduction as converter-connected wind generation replaces conventional plants.

3.8. Benefits of synthetic inertia from variable generators

The potential and implications of intermittent generators (wind and solar) in providing flexibility services are not fully understood, and there are limited incentives on renewable generators to provide system flexibility in the current GB system. Since the growth in renewable generation drives the need for more flexibility, while at the same time displacing conventional thermal plant that traditionally has been the source of this flexibility, enhancements in the capability of renewable generation to offer some of these services would be beneficial.

There is evidence that wind farms can provide some of these services and hence lower the costs associated with the provision of flexibility. Studies on the provision of synthetic inertia (SI) by wind generation show that at 60 GW wind capacity installed, the annual costs associated with frequency response provision can be halved if wind provides SI, as shown in figure 16.

There are different ways in which SI from intermittent renewable sources can be exploited. For example, through changes in the industry codes as in 2005, Hydro-Québec (North American utility, 40 GW peak load) amended its grid code that new wind turbines be capable of delivering a power boost equal to 6% of their rated capacity during low-frequency events. Manufacturers responded with SI designs, and the first was...
Figure 16. Benefits of providing synthetic inertia by wind [3] due to less part-loaded thermal generators which are traditionally the primary sources of inertia.

installed in 2011. Today, inertia-compliant turbines account for two-thirds of Quebec’s wind capacity [59]. However, this may not be the most cost-effective solution for the GB system as a large amount of wind capacity is already installed and the ease and cost of retrospectively applying the new requirements to existing generators are unknown. Furthermore, we may not need all plants to be able to provide this.

Another approach to exploit the flexibility resource embedded in intermittent generation sources is market incentivisation—for example, by remunerating the inertia services provided by generators (i.e. SI in case of wind generation).

The issue of providing sufficient volumes of SI in a 100% renewable system has also been addressed in [17], proposing that the provision of SI by wind and solar generators as well as fast-responding batteries will need to become mandatory in fully renewable systems, given that relying on synchronous generators’ inertia is likely to result in unstable system operation.

3.9. Benefits of micro-CHP

Emissions from the power sector and buildings account for 40% and 15% of the overall UK emissions, respectively. While there is significant progress in decarbonising the power sector through massive deployment of low-carbon generation, especially renewables, there is a lack in heat decarbonisation as gas boilers fuelled by natural gas remain the dominant technology to provide space and water heating in the UK. Amongst other low-carbon technologies, fuel cell micro-combined heat and power (CHP) offers an opportunity to generate electricity and heat at high efficiency (90% above) and at close proximity to the demand. Deployment of this technology can, therefore, reduce system losses, improve the combined efficiency of the energy system (power and gas), increase the utilisation of energy infrastructure which reduces the capacity of the power and heat infrastructure needed to meet the peak demand. The 90% efficiency of micro-CHP is the maximum efficiency that can be achieved when the micro-CHP produces heat and power concurrently. As the heat demand is seasonal, there are possible operating conditions where heat is not needed (e.g. during summer) but electricity is needed or vice versa. In those conditions, the efficiency will be less substantially.

A range of studies has been carried out to enable quantitative analysis investigating the benefits of fuel cell micro-CHP on the future GB energy system. The 2030 Climate Change Committee scenarios, i.e. 50 g and 100 g carbon intensity of the power and gas sector, are used for the studies. The gross benefits of fuel cell micro-CHP are derived from the economic savings obtained by deploying this technology against the counterfactual scenario, i.e. a system without micro-CHP.

Figure 17 presents the system benefits of three different designs of micro-CHP for displacing investment in infrastructure in power and heat systems. In this analysis, all of the micro-CHP is characterised by the same overall energy efficiency of 90%, but the ratios between electricity and heat production are different. The results demonstrate that the net savings across the three designs are similar but with different cost components.

There is also a trend where the increased penetration of micro-CHP will also save gas OPEX at the expense of increased OPEX of electricity; this is expected and as a consequence of allocating the operational cost of micro-CHP cost to the electricity sector in this study. The CAPEX savings are dominated by the savings in G CAPEX, both for low-carbon and other, and distribution network CAPEX. The ability of the micro-CHP to reduce the capacity need of other low-carbon technology demonstrates the positive
environmental impact of this technology in the context of carbon. In addition, there are also savings in HP and Boiler CAPEX.

These savings are possible as the micro-CHP, in contrast to variable low-carbon technologies, can provide firm capacity for both the power and heating sectors. Moreover, as micro-CHP may displace heat pump systems and therefore, lower the peak electricity demand, the capacity value of micro-CHP can be considered higher than other traditional power only sources. As the electricity peak demand reduces, this will also yield lower distribution network reinforcement cost.

3.10. Benefits of flexible concentrated solar power with thermal storage

The study in [60, 61] discussed the benefits of concentrated Solar power (CSP) installed in Tunisia in supporting cost-effective decarbonisation of the European energy system. The system implications of integrating a flexible CSP plant with thermal storage into the European electricity system (via a direct cable link to Italy) were investigated by analysing the changes in requirements for generation back-up capacity, cross-border transmission capacity and system operating cost. The analysis demonstrated that firmness of capacity of a CSP plant was significantly higher than a variable renewable generation, such as solar PV or wind generation. The capacity value of CSP was further enhanced by the thermal storage, which was characterised by very low losses. The thermal storage enables the CSP to produce during peak demand periods. As a consequence, CSP plants could produce savings in terms of generation capacity if it was used to displace the non-firm capacity of intermittent renewable technologies such as wind power and PV.

The impact of the CSP on the European transmission network requirements mostly depend on the location of generation technologies displaced by CSP. The largest cost savings are obtained when the CSP was utilised to displace wind power in Northern UK as the network reinforcements driven by wind generation can be avoided. In this particular case, the construction of 2.5 GW of new transmission capacity can be avoided on the UK network, which delivers a significant transmission capex cost saving.

Furthermore, the analysis demonstrated that displacement of intermittent renewable generation by the CSP plant reduces the need for short-term operating reserves leading to a corresponding reduction in generation operating costs. The total annual benefits of the CSP were found between 3 and 120 €/kW of CSP capacity. The study demonstrates the value of flexible firm low-carbon generation being located in a place with a high capacity factor.

It is worth noting that despite the potential benefits of a dispatchable low-carbon technology such as CSP, several publications such as [1] or [62] present results of least-cost modelling of highly renewable systems that suggest that the economics of CSP and the presence of alternative flexible options such as ES make it likely that CSP will contribute a much lower share to electricity supply than solar PV.

3.11. Impact of competing balancing options

In [63, 64], based on UK future development scenarios, the potential competition between ES and other flexible options was investigated. Figure 18 (top) illustrates the interaction and competition among the options. Although no two options will be direct substitutes, there will be a degree of competition among them. Figure 18 illustrates how the net benefits of ES deployment change as a consequence of having other flexible options present in the system.

The availability of flexible generation reduces the opportunities for new distributed ES (DSt) to generate operating cost savings due to more efficient operation and lower curtailment of renewables. Conversely, the
Figure 18. Competition between storage and other technologies.

system cost savings for generation and distribution CAPEX are not affected. Compared to the storage only scenario, the total annual net benefits of ES drop to the range of 0.4–1.4 £bn yr$^{-1}$. On the other hand, in the case without flexible generation, the marginal system benefits for the first gigawatts of storage capacity are higher; hence, the total cumulative benefit up to the break-even point is also greater.

With the presence of DSR, the net benefits that ES can provide are even further reduced. With low ES cost, the net benefits materialize at £0.38 bn yr$^{-1}$ (significantly lower than with storage only); in the case of high storage cost, the system net benefits are virtually zero.

In the situation where ES competes against all other flexible options, the results are similar to the case where only DSR competes against ES confirming that DSR represents the key competitor to distributed ES.

3.12. Option value

Key decisions need to be made soon that will have a lasting impact on the future energy system. This is primarily because energy generation assets and network configurations have long lifetimes, and so choices made about what is deployed imminently will have impacts on the cost of the system for decades. However, greater flexibility in the electricity system provides option value: small investments in flexibility enable the room to delay decision making until there is better information, reducing the need to make potentially high regret decisions [51].

A pathway where no additional flexibility technologies are deployed by 2020 and deployment between 2020 and 2025 is constrained by this slow start, leads to the highest regret of all the pathways considered in this analysis. The additional cost of the UK electricity system due to this ‘do nothing’ pathway could reach £9 bn by 2050, as shown by the 1st bar in figure 19 below.

This highest regret occurs in scenarios where there is high demand across the system, both DSR and storage see substantial cost reductions by 2025, and the pipeline of scheduled interconnector deployment is delayed. The very low deployments of flexibility technologies caused by this pathway lead to the highest levels of regret seen across all of the analysis, because of the missed opportunity to reduce the cost of the electricity system. The avoided costs of not deploying DSR and storage are overwhelmed by the extra costs in generation, transmission and distribution.

In contrast, by investing in a diverse portfolio of flexible technologies deployed by 2020 (e.g. 1–5 GW of DSR, 0.5–3 GW of electricity storage and 1 GW of flexible CCGT), the maximum regret, shown in the 2nd bar of figure 19, is much less (£1.3 bn). The regret costs are driven by the possibility of having a lower cost of flexible technologies in future which make the investment decisions for 2020 sub-optimal. The future uncertainty will be the key challenge for investment decisions; however, it can be concluded from this study that adding flexibility is the least-regret pathway for the UK energy system.

3.13. Maximising the value of flexible technologies via a whole system coordinated approach

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.

As a consequence, 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 the different networks. A whole-system approach will be required for both operations of the system and management of future networks at maximum efficiency. The modelling results in figure 20 show that a whole-system-based network management approach may result in about 30% and 100% higher savings in the investment and operating cost of the system relative to transmission- or distribution-centric approaches, respectively.

In this case, the distribution system operator (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. On the other hand, the transmission system operator-centric approach focuses on deferring transmission and interconnection investment as well as reducing system operating costs, while ignoring the potential value of using DER in reducing distribution network costs. 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. 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.

Figure 21 shows the total system benefits between the solutions that optimise the utilisation of demand-side flexibility obtained using the whole-system and DSO-centric approaches, in the case of relatively inflexible generation system (with respect to the ramping, start-up and frequency regulation capabilities of conventional generators). The whole-system solution is expectedly characterised by lower cost than the DSO-centric approach, hence resulting in net savings.

The benefit of the whole-system solution highlights the need for more intensive system coordination, as the modelling demonstrates that the whole system would benefit from investment in distribution network reinforcement. Such investment would enable end-user flexibility to reduce the system operating cost and also reduce the corresponding generation CAPEX needed to reach the CO₂ 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 overall energy bills.

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 decentralized, market-integrated flexibility will enable consumers to make appropriate choices to facilitate cost-effective decarbonisation while reducing their energy bills. There is a growing interest in the EU in coordinating the operation of distribution and transmission networks. A number of trials are being conducted to demonstrate the challenges and benefits of the whole-system concept.

3.14. Role of flexible non-network technologies in displacing reinforcement of electricity grids

The Smart Grid paradigm envisages a penetration of various forms of flexible DER, such as DSR technologies, including a demand-led response in the form of controllable/responsive loads and generation-led response in the form of distributed generators and ES technologies. In this context, there is a significant potential for incorporating these non-network technologies to provide flexibility in the operation and design of future electricity grids.

One of the first departures from the historical grid planning processes towards delivering network security by incorporating flexible non-network solutions has been carried out in the UK. Although the focus of the current activities has been on including distributed generation into distribution network planning, similar approaches are now being considered to be applied to flexible demand technologies and ES.
A crucial emerging question is centred on assessing the contribution of these flexible DER technologies to network security, i.e. their ability to displace network reinforcement. An illustrative example of this issue is indicated in figure 22 in which several solutions are considered: (a) traditional network reinforcement through network-based solutions and there flexible non-network solutions including (b) distributed generation-based approach, (c) storage-based solution and (d) demand-side management-based approach, which can include flexible commercial, industrial and domestic demand.

In the case of load increase, as indicated in the figure, traditional planning approaches would require network reinforcement (e.g. installation of a third transformer) as indicated in the solution (a) of figure 22. Regarding the other three flexible non-network solutions, the key question is associated with assessing the ability of these alternative flexible solutions to substitute network reinforcement. In other words, the network planners will need to determine the ‘capacity value’ of the alternative flexible non-network solutions, which requires an assessment of the reliability performance.

In this context, a fundamental review of the network security standards [66] has been recently carried out in the UK, aimed at quantifying the security contribution of flexible DSR and ES technologies by accounting for the combined effects of the distribution network and non-network properties. This is based on the concept of equivalent load carrying capability, that has been recognised as an appropriate approach to compare traditional network reinforcements with flexible non-network technologies [67]. A comprehensive analysis has been carried out to assess the impact of key factors on the security contribution of flexible DER has been investigated. These include (a) network related factors, such as the failure rate and repair/restoration times of network assets, the level of network redundancy and the number of parallel network circuits; (b) flexible DER related factors, including the relative size of DER, the DER availability, the number of DER facilities, the coincidence in delivery of multiple DER facilities and the ability of DER to operate under islanding conditions.

3.1.5. Flexibility reduces the system integration cost of renewables

The modelling results and analysis [68, 69] based on the future UK scenarios, demonstrated that system flexibility and the penetration of variable renewables in the system were the key drivers behind the system integration cost (SIC) of VRES technologies. To emphasise this functional relationship, figure 23 shows the SIC results obtained through a diverse range of case studies, presented as a function of VRES penetration in the system, with the level of system flexibility as a parameter. The figures are plotted for offshore wind (left diagram) and onshore wind (right diagram).

The SIC results are grouped by trend lines according to the level of improvements in system flexibility, ranging from No progress (very limited improvements in system flexibility, comparable to the current system) to Maximum progress (characterised by very high system flexibility). It is immediately obvious from figure 23 that higher VRES penetrations yield higher SIC values, but the magnitude and the rate of this increase depend significantly on the enhancements in system flexibility that accompanies the expansion of VRES, i.e. on the volume of deployed flexible options such as DSR, storage and interconnection. At current flexibility (‘No progress’) levels the SIC increases sharply already at low wind penetration levels. In a system with no added flexibility compared to today’s situation, the SIC of offshore and onshore wind would increase beyond £40 MWh⁻¹, making it very costly to integrate large penetrations of these technologies.
Conversely, with higher flexibility (‘Moderate’ or ‘High progress’) SICs remain at a relatively low level even at penetration levels that are three times higher than today, provided there is a moderate improvement in system flexibility (such as through the deployment of a moderate amount of ES and/or DSR). Clearly, to ensure the integration of increasing VRES generation at low cost, the system would require a simultaneous increase in the deployment of flexible options—DSR, ES and interconnection.

4. Flexibility from cross-energy vector coupling

4.1. Integration between electricity and heat sectors
A higher degree of integration between electricity and heat sectors presents unique opportunities to make use of cross-vector flexibility to support the integration of low-carbon generation technologies and to reduce the cost of decarbonisation [32–34] significantly. Heat pumps [71–73] and heat networks [74, 75], as promising low-carbon heating technologies, may play important roles in providing flexibility to facilitate the transition towards a low-carbon energy system. In [43] a modelling-based analysis of coordinated design and operation of low carbon heat and electricity systems, which assumed heat demand is met by heat networks in which CHP, industrial network heat pumps (NHP) and thermal energy storage (TES) showed the value of the heat-electricity integration on the UK energy system. Where the heating system was decoupled from the electricity system (i.e. it did not provide flexibility services like reserve and response service), costs of operating the overall system were higher than the case when they were integrated (as shown in figure 24).

The net benefits of coordinated operation of the heat and electricity system were between £2.4 bn yr⁻¹ and £5.4 bn yr⁻¹ for 100 gCO₂ kWh⁻¹ and 50 gCO₂ kWh⁻¹ scenarios (by 2030) respectively. Given that CHP can provide ancillary service to the electricity system besides providing heat, which enhances the overall generation efficiency, CCGT plant would be replaced by CHP in the integrated system, delivering fuel cost savings. Furthermore, increases in efficiency achieved through the coordinated operation of heat and electricity sectors can achieve carbon targets with a reduced amount of low carbon generation. It can also be
observed that higher penetration of CHP leads to the reduction in the amount of industrial NHP capacity, which also reduces high-voltage distribution network reinforcement requirements.

4.2. Role and value of hybrid heat pumps

The combination of the potential environmental benefits along with the high capital costs associated with the electrification of the domestic heat sector has attracted significant interest in the role of hybrid technologies. Authors in [76] reviewed major hybrid heating technologies, indicating that HHP as an extended application of EHP, can improve the thermal efficiency and markedly reduce carbon emission. The economic benefit of HHP over a series of other low-carbon heating technologies was assessed in [43, 77]. Numerical studies on the application of residential HHP have been carried out in [78], demonstrating that HHP provides a lower-cost solution to EHP as further discussed below.

The performance of HHP that combine domestic gas boiler with air-source EHP has been investigated in [43, 44]. Given this hybrid nature, the consumers’ heating demand can be met by the consumption of either gas or electricity, implying a ‘dual-fuel’ capability.

The FREEDOM project [44] has demonstrated that this technology can still achieve the environmental potential of a fully electrified heat sector, yet with significant economic savings with respect to a standalone EHP pathway. This is because this hybrid technology can reduce both the upfront building costs as well as the electricity system costs to a great extent.

Regarding the first aspect, HHPs involve significantly lower upfront costs, since the rated capacity of the heat pump component in the HHP configuration is lower than in the standalone EHP configuration. Furthermore, there is no need to replace the existing radiators with low-temperature ones as in the standalone EHP case. According to the studies carried out in [79], the savings in upfront costs achieved by the HHP technology are in the order of £450–£2800 for a typical UK semi-detached house.

Regarding the second aspect, according to the results of the system studies using the 2030 scenario undertaken as part of the FREEDOM project, the HHP technology can bring very significant system cost savings with respect to the standalone EHP case, the results are presented in figure 25 below.

The results demonstrate that the HHP technology brings gross savings in total system costs of 7–12 £bn yr\(^{-1}\) in the 100 gCO\(_2\) kWh\(^{-1}\) cases and between 5.8 and 9.3 £bn yr\(^{-1}\) in the 25 gCO\(_2\) kWh\(^{-1}\) cases, compared to the standalone EHP case. The benefits of HHPs to EHPs vary depending on the system flexibility. The benefits of HHPs over EHP are lower in the highly flexible system as the flexibility from HHPs competes with the flexibility from other sources such as controllable loads (industrial and commercial loads, EVs, smart appliances) and electricity storage.

On the other hand, the HHP technology requires an additional annual spend of 0.8–1.8 £bn yr\(^{-1}\) for the operation of the gas system. Systems with HHPs also require additional investment in the low-carbon generation to offset gas emissions by decarbonising more of the electricity system; this adds the system cost by £0.8 bn yr\(^{-1}\) and £1.1 bn yr\(^{-1}\) in the low-flexible system for the 100 and 25 gCO\(_2\) kWh\(^{-1}\) cases, respectively. The cost is less (between 0.1 and 0.5 £bn yr\(^{-1}\)) in the high-flexible system. The net benefits of the HHP technology are between 5.5 and 9.3 £bn yr\(^{-1}\) in the 100 gCO\(_2\) kWh\(^{-1}\) case, and between 4.9–7.4 £bn yr\(^{-1}\) in the 25 gCO\(_2\) kWh\(^{-1}\) case.

A very significant portion of these gross benefits is associated with savings in electricity distribution network investment cost, given that the ‘dual-fuel’ capability can be exploited during peak electricity demand.
conditions (where the heating will be provided through the consumption of gas) relieving the electricity system stress. Another significant part arises from avoided investments in peak generation capacity, again driven by the ability of hybrid heating systems to reduce electricity consumption during peak load hours on the system. Finally, a significant proportion of savings is associated with operating cost reduction, given that less electricity needs to be produced by the generators on the system since part of the heat demand is now met by gas. The impact on transmission network and interconnection investments is modest.

Beyond the cost savings brought by the ‘dual-fuel’ capability, HHPs can also deliver a number of valuable, flexible demand response services to the electricity system (which also apply in the case of standalone EHPs), provided that some sort of flexibility is available. One important aspect of the flexibility of HHPs operation is related to ‘preheating’, that involves heating the households earlier than it would be otherwise carried out while utilising inherent heat storage in the fabric of the houses and not compromising user comfort requirements. This type of flexibility is important for reducing system peaks, enhancing the value of the provision of balancing services by HHPs and increasing utilisation of renewables, which significantly reduces the cost of decarbonisation. Furthermore, smart control of HHPs can increase their operating efficiency.

In this context, system modelling carried out demonstrates that rolling out of smart control strategies carried out by PassivSystems would considerably improve the value proposition of HHPs. According to the results of the system studies [80], the additional benefits of smart control strategies accruing to the energy system as a whole are considerable, 2.1–5.3 £bn yr\(^{-1}\) in 100 gCO\(_2\) kWh\(^{-1}\) scenario and 5.1–15.2 £bn in 25 gCO\(_2\) kWh\(^{-1}\) scenario, as shown in figure 26 below.

The most significant value stream of this flexibility, which is evident when the carbon target becomes stricter, is associated with reductions in investments in low-carbon (including renewables and nuclear) generation capacity. This is driven by the flexibility of the HHPs with smart controllability to provide system
balancing services and therefore increase the utilisation of available renewable generators and meeting the carbon targets cost-effectively.

4.3. Flexibility in gas infrastructure to support the electricity system
The future growth of intermittent generation will also increase the complexity of gas network management as a gas-fired powerplant is expected to play a significant role in providing flexibility. Unlike electrical energy, it takes a significant amount of time to transport gas from supply sources (terminals and storage facilities) to gas demand centres. One of the cost-effective solutions to deal with this would be to enhance the flexibility of gas network infrastructure by installing multi-directional compressors that can deal with the growing variability in the gas demand across the system. The value of the flexibility that gas infrastructure can potentially provide for the power system has been evaluated in [81–83]. In [83], it is demonstrated that investing in physical assets of the gas infrastructure (i.e. gas pipelines and compressors) can lead to more savings in electricity system investment. In [84], the flexibility of power-to-gas seasonal storage was modelled.

A high-level modelling analysis was carried out for assessing the value of flexibility in the gas system for supporting the electricity system. Figure 27 shows that enhancing the flexibility of gas infrastructure (improves the operability of gas generation and reduces more costly coal generation and interconnection imports. This would deliver an annual reduction in the operating cost of £612 m and does not account for the reduced amount of low carbon generation needed to meet the carbon target.

4.4. Interaction between heat, gas, and electricity system
Improving energy system flexibility is necessary for enabling the cost-effective integration of low-carbon generation into the electricity system. It is important to note that cross-vector flexibility is inherently taken into account in all scenarios, and hence the benefits of flexibility presented refer only to the value of other sources flexibility (e.g. pre-heating, smart charging of EVs, etc).

A range of studies has been carried out to model the integrated electricity-heat-gas system and investigate the overall benefits achieved through the interactions across different energy vectors [85–88]. Strong sector coupling is seen as an important route for providing flexibility to the power system to support the integration of VRE in a cost-effective manner. For instance, Aghahosseini et al show that substantial benefits can be achieved through sector coupling to facilitate 100% renewable energy systems for the Middle East and North Africa region [62].

The studies [25] suggest that the availability of firm low-carbon resources (such as nuclear, hydrogen CCGT or CCS plant) is critical for fully de-carbonising the energy system. As the study demonstrates, firm low-carbon generation is significantly less critical in systems with less demanding carbon targets. Given this finding, the analysis was carried out to investigate the possibility of delivering a zero-carbon energy system without nuclear power. An alternative approach is to quantify the renewable electricity capacity needed to meet a zero-carbon energy system without nuclear. The study demonstrates that it would be feasible to achieve a zero-emissions energy system without nuclear generation, subject to the presence of hydrogen storage and corresponding hydrogen-based power generation as shown in figure 28 below and later in figure 31.

Figure 28 presents a comparison between optimal generation portfolios for a future UK system with zero-carbon emissions where the heating sector is fully decarbonised through electrification (Electric 0 Mt
Figure 28. Comparison of generation portfolios for the Electric pathway with and without nuclear technology.

pathway) with and without nuclear generation. The capacity of PV and wind needed in a zero-carbon Electric system without nuclear plants are 175 GW and 185 GW respectively, which is above the estimates of UK potential for these technologies considered in this study. Unless the potential level of PV and wind can be increased to such a level, the system will require nuclear power to meet the zero-emission target. An alternative solution is to use low-cost hydrogen imports, allowing the system to achieve zero-carbon emissions within the defined constraint of PV and wind capacity, but it requires a higher capacity of hydrogen-based power generation.

To achieve zero-carbon emissions without firm low-carbon generation, there is a need for seasonal ES that could be provided by hydrogen. This is in addition to significant short-term energy system flexibility provided by demand shifting via pre-heating and thermal storage in homes (50% of potential demand flexibility is assumed available). As shown in figure 29(a), during periods of high renewables output, the excess energy is converted into hydrogen by electrolysers (‘Power-to-Gas’). This drives the need for investment in electrolysers to enhance the utilisation of renewables. The energy in the form of hydrogen can then be stored across long time horizons as losses in hydrogen storage are assumed to be minor and not time-dependent. Electrolysers can also provide balancing services during periods of high renewables output, and therefore, reduce the need for these services from other sources (generation, DSR, storage, etc). During low renewables output, the stored energy can be used to produce electricity via hydrogen-based power generation. Hence the capacity of hydrogen-based CCGT increases significantly—from 23 GW in the system with nuclear (43 GW) to 51 GW in the system without nuclear. It can be concluded that ‘Power-to-Gas’ and hydrogen-based generation can substitute nuclear generation. It is important to note that electrolysers (as part of the ‘Power-to-Gas’ system), due to higher costs, are not selected by the model in the core Electric pathways when nuclear generation is available, as other technologies, such as DSR and battery storage are able to provide system flexibility services at a lower cost.

It is important to highlight that hydrogen-based CCGTs and OCGTs can provide system balancing services which facilitate cost-effective integration of other low-carbon generation such as renewables and nuclear. Figure 29(b) shows the hourly generation output and load profiles for the same period in the Electric 0 Mt core scenario. The availability of nuclear reduces the need for hydrogen-based CCGT and other low-carbon generation such as wind and PV, as shown in figure 28.

IWLC: baseload including Industrial and Commercial load, EV: Electric Vehicle, SA: Smart Appliances, HP: Heat Pump, RH: Resistive Heating, P2G: Electrolysers

The comparison between the system costs of the core Electric 0 Mt case with and without nuclear is shown in figure 30 [25], showing that a scenario without nuclear power (or similar firm low-carbon capacity) costs around £10 bn yr⁻¹ more than a scenario with nuclear power generation.

The results of the study [25] demonstrate that in the absence of firm low-carbon generation such as nuclear, the system would require long-term storage that could be supplied by hydrogen through investment in the hydrogen electrolysers and storage. The capacity of hydrogen production plants, hydrogen networks, and storage, are optimised and tailored to system needs to minimise the overall system cost.

To achieve zero-carbon emissions without nuclear generation, there is a need for 3.6 TWh hydrogen ES (figure 31) that can provide both support in the short-term energy balancing and long-term storage. The
Figure 29. The role of electrolyzers, hydrogen storage and generation in balancing the system with large penetration of renewables and the use of biogas for peaking plants.

Figure 30. System costs of the electric pathway with and without nuclear technology.

The volume of hydrogen storage needed is around 1100 million cubic meters (mcm), which, for context, is roughly about 21% of the volume of the recently closed Rough gas storage facility in the UK. The annuitized investment cost of the hydrogen storage across GB in this scenario is around £3.2 bn yr$^{-1}$.

The need for investment in hydrogen infrastructure (production plant, networks, and storage) can be reduced by importing hydrogen at low-cost (if available) rather than producing it in GB, as importing hydrogen reduces demand for ES and Power-to-Gas schemes. The cost of importing hydrogen should be less than its system benefits.
4.5. The interaction between thermal and electricity storage

Thermal storage \([89–91]\) and preheating \([92, 93]\) can provide significant flexibility to the system as it can shift thermal loads to off-peak periods, reducing the overall system capacity requirement, improving the utilisation of renewables, and reducing operating costs. The benefits of thermal storage and preheating are illustrated in figure 32. The results show two consecutive days of extremely cold weather. The model considers ‘1-in-20’ winter extreme cold days to ensure there is sufficient infrastructure capacity installed in the system to deal with these conditions.

The modelling results \([25]\) demonstrate that thermal storage is charged, and the building is pre-heated during the night. The upper diagram shows the heat output of the heat pump (HP), natural gas (NG) boiler, resistive heating (RH), and thermal storage. Thermal storage is discharged during high demand conditions resulting in a smaller capacity requirement for heat pumps and resistive heating. The ability to shift thermal load provides significant benefits through reducing system peak capacity requirement, and the associated costs—150 GWth of peak load can be reduced by using thermal storage and preheating.

Other forms of ES investigated in this study include TES and electricity storage. The integrated whole-energy system (IWES) model optimised the portfolio and size of the ES system, considering the technical and cost characteristics of each storage technology. Studies have also been carried out investigating the correlation between thermal storage and electricity storage. The studies involve a number of different levels of predefined thermal storage availability and preheating capability from High to Zero thermal storage. The High scenario represents around 58 GWth of TES and more than 100 GWth preheating. The Medium and Low scenarios are 50% and 25% of the capacity in the High scenario respectively, and the last scenario (Zero) is an extreme scenario where there is no domestic TES and preheating capability available. In this study, the level of thermal storage and preheating is given as an input and not optimised; the IWES model optimises the other infrastructure requirements, including electricity storage. The studies show a 0 Mt
Electric pathway as the role of storage in reducing the infrastructure requirement is high in this scenario. The results are shown in figure 33.

The modelling results [25] demonstrate that in the absence of thermal storage and other flexibility sources, there would be a need for more than 55 GW of new electricity storage as well as substantial additional power system capacity in the Electric scenario; however, if 58 GWth of TES (1.7 kWth/household) and preheating (more than 100 GWth) is available, the need for new electricity storage reduces to below 10 GW, since the cost of thermal storage is considerably lower than the cost of electricity storage, and the cost of preheating is assumed to be applied at low cost. Smart control could be installed to manage the operation of heating appliances and thermal storage, including preheating to minimise costs to consumers (and the overall system costs) while maintaining the comfort levels. For example, preheating could be carried out when there is a surplus of low-carbon energy production while reducing the heat demand during peak periods. Preheating and thermal storage also reduces the capacity of heating appliances.

Although there is a strong interaction across different ES technologies (electricity, gas, and thermal); different technologies may not be able to substitute the functionalities of other storage technologies fully. Storing energy in the form of electricity can be more flexible than heat ES. For example, the batteries in the electrified transport sector will provide services to the local and national grid via the V2G concept. Therefore, electricity storage is still needed (although with less capacity) even with a large capacity of thermal storage. Another alternative ES is in the form of long-term TES is discussed in the next section.

Another industry offering sector coupling potential, especially in the MENA region, is seawater desalination sector with its significant capability for water storage. However, Caldera et al find that due to the high investment cost of desalination plants they are preferably run at close to maximum full-load hours i.e. as baseload plants, while flexibility can be more cost-efficiently provided by a combination of solar PV and battery storage than by desalination plants and water storage [94]. In another assessment [95], the benefits of coupling power and desalination sectors for the 100% renewable-based power system of Saudi Arabia are estimated at just 1%–3%.

4.6. Impact of long-term energy storage

The increased penetration of renewables in the UK attracts discussions on the use of long-term ES to store the excess of renewable output over longer time horizons [96–98]. There are a number of long-term ES technologies such as underground thermal ES, chemical storage such as hydrogen, salt hydrate technology, phase-change materials etc. The benefit and value of thermal ES technologies in enabling the use of more variable and lower cost RES instead of higher-cost but firm low-carbon generation such as nuclear has also been investigated through two cases studies assuming the availability of TES that can store 10 and 20 d of heat demand. The modelling of long-term TES is technology-agnostic, and it is assumed that there are no significant losses (cycle losses of 10%). The counterfactual (reference) scenario used in this comparison is the Electric 0Mt case with zero flexibility. The results of the study [25] are demonstrated in figure 34.

The results demonstrate the following:
Long-term thermal ES can facilitate the integration of larger volumes of renewables, such as increased wind capacity. It is important to note that even though the proposed capacity for PV is lower than the counterfactual (first case with no flex), the utilisation of PV output is higher as less curtailment will be needed during periods of high output. This is demonstrated in figure 35. The ability to use more RES reduces the need for nuclear power, and therefore, the installed capacity of nuclear in a system with thermal ES decreases (from 45 GW to 26 GW). This leads to a reduction in the share of nuclear power in the energy mix as annual production falls from 336 TWh to 202 TWh (out of 748 TWh total). There is only a marginal difference between the results of a system with 10 d and 20 d of TES, suggesting that there is a limited additional benefit in having longer duration ES though much longer durations (>20 d) have not been examined. The size of TES should be optimised to minimise the system cost.

Further studies investigating design options for long-term storage would allow an in-depth understanding of the optimal ratings, ES capacities, and the impacts of these technologies on the overall energy system.

4.7. Applications of long-term energy storage to deal with uncertainty in the availability of wind energy

The availability of wind varies in time, and there may be periods with the prolonged low level of output during cold-spell conditions (peak demand periods) which can lead to scarcity in energy supply if it is not anticipated priorly [61, 62]. To minimise this risk, a sufficient volume of energy needs to be reserved in a cost-efficient manner, e.g. in the form of hydrogen. Based on the study in [52], the range of hydrogen that needs to be reserved is calculated as a function of the number of weeks with low wind output; the results are shown in figure 36.
Figure 36. Range of hydrogen reserve needed to deal with prolonged low-wind periods.

The method is to calculate the range (min-max) of wind power energy that needs to be compensated if such event (prolonged low wind output) occurs. The volume of reserve increases to deal with longer low-wind periods. Further investigations on the impact of climate change and weather variations and their associated risks to the reliability of energy supply are needed to enable the development of a low-carbon, cost-efficient, and resilient energy system.

5. Summary and future work

Flexible technologies and resources are crucial for delivering cost-effective decarbonisation of the energy systems with high penetration of variable RES and increased electrification. The paper demonstrates the whole-system value and the benefits of flexibility from flexible generation, interconnection, DSR, and ES technologies. Enhancing flexibility will improve the integration of variable RES, reduce curtailment, provide more balancing resources which reduce the need to part-load thermal generation, increase operating efficiency, reduce opex and system capacity requirements.

A summary of the issues that have been discussed in this paper is listed as follows:

a. Flexibility enables higher penetration of variable low-carbon generation because improving system flexibility reduces the SIC of renewables. This also implies that going to net-zero emissions with higher penetration of RES, the system will require a higher level of flexibility.
b. Cross-border flexibility is critical to allow sharing of system capacity and flexibility resources between regions. This will require planning, control, and market coordination across regions.
c. Cost-efficient deployment of renewables should be facilitated. This will require stronger Pan-European grids and increased flexibility.
d. Installed capacity and value of ES will be likely to increase responding to the increased need for system flexibility.
e. EVs and smart control of HHPs also provide new flexibility sources to the electricity system. The benefits of smart EV charging and V2G in reducing carbon emissions have been demonstrated.
f. Flexibility sources may provide multiple services, e.g. demand response providing primary and secondary reserve services. The interactions across different services are important to be considered to avoid overestimation of the total value of services.
g. Enhancing the flexibility of CCGT by reducing its operating constraints (e.g. allowing it to connect faster, to operate at a lower MSG level and to have a higher frequency response capability) will be valuable especially in the system with high wind penetration levels.
h. Providing SI, e.g. from wind power, can reduce the system cost for providing frequency response services.
i. Decarbonisation of power and heat sectors at residential buildings also opens opportunities for technologies such as micro-CHP which can improve the overall energy efficiency and provide an alternative to conventional technologies.
j. CSP technologies with thermal storage can also provide system flexibility and becomes an alternative to mainstream renewable technologies.
k. There will be market competition across different flexibility sources, and the value of a certain technology will be influenced by the presence of other technologies.
l. Deploying diverse, flexible technologies could be the least-worst regret strategy to deal with future uncertainty in the availability and cost of technologies. ‘Do Nothing’ will likely lead to a high regret cost.
Flexible DER such as DSR and ES 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. The presented studies demonstrate that the resulting benefits of a decentralised market supporting distributed flexible technologies are real and significant.

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. 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. Moreover, to optimally utilise the cross-energy vector flexibility, coordination problems in planning and operation of the multi-energy system need to be solved.

Flexible non-network technologies should play a role in displacing reinforcement of electricity grids and compete on the same level of playing field with network assets in future. This requires the development of suitable commercial frameworks and new network security standards that can integrate the non-network technologies based on their risk profiles to enable reliability and cost-benefit analysis.

Increased sector coupling requires stronger planning and operational coordination across energy vectors. For example, the co-optimisation of electricity and heat systems can improve the electricity system capability to integrate renewables by harnessing the flexibility from the heat sector. Having the flexibility to switch heat sources between electricity and gas also provides the flexibility that minimises the cost of decarbonisation.

The use of electrolysers, hydrogen storage, and hydrogen-fuelled power generation enables a higher capacity of renewables to be integrated and to displace firm low-carbon generation.

Hydrogen storage and seasonal thermal ES can be used as long-term ES to carry over the excess energy produced across seasons and to deal with uncertainty in RES output, e.g. prolonged low-wind output.

While there is a range of technologies that can enhance system flexibility, there are still many challenges in integrating those technologies into the incumbent planning and operational standards, regulatory and commercial frameworks. This will require further and comprehensive research in those areas to remove the barriers for those technologies to stimulate a wide deployment of those technologies to support least-cost decarbonisation pathways. Although many of the case studies presented in this article are based on the UK, and to some extent the EU decarbonisation pathways, the overall conclusion regarding the value of flexibility are relevant for the global energy transition.

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