Flexibility in Great Britain

CARBON TRUST

Imperial College London Consultants

Foreword

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The race to achieve net zero is on. Around the world, the enormity of this challenge is coming clearly into focus. The move to accelerate action to meet this target is highlighted in the UK's latest commitment to reduce emissions by 78% from 1990 levels by 2035, incorporating international aviation and shipping emissions for the first time.

Concurrent decarbonisation at pace and scale, beyond the energy sector, of heat, transport and industry is critical, requiring large amounts of sustained investment. As we move away from direct use of fossil fuel, these sectors will become increasingly coupled to the electricity system via direct electrification and hydrogen use.

This economy-wide effort will no doubt put stresses on the energy system, at a scale not seen previously in its history. While this increased coupling brings new and complex challenges, it also presents us with an opportunity to super-charge the net zero transition.

The energy system must become both smart and flexible to handle these increasing linkages effectively, both in terms of cost and security of supply. Security of supply is particularly important in the context of being resilient to extreme weather events. A portfolio approach, such as using CCS and hydrogen together with electrification underpinned by energy system flexibility, will help create a more resilient future energy system.

This Flexibility in Great Britain report led by the Carbon Trust unpacks these complex dynamics between achieving net zero, decarbonising heating and whole energy system flexibility at all scales. This analysis is underpinned by Imperial College London's cutting-edge modelling of the power, heat, transport and industry sectors in the UK, providing an integrated whole systems approach.

The work examines the different uncertainties the net zero transition throws up and in doing so, offers a comprehensive evidence base on the role and value of energy system flexibility under different energy system futures. The report demonstrates that energy flexibility can reduce the cost of meeting net zero and mitigate the impact of wider changes in the energy system, ensuring we reach net zero efficiently, effectively and at lowest cost.

Delivering net zero in 2050 cost-effectively requires immediate action, and this report goes beyond modelling and identifies the key barriers that could delay or even prevent the development of a smart, flexible net zero system.

As the UK prepares to host COP26 in Glasgow this year, this report presents an evidence base for the role and value of flexibility, and identifies the challenges which government and industry need to address to deliver concerted and immediate action on climate change.

Executive summary

Background to this report

Between 2016 and 2017, the Carbon Trust and independent researchers from Imperial College London delivered two milestone reports covering the role and value of electricity storage and analysis of wider flexibility within the electricity system in Great Britain (GB). Both reports used a systems approach to analyse the GB energy transition and made recommendations on flexibility technology integration that could deliver net savings across the system. While these reports and their findings continue to be used by industry and government alike, the context and ambition continues to change significantly. The net zero target has brought focus and urgency to decarbonising the energy sector beyond power to heat and transport. This created a strong rationale to develop a robust evidence base that is up to date, covers the entire energy system and considers recent advancements in technologies.

The Carbon Trust has once again collaborated with Professor Goran Strbac from Imperial College London, this time using the advanced integrated whole energy system (IWES) model to analyse the role and value of flexibility in various energy scenarios through to 2050. The scope of the analysis has been extended to cover heat, transport and hydrogen to allow due consideration to multi vector flexibility and its wider impact, ensuring comprehensive results. In addition to the previous reports, a new chapter has been added that focuses on delivering flexibility in the medium term to get us on the trajectory to a smart, adaptable and cost-effective system in 2050. This analysis takes its strategic insights from the IWES model and examines the building blocks such as policy, regulation, business models and skills required to achieve this transition. This is key as we need to consider the entire landscape in order to make the right decisions now so that we make this transition as inclusive and seamless as possible. This will give us the best chance of meeting net zero.

Given the wide-ranging scope of the analysis and insights for supporting multiple aspects of energy system development through to 2050, the report's writers convened 12 organisations across the sector from generation, energy infrastructure, retail and flexibility developers through to local government. This breadth of expertise was used throughout the project to guide its direction, challenge the results and provide insights into developments across the energy system to make the analysis as relevant as possible.

This report is therefore a response to the call from both the energy industry and government for an objective, evidence-based assessment on the role and value of flexibility in a net zero 2050 system.

Key findings

The role and value of flexibility in a 2050 net zero system

Investing in flexibility is a no-regrets decision as it delivers material net savings of up to £16.7bn/yr across all net zero scenarios analysed in 2050

Across all the heating scenarios analysed, flexibility always delivers a net saving ranging between £9.6-16.7bn/yr and supports a cost-effective decarbonisation of the energy system. This value is delivered by a portfolio of flexibility technologies including: battery storage, thermal storage (in homes and integrated with heat networks), interconnectors and a range of demand side response technologies across domestic, non-domestic and EV demands. The savings predominantly come from avoidance of gas generation (CapEx and OpEx), reduced reliance on carbon negative technologies and reduced network reinforcement. Beyond technologies such as these, flexible operation of systems like hybrid heat pumps and coordination of the hydrogen system (production, storage, conversion and use) help to maximise synergies with the wider system. High levels of flexibility deployment are required from different sources to help deliver the scale of savings in a net zero system. Up to c.48GW of flexibility from EVs, 12GW from domestic smart appliances, 11GW from non-domestic DSR, 83GW of battery storage and 900GWh of thermal storage are deployed across the different scenarios. These are significant additions to the energy system and, to put it into context, there was c.51GW of flexible electrical capacity installed in 2019 out of which 75% were gas plants.

For more details on analysis of the value of flexibility across different heating scenarios, please refer to '3.2 Electric heating pathway', '3.3 Hybrid heating pathway' and the '3.4 Hydrogen heating future' sections.

Flexibility supports a net zero energy system to cope with dark, cold and windless days in winter

It is important to consider the impact of weather patterns that cause very cold temperatures and very low wind speeds in a system that has a high penetration of renewables. This study has considered such an event across all scenarios where there is a 72 hour-period of extreme cold weather driving up heat demand coinciding with very low wind and solar PV output (<5% of maximum). An important implication of this weather event is the requirement for low-cost fossil fuel plants, particularly in the low flexibility scenarios, which are mainly used to support the system during this high stress period.

The addition of flexibility helps to reduce the peak demand for electricity and heat during this high stress period which helps to significantly reduce fossil fuel generation capacity required and its associated costs. For example, the deployment of additional flexibility in a fully electric scenario displaces over 95% of the Open Cycle Gas Turbine (OCGT) capacity which predominantly supports the system during peak stress times. This highlights the importance of modelling extreme future weather events to determine factors such as system security and adequacy.

For more details on how the model is set up, including assumptions on future weather patterns, please refer to '2.2 Integrated whole energy systems modelling - overview of modelling approach'.

Embedding flexibility in zero carbon heat and transport solutions will help to reduce their system impact and costs making their decarbonisation economically more feasible

Having smart charging and V2G allows large scale EV charging to be delivered aligned to renewable generation, whilst reducing the impact on the network through peak demand reduction. Similarly, having large scale deployment of thermal storage (up to 900GWh) allows the heat demand to be made flexible. This provides several whole system benefits: including balancing of supply and demand, better use of renewable output and peak electricity demand reduction leading to lowering the cost of network reinforcement. Additionally, the coordinated interaction between energy for heating and EV charging further helps to reduce overall system cost highlighting the importance of coordination between different flexibility sources.

For more details on analysis of the value of flexibility including those integrated within heat and transport solutions, please refer to '3.2 Electric heating pathway', '3.3 Hybrid heating pathway' and the '3.4 Hydrogen heating pathway' future sections.

Developing a portfolio of flexibility, including on the demand side, across the energy system is an effective strategy to manage uncertainties and reduce costs

Delivering flexibility from multiple sources across the energy system allows any impact of price or technology availability to be minimised. We find a variety of flexibility sources being deployed across all heating scenarios to minimise system cost rather than a few dominant ones given their individual value. For example, if sources of demand side reponse (DSR) flexibility across domestic, non-domestic and EVs are not developed and available, this creates significant pressure on other sources leading to an overall increase in 2050 system cost up to £4.5bn/yr in the electric heating scenario. This highlights the importance of having a portfolio of flexibility sources to manage risks such as high costs or low availability. Even in the electric heating scenario that relies heavily on battery storage, there is only a marginal increase in costs (c.0.2bn/yr) due to lower than anticipated cost reduction of batteries. This risk is mitigated by drawing on additional thermal storage capacity. There is also a similar effect when thermal storage's availability is minimised and additional battery storage is able to compensate, thereby increasing the cost only marginally (c.0.9bn/yr).

For more details on the sensitivities conducted on the value of different flexibility sources, please refer to section on '3.6 Impact of flexibility technology availability'.

Flexibility is deployed more locally in 2050 and delivers significant value nationally

A large proportion of the flexibility across scenarios will be distributed sources deployed locally, closer to demand. This is a significant departure from the current flexibility portfolio which is dominated by large scale plants. Analysing the distribution of benefits of deploying flexibility across different regions in this study suggests a significant value is returned back to these regions via savings in the local distribution network infrastructure. While these values are material in 2050 (£0.48bn/yr for London as an example), the local flexibility unlocks close to twice this amount in the wider system (0.94bn/yr). This highlights the materiality of system wide value of flexibility installed locally. Additionally, using flexibility to focus on only local value, such as distribution network cost reduction, increases cost marginally (£0.6bn/yr). This outlines the importance of focussing on whole system value even as the sources of flexibility and energy system development become more localised.

For more details on dynamics between local and national value of flexibility, please refer to the case study on '3.10 Local versus system benefits of flexibility'.

Energy system considerations for achieving net zero by 2050

Reaching net zero by 2050 whilst meeting security of supply requires unprecedented build-out across the energy system

Regardless of the scenario or sensitivity, the 2050 net zero energy system, is significantly larger relative to the current GB system particularly when additional flexibility is not deployed. Across the core heating scenarios analysed, the total electricity required to be delivered in 2050 rises to a maximum of c.830TWh, which represents a three times increase relative to 2019. The network build-out required is also significant, driven by an increase in total peak demand on the distribution network up to 228GW in an electric heating scenario. Flexibility present in the distribution network needs sufficient capacity to be able to charge up and discharge in response to system needs. Thus, investment in networks is also important to unlock flexibility that can deliver wider system benefits.

Depending on the scenario and carbon target imposed on the energy system, there is also a significant need for deployment of carbon negative technologies such as BECCS and DACCS up to several tens of GW by 2050. The key area of convergence between the three core heating scenarios (fully electric, hydrogen and hybrid heating) is maximising deployment of flexibility and renewables particularly offshore wind (120GW) and PV (30-55GW), thus making these no-regret actions for achieving net zero targets.

For more details on analysis of the wider system implications across different heating scenarios, please refer to '3.2 Electric heating pathway', '3.3 Hybrid heating pathway' and the '3.4 Hydrogen heating pathway' future sections.

Pushing the energy system to go beyond zero carbon has material cost and infrastructure implications

The cost of meeting a net-negative carbon target of -50MtCO_2/yr by 2050 could add up to c.£5bn/yr to the energy system. The increase in cost in our analysis is primarily driven by additional electricity generation capacity and negative carbon technology deployment in the hydrogen heating scenario where this was analysed. Beyond just a scale-up of the energy system to meet the negative emissions, this target has an implication on the wider system including the cost optimal strategy for heat decarbonisation. For example, a more stringent carbon target in a hydrogen dominant scenario drives a shift in the cost optimal production methods by reducing the proportion of hydrogen generated via natural gas reformation.

For more details on the system and flexibility implications of a net negative and zero carbon target, please refer to '3.9 Zero carbon versus net negative carbon targets for the 2050 energy system' section.

Carbon negative technologies have an important role in helping to meet the net zero target in 2050

There is a consistent deployment of negative emission technologies including BECCS and DACCS across all scenarios analysed. A key finding from this study is that the negative emissions technologies are important even when the carbon target for the energy system in 2050 is zero rather than net negative (i.e 50MtCO_2/yr). This is driven by the need to negate emissions from use of natural gas for electricity generation, hydrogen production and/or for home heating via boilers. While the deployment of BECCS is linked to the level of hydrogen demand in the system across heating and other uses, DACCS is predominantly linked to the use of natural gas in the system. In scenarios of significant natural gas use such as the hybrid heating scenario, unavailability of DACCS drives heating to be predominantly electric, needing significant additional build out of renewables and CCS capacity. In a low flexibility scenario this drives a £22bn/yr increase in system cost, while in a high flexibility scenario this is only £3bn/yr owing to peak demand management and capacity optimisation. This further highlights the value of having a flexible system which is able to mitigate against risks of technology development uncertainty with only marginal cost increases.

For more details on value of carbon negative technologies and interaction it's with flexibility, please refer to the sensitivity on '3.8 Impact of negative emissions technology availability'.

Any single heating solution dominant future has a significant cost and infrastructure impact on the energy system in 2050

GB's choice of heating decarbonisation has a significant impact on several aspects of the energy system including scaling up existing technologies and networks to needing new technologies including those that can negate carbon emissions. For example, a fully electric heating scenario without additional flexibility requires significant additional electricity generation capacity (c.422GW required - current capacity is c.108GW), with just over 50% being in reserve with very low utilisation (<5%). Similarly, a hydrogen heating scenario needs a significant scale-up of relatively new technologies such as electrolysers (35GW), hydrogen storage (c.8TWh), bio energy gasification plants (14GW) including CCS infrastructure. Hybrid heating has the ability to coordinate the use of natural gas and heat pumps that allows it be built and operated at lower cost relative to the other heating scenarios, highlighting the importance of cross-vector optimisation. However, even such a scenario requires significant increase in electricity generation capacity (294GW) and the largest deployment of DACCS across the three core heating scenarios.

Strategic areas that are therefore particularly sensitive to the choice of heat decarbonisation are: levels of carbon negative technologies required, natural gas infrastructure, hydrogen infrastructure (including storage) and electricity distribution infrastructure.

For more details on how the different heating scenarios are set up, please refer to '2.3 Background to core pathways and sensitivity scenarios'.

The use of hydrogen across the energy system brings carbon and cost benefits and requires a portfolio of production methods and availability of CCS infrastructure

Development of hydrogen use and associated infrastructure (electrolysers, hydrogen turbines and storage) for 2050 has significant system benefits if coordinated effectively. The ability of the system to optimise production to high energy supply times, store hydrogen and then use it for heating, power production and other applications across transport and industry, drives this value. This optimisation enables significant cost reduction in network and generation investment relative to an Electric Heating scenario in which this level of system-wide coordination is not possible. Integrating additional flexibility into a hydrogen dominant system has a significant effect on cost reduction and has the largest impact across all the scenarios in terms of reducing the total electricity generation capacity requirement.

The total cost of the hydrogen system is sensitive to technology (production and conversion) costs, fuel costs and availability of carbon negative technologies. Thus, retaining a diverse portfolio of hydrogen production routes (gasification, reforming and electrolysis) along with the integration of flexibility can help to avoid shocks if one or several of these dependencies become expensive and/or unavailable. However, even across this diverse portfolio, the ability to deliver hydrogen needs across the system cost-effectively is dependent on the availability of CCS infrastructure, without which significant additional costs will be incurred.

For more details on the implications of a hydrogen dominant scenario, please refer to the Hydrogen heating future section. For details on the implications of different hydrogen production routes and other key sensitivities, please refer to '3.7 Impact of hydrogen production route' section.

Considerations for delivering a smart, flexible energy system

Flexibility should be integrated into enabling infrastructure including low carbon heat and transport solutions from the start

A key consideration across the different flexibility technologies assessed is the importance of enabling infrastructure for its cost-effective and large-scale deployment by 2050. For technologies such as DSR (domestic and non-domestic), this is about ensuring the smart meter roll out does not face additional delays and having a clear route to secure cost-effective data access across millions of potential sites/devices. For technologies that are tied to broader strategies around heat and transport decarbonisation, it is important to build flexibility into technologies and service offerings right from the start rather than retrofit in the future which could make it prohibitive. Examples of such integration includes thermal storage in district heating schemes with heat pumps in domestic and non-domestic buildings and building in smart charging for all EV charging points. Delivering flexibility and associated cost-effective decarbonisation requires coordinated planning and operation across all energy sectors including electricity, gas, hydrogen and transport.

Consumer engagement on flexibility beyond just commercial value is a critical aspect to scaling up flexibility technology deployment

Unlike previous decarbonisation challenges such as large-scale generation, the roll out of flexibility needs to consider users across all stages of deployment. While early adopters of flexibility technology might find the commercial value from participating sufficient and/or be driven by other factors such as interest in new technology, translating this to 'late majority' and 'laggards' will be difficult but important. Taking a rational approach to consumer engagement that is focused solely on commercial value is unlikely to put the sector on a pathway to achieving the GW scale required to deliver material system benefits. Understanding consumer needs, crafting appropriate narratives for different segments and building them into the user experience requires significantly greater focus in technology development and demonstration programmes going forward. This is especially critical for the success of DSR, EV and TES flexibility in which the flexibility integration is tied to the broader challenge of consumer acceptance of new solutions for mobility and heating.

An evolving regulatory environment, combined with potentially low financial gains in the long term, creates challenges for business model development

Business models for flexibility have to straddle the constantly evolving regulatory environment that affects how to access, and what the value of flexibility is, with the consumer need for consistent and secure revenue streams. Novel business models and propositions that go beyond focusing on financial value of flexibility into embedding into core transport and heating service provision is important to avoid high drop off rates going forward and mitigating ‘willingness to pay’ issues. Improving routes for cost-effective data access, leveraging the significant investments into infrastructure such as the DCC will help alleviate some of the cost burden in the business models and avoid redundant investments. Fundamentally, market signals need to reflect whole system benefits across generation, networks, carbon savings and system security to incentivise the effective deployment and operation of different flexibility technologies including those on the demand side. This will also require effective coordination between actors to support deployment of flexibility for not only their benefit but also for the wider system. Greater focus to ensure effective market signals incentivise consideration of flexibility into long life time infrastructure even though the system value in the short-term might not be present or material is also important.

A smart and flexible system can only be enabled by digitalisation of the energy system

As shown this in study, the value of flexibility is unlocked through real time coordination between assets to operate in-sync to deliver whole system benefit. For example, we see the coordination between smart EV charging V2G and thermal storage in heat networks working together to minimise demand during periods of system stress. These assets sit at different levels in the energy system and also across vectors and between different ownership boundaries. Thus, a critical consideration to enable this future is the need for digitalisation across the energy system to allow information sharing, monitoring and coordination between assets and organisations at this scale. Building-in interoperability and cyber security into these plans will be important, to minimise the risk at stake for the system, retain consumer confidence and trust and to allow novel business models to flourish.

Continued efforts for new technology development and innovation focused on cross vector integration is important to have them ready in time

This study has found significant flexibility deployment needs by 2030 - for example the system could require 1GW of domestic DSR, 1GW of hydrogen electrolysers, up to 3GW of EV flexibility and significant roll out of thermal storage. Innovation is important to bring technologies such as TES and electrolysers to the market at the appropriate cost point and technical capability ahead of 2030. Given the linkages between these technologies and the wider system, especially electrolysers, it is important to design and integrate them from a whole-system perspective rather than in isolation.

For technologies such as DSR, battery and thermal storage and EV flexibility, development efforts should focus on cost-effective system integration and engaging consumer experience going forward. Additionally, a greater focus on innovation that demonstrates cross-vector flexibility is important to understand the issues and scale of complexity (technical, regulatory and social) in delivering this in practice.

Structure of the report

This report is structured across five main chapters excluding the appendices. The details covered in each chapter is outlined below.

Chapter 1

Provides an overview of the current GB energy system and an introduction to different forms of flexibility.

Chapter 2

Describes the integrated whole energy systems (IWES) model and the scenarios modelled.

Chapter 3

Sets out the results of the IWES modelling and the value of flexibility under various energy system futures in 2050.

Chapter 4

Considers what flexibility needs to be deployed by 2030 and examines the barriers facing these different types of flexibility.

Chapter 5

Sets out the key recommendations based on the findings in Chapters 3 and 4.

Appendices (separate download)

Describes the IWES model and model inputs and provides more detail on the evidence collected about barriers to flexibility deployment.

Overview of methodology

Modelling overview

This work is underpinned by Imperial College London's integrated whole energy systems (IWES) model. IWES is a least cost optimisation model that can simultaneously minimise long-term investment and short-term operating costs across the whole energy system while meeting required carbon targets and system security constraints. IWES is an enhancement of the Whole Energy System Investment Model (WESIM), which has been used extensively, including in the Carbon Trust and Imperial College London's 2016 reports 'An analysis of electricity system flexibility for Great Britain' and 'Energy storage report: can storage help reduce the cost of a future UK electricity system?'. The key enhancement in the IWES model is the addition of other heating technologies, including the ability to optimise natural gas, hydrogen, district heating (DH) networks, thermal and hydrogen storage. This advancement has allowed this work to take a comprehensive whole systems approach to analysing the role and value of flexibility across the energy system.

Summary of scenarios and sensitivities undertaken

The report's focus is on understanding the role and value of flexibility in a net zero 2050 energy system. It takes a scenario-based approach to lay out three different 2050 futures driven primarily by the heat decarbonisation strategy - electric heating, hydrogen heating and hybrid heat pump heating. These were chosen as heat decarbonisation was found to have the greatest uncertainty but also the most impact on the shape and form of the energy system.

The electric heating scenario is dominated by air source heat pumps (ASHP) across domestic and non-domestic buildings. The hydrogen heating scenario deploys mainly hydrogen boilers while the hybrid heating scenario uses ASHPs coupled with a gas boiler. Across all three scenarios there is assumed to be DH networks consisting of ASHP or water-source heat pumps supplying around 20% of all domestic heat demand. Properties not connected to the gas grid are assumed to have individual ASHP and resistive heating in all scenarios.

In reality, heat decarbonisation is likely to consist of a mixture of technologies. However, in this report we have looked at scenarios dominated by one heating technology to highlight the role and value of flexibility alongside these heating approaches. This allows a greater understanding of the type of flexibility technologies required, including how they interact with the heating system to deliver the demand and with the wider system to reduce costs. Each scenario is analysed with (high flexibility) and without (low flexibility) additional flexibility technology deployment to help determine the impact of flexibility across key metrics such as system cost, system demand, electricity generation capacity and emissions profile.

In addition, the report undertakes a range of sensitivity analyses across the three scenarios to develop diverse results not only on the role and value of flexibility, but also on the impact on the wider system of key uncertainties in a 2050 energy system. These include: the cost and availability of key flexibility technologies; diversified and dominant hydrogen production pathways; unavailability of carbon negative technologies; reducing the carbon target of the energy system from net negative to just zero to reflect potential solutions development in currently hard to decarbonise sectors; and optimisation of system costs for local or national energy system benefits.

Overview of delivering flexibility analysis

This section focuses on identifying key actions required between now and 2050 to achieve the scale of deployment of each source of flexibility indicated by the model in the 'high flexibility' scenarios. The technologies include domestic demand side response (DSR) from smart appliances, non-domestic DSR, electric vehicle flexibility (smart charging and vehicle-to-grid), thermal energy storage (TES) integrated with DH schemes and within buildings, electricity storage and hydrogen electrolysers.

This analysis has been carried out by first developing an indicative 2030 deployment trajectory for each source of flexibility using a simplified diffusion curve. These indicative interim deployment goals have then been used to assess any barriers using the Deployment Readiness Assessment framework. This framework takes a holistic view of market enablers, business models and other key factors required to successfully deploy flexibility on a large scale.

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