INNOVATING TO NET ZERO 2026

CATAPULT Energy Systems

Innovating to Net Zero 2026:

Scaling flexibility to meet the five peaks challenge

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Key messages

1. **The gaps between electricity supply and demand shape the overall scale and architecture of the future energy system.** Our analysis identified five different gaps that need to be considered: the Peak Power and Peak Energy Gaps within a single day; the Peak Daily and Peak Duration Gaps over multiple days; and the Peak Heat Gap during times of extreme cold weather.

2. **Higher levels of renewable generation deliver the most cost-effective energy system, but only if appropriate levels of flexible storage and dispatchable generation are also provided.** Our modelling suggests a high-renewables, high-flexibility pathway reduces cost by 1.5% – around £70 billion – compared to a scenario with lower renewables.

3. **No single flexible technology is most cost-effective in addressing all peak gaps.** Three key metrics (£/GWh of storage, £/GW of capacity and %round trip efficiency) characterise flexible technologies and determine the choice of technology.

The Peak Power and Peak Energy Gaps – intra-day flexibility

4. **Most intra-day flexibility requirements can be met by static batteries or electric vehicle (EV) batteries. EV batteries are especially valuable as their cost is not carried by the energy system.** From an energy system perspective, static batteries will always be a more expensive option than EV batteries for flexibility. Vehicle to grid (V2G) provides more system benefit than smart EV charging, but the latter has a lead in both level of deployment and consumer acceptance.

5. **The opportunity for static battery deployment appears to be time-limited. The 23-27 GW of static batteries planned within the government's Clean Power 2030 Action Plan meets the need for intra-day flexibility to 2030, buying time for smart EV charging and V2G to mature.** Only if innovation in smart EV charging and V2G fails to deliver do we foresee further deployment of static batteries.

6. **Increased penetration of EVs has the potential to provide all the growth in flexibility from 2030 needed to meet the intra-day Peak Energy and Peak Power Gaps to 2040**. By 2040, between 20-35% of flexibility requirements of the Peak Energy and Peak Power Gaps is met by EV flexibility. Innovation remains critical to ensure this flexibility can be deployed effectively. This is a major opportunity for artificial intelligence (AI) and digital innovators. This is set out in more detail by the AI for Decarbonisation's Virtual Centre of Excellence (ADViCE) programme in Grand Challenge 8 on intelligent EV charging.

7. **Smart EV charging, to shift demand away from the Peak Power Gap, could rise to 40 GW by 2040, and will also be essential to reduce local grid constraints.** Co-ordinating and scheduling EV charging to manage constraints requires solutions from both a technical and market-design perspective.

8. **V2G's potential to reduce peak electricity demand makes it especially valuable, providing almost twice the flexibility per EV as smart charging. By 2040, V2G could provide the equivalent of 25 GW of flexibility, but challenging questions remain around consumer uptake.** Improved consumer propositions, a wider range of V2G-capable EVs and chargers, and innovation in control and integration will all be needed if V2G is to reach its potential. By 2040, up to 22 million EVs shift around 1 TWh of energy through smart charging in a typical winter week while only 4.2 million V2G-equipped EVs deliver around 350 GWh of energy in a similar period.

9. **Other smart energy appliances such as heat pumps have a potential role to play in managing intra-day flexibility, particularly if EVs do not deliver to their expected potential.** Heat pumps could represent around 20% of typical winter electricity demand by 2040 with a peak demand of around 16 GW. Heat pumps sized to operate flat out on the coldest day could still turn down the heat to offer some flexibility, but it is not clear if this will be acceptable to customers. Hybrid heat pumps, that include a gas boiler, offer greater potential for flexibility.

The Peak Daily and Peak Duration Gaps – between-day flexibility

10. **A combination of nuclear and renewable generation provides a lower total system cost than either technology alone. Nuclear also reduces the need for between-day flexibility, particularly in respect of the Peak Duration Gap.** In our analysis the ratio of nuclear to renewable capacity ranges from 1:3 to 1:4 by 2040, with nuclear generation reducing the total size of the Peak Duration Gap by as much as 10 TWh. In sensitivities without new nuclear capacity, we saw an increase in system costs of up to 1.1% (£50 billion) by 2050. This underlines the importance of innovation to accelerate deployment of new nuclear.

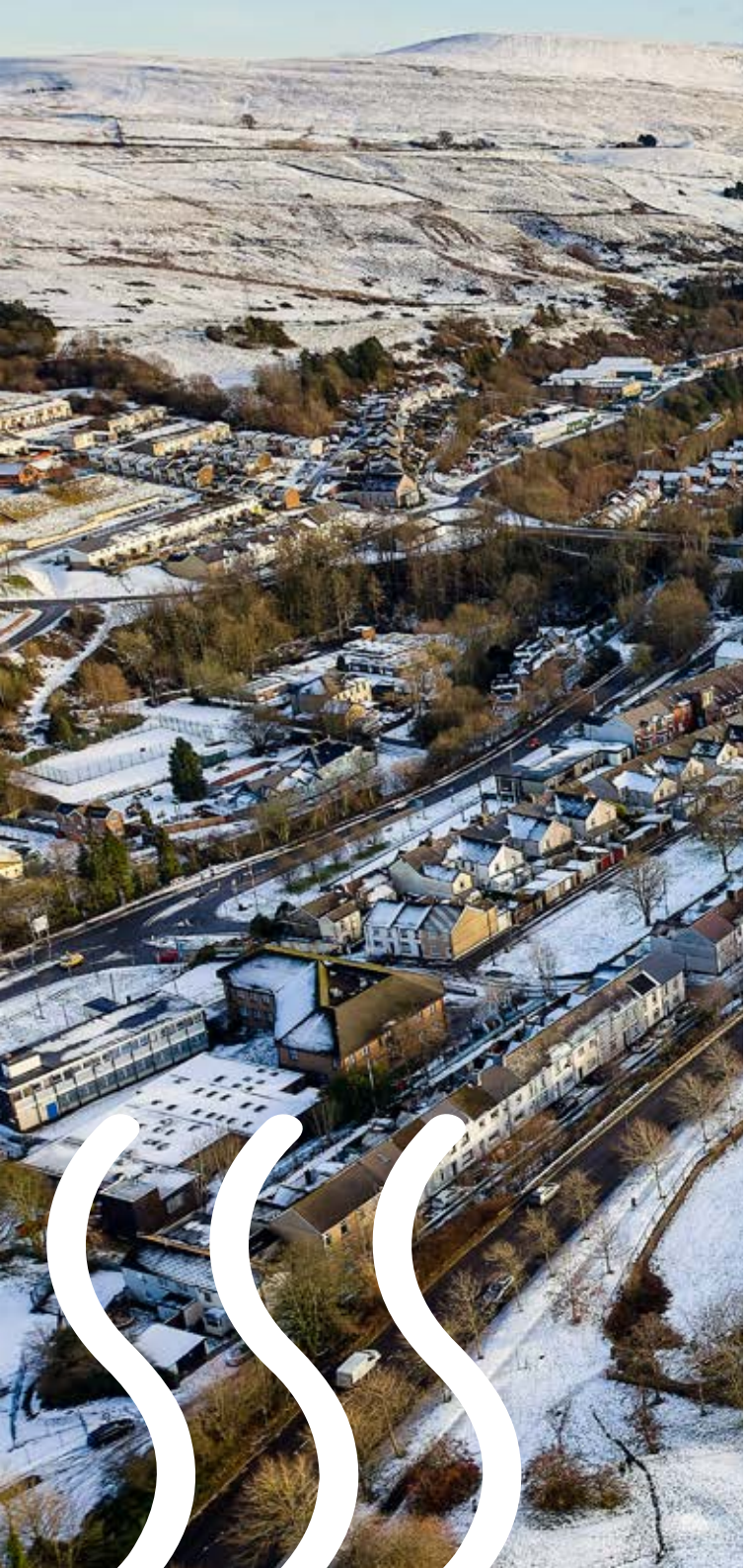
11. **While carbon capture and storage (CCS) is used extensively in industry, gas turbines with CCS for power generation appear too expensive to be deployed at scale, increasing to only 4 GW by 2040. Those that are built run for long periods of time displacing renewables rather than unabated gas peaking plant.** Innovation in solvent and process design as well as learning by doing through large-scale demonstrators are needed to drive down cost to compete with nuclear generation for baseload power, or hydrogen turbines if acting as peaking plant.

12. **Unabated gas peaking plants remain an important part of the generation mix to meet the Peak Duration Gaps throughout the energy transition, with at least 20 GW still required in 2040.** Innovation is needed to drive down costs of maintenance and life extensions, for assets that will be used with decreasing frequency.

13. **Hydrogen turbines are deployed to meet the peak daily and duration gaps in preference to gas turbines fitted with CCS, saving 0.2% of total system cost (around £10 billion).** The difference in system cost is driven mainly by the need for a much larger CCS infrastructure for the gas turbine as it runs intermittently, compared to CCS for a methane reformer to produce stored hydrogen that can run continuously.

14. **Hydrogen turbines have high potential and could provide 35% of the capacity to meet the Peak Daily Gap, with up to 6 TWh of hydrogen salt cavern storage meeting the Peak Duration Gap by 2040. This hydrogen is produced largely from methane using CCS rather than by electrolysis.** If CCS fails to achieve the expected carbon capture rate or if the whole systems costs of electrolysis including the system cost of its power can be reduced, then there may be a larger role for hydrogen electrolysers. It's important that demonstrators for hydrogen for power and storage are deployed in the next five years.

15. **Technologies such as pumped hydro storage, compressed air energy storage and novel battery chemistries may have a role to play in the transition from intra- to inter-day flexibility, but current cost projections limit their deployment.** The scale and nature of each technology's participation will be determined by how innovation can improve each of their three key performance metrics (£/GWh of storage, £/GW of capacity and %round trip efficiency).



The Peak Heat Gap – managing heat demand

16. **The Peak Heat Gap during sustained periods of cold, calm winter weather creates up to an additional 2.5 TWh per day of heating demand. This puts severe strain on an electrified energy system and presents probably the greatest unsolved challenge to the energy transition.** The scale of this challenge and the potential for cross-vector solutions that don't apply to other peak gaps have led us to consider peak heat as a fifth separate type of gap.

17. **Energy efficiency remains an important way to reduce all the peak gaps, particularly for buildings where reducing heat demand is essential to address the Peak Heat Gap.** Innovation is needed to develop insulation measures that are easier to install and less prone to poor quality. Technologies and approaches to measure in-situ energy performance of the home exist (e.g. SMETERs[1]) but need to be integrated into policy and matched with attractive pay for performance-based customer propositions.

18. **Thermal storage can be used to bridge the Peak Energy and Peak Power Gaps in homes, particularly those connected to heat networks where large hot water stores are practical.** A typical domestic hot water tank (for which many homes no longer have space) is useful for managing intra-day peaks but can store only a tenth of the energy needed to heat a typical home on a cold day. The development of higher energy-density thermal stores could provide more flexibility for homes without access to heat networks.

19. **If innovation fails to curtail electricity demand during the Peak Heat Gap several difficult options remain.**
    - Provide up to an additional 50 GW of peaking plant.
    - Increase heat network penetration potentially four-fold.
    - Retain the gas grid, potentially switching mainly to biomethane, with a fallback boiler in most homes.
    - Curtail much of industry during these periods.
    - Or rely on behaviour change and manage the impact of colder homes.

    Finding the most effective solutions to meeting the Peak Heat Gap will require further research and a targeted programme of innovation to ensure they are ready for implementation by 2040.

Integration

20. **While modelling has been the historical tool of choice to develop pathways for the shape and scale of the energy transition, new tools are needed to understand and determine how to integrate all aspects of the whole system. Energy Systems Catapult has developed the energy System of Systems Map to support this integration.** The System of Systems Map allows users to visualise how technologies, markets and organisations interact across the energy system and the information flows between them, allowing more effective solutions to be developed to coordinate and enable system operation.

21. **The System of Systems Map underlines how we need to change the way we think about and operate the energy system – a shift from commanding generation to orchestrating flexibility. This needs to address not just the way we produce, store and use energy, but also the enabling areas of the system:**
    - Networks to move energy from where it's available to where it's needed.
    - Digital infrastructure and AI needed to enable system visibility and operation.
    - An understanding of consumers and how they respond within the system.
    - Policy, regulation and markets to underpin how energy is created and used.

Networks

22. **Energy networks are changing as the system transforms. Electricity networks will be expanded and reinforced. The gas network will remain to 2040 and beyond but with substantially reduced demand from 689 TWh per year in 2024 to as low as 347 TWh by 2040. Heat networks will expand to over 3.2 million homes. And a new localised hydrogen networks may be required for industrial clusters.** All present challenging innovation opportunities such as maximising useable capacity in the electricity network, managing rarely-used gas assets, integrating waste heat from nuclear power into heat network, and repurposing existing pipelines for hydrogen distribution.

Digitalisation and AI

23. **Innovative digital solutions, including those that harness AI, are essential for the integration and control needed for a smarter, more efficient and lower-cost energy system.** Digitalisation can deliver most impact by improving information flows that provide:
    - Real-time visibility and control;
    - Smarter forecasting and decision making;
    - Coordination across distributed assets.

    While the technologies needed to process data at the required scale have been proven in other sectors, there is still much development and innovation needed to apply them across the energy sector.

Consumers

24. **Enabling household consumer flexibility will require smart, flexible solutions that are controllable, reliable and low-cost; more than it will require behavior change.** Households could provide around 76 GW of electricity flexibility by 2040. While automation makes flexibility far easier, consumers are not removed from the process entirely. The right consumer propositions and tools are needed to encourage uptake.

25. **The commercial and industrial sectors could provide around 10 GW of flexibility by 2040, but this is uncertain and there may be opportunities to further increase the potential for flexibility.** Barriers to uptake include lack of alignment with an organisation's core business, lack of visibility of benefits, and highly complex customer journeys.

26. **Data centres are expected to add substantial new load to the energy system, equating to around 5% of total electricity demand by 2040. This presents significant opportunities for flexibility.** Innovations in load shifting both temporally and geographically, local heat stores and reuse of waste heat, could all help manage peak gaps. Data centres that install their own gas-fired generation to overcome grid constraints could be used as an alternative to replacing aging gas-peaking plant.

Policy, regulation and markets

27. **Markets should be developed to reveal the best combination of flexible technologies to address the requirements of the peak gaps, rather than picking specific technologies.** Market dynamics should reveal the scale of the five peak gaps and incentivise market participants to deliver the most cost-effective combination of solutions wherever possible. This includes consistent carbon pricing, more temporally and spatially granular markets (including nodal pricing) and reform of the capacity market.

28. **Usage for unabated gas turbines is rare and hard to predict, limiting the ability of the wholesale market alone to deliver sufficient capacity.** Alternative funding mechanisms will be required for this, including strategic reserves.

29. **If we are to unlock the potential of flexibility to reduce costs, we need to develop processes for policy and regulatory change that more closely follow the speed of technology innovation and progress.** The emergence of digitalisation, data and AI makes this even more urgent. Greater diversity in regulation is to be encouraged to allow innovative technologies and services to rapidly emerge, driving down costs for consumers.

Innovators

30. **UK innovators are well-placed to meet these flexibility challenges having raised over £12 billion of investment in this area since 2000.** Innovation in flexibility not only drives out costs in the energy system, but it also creates wider value to the UK through technology export. Much can be done to support UK innovators achieving these goals through improvements to policy, markets and regulation; greater clarity and simplicity of revenue streams; funding for innovation; better access to data; and stimulating consumer awareness and engagement.

Context and defining the ‘peak gaps’ of the future energy system

Driving cost out of the energy system is essential if we are to transition at the pace and scale needed

The UK’s energy system has been transformed over the last two decades, with all coal-fired generation phased out, over 46 GW of renewable power deployed, and new demand-side technologies such as EVs and batteries emerging at a faster-than-expected rate, partly thanks to tumbling costs.

High international commodity costs during the gas crisis forced the government to spend £44 billion supporting customers – an unprecedented bailout. But despite falling global gas prices since, electricity prices, particularly for industrial and commercial consumers remain stubbornly high compared to our international competitor markets. This is partly because of the legacy costs of supporting renewable technologies when they were emerging.

This has helped erode the political consensus for climate action in the UK, which is also reflected internationally. Yet the economic and environmental risks of climate change remain profound and urgent.

Creating a low-cost electricity and wider energy system is essential to maintain political support for the transition. Unlocking the potential of flexibility is therefore an urgent priority, both for the UK and its climate ambitions, but also internationally.

The changing generation mix, the carbon price and competitive low-cost flexible technologies mean it’s no longer cost-effective to build large-scale fossil fuel plants to balance the electricity system day-to-day. Therefore new, more cost-effective low-carbon options for balancing the system and ensuring supply always meets demand are emerging. More are needed.

Beyond the power sector, the wider energy system needs to accelerate decarbonisation through a combination of more energy-efficient processes, electrification and new gaseous-based technologies, particularly for those demands which cannot electrify.

Recognising that clean electricity will be the backbone of the future energy system, the current government committed to **Clean Power 2030.**

The specific commitment set out: **“In a typical weather year, the 2030 power system will see clean sources produce at least as much power as Great Britain consumes in total over the whole year, and at least 95% of Great Britain’s generation; reducing the carbon intensity of our generation from 171gCO2e/kWh in 2023 to well below 50gCO2e/kWh in 2030.”**[2]

This is a hugely ambitious target. It has led to an acceleration of both the deployment of renewables and grid expansion, particularly electricity transmission. This ambition makes it even more urgent that we unlock the potential of flexible technologies, both to support the Clean Power 2030 mission, but also to ensure our energy system beyond that date can capture the value of emerging low-cost technologies, and remains as resilient as is needed for a modern economy.

Our Innovating to Net Zero work breaks down this challenge and looks at why building a more flexible future energy system is so important. It identifies the key technologies that will support the transition and the huge market opportunities for innovators who can commercialise the products and services needed.

Innovating to Net Zero 2026 explores how flexibility can bridge gaps between supply and demand, reducing the overall cost of the system

Innovating to Net Zero is Energy Systems Catapult's flagship publication exploring the market opportunities for innovators in the energy transition. Each report uses detailed modelling to provide evidence-backed insights into many aspects of the energy transition. It draws on the Catapult's extensive back catalogue of work with high-potential innovators and our thought leadership about the architecture of a future clean energy system.

Innovating to Net Zero 2024 identified that the way we meet the need for electricity at times of low renewables and high demand is one of the biggest innovation challenges we face on the path to 2050. This report delves further into these gaps between supply and demand, how we can use flexibility to address these gaps, and what opportunities this creates for innovators.

We define energy system flexibility as **"balancing energy demand and supply across all time and spatial scales, keeping within the physical constraints of the system."**

The energy system has always needed flexibility. Think of stockpiles of coal, tanks full of petrol and pipes full of gas.

The transition to a cleaner energy system, with more of our energy services electrified and the replacement of dispatchable fossil fuel generation with variable renewable generation, profoundly changes the nature of this flexibility challenge.

Without flexibility to provide real-time balancing, electricity networks will not be able to maintain power quality, creating the risk of localised interruptions and, in worst-case scenarios, national blackouts. Flexibility in the power system can also provide other benefits such as managing the delivery of network upgrades by deferring network reinforcement and supporting system recovery, for example after a power interruption. Whilst we recognise these additional benefits of flexibility, our numerical analysis focused on flexibility for balancing supply and demand.

Even for other vectors such as natural gas and hydrogen, which don't need to be balanced over short timeframes, there still ultimately needs to be a balance between energy provided and energy used. Different types of flexible technologies are therefore essential to ensure we continue to have a reliable and resilient energy system.

And meeting this challenge provides national and global market opportunities for the innovators who are most successful in bringing their flexibility solutions to market.

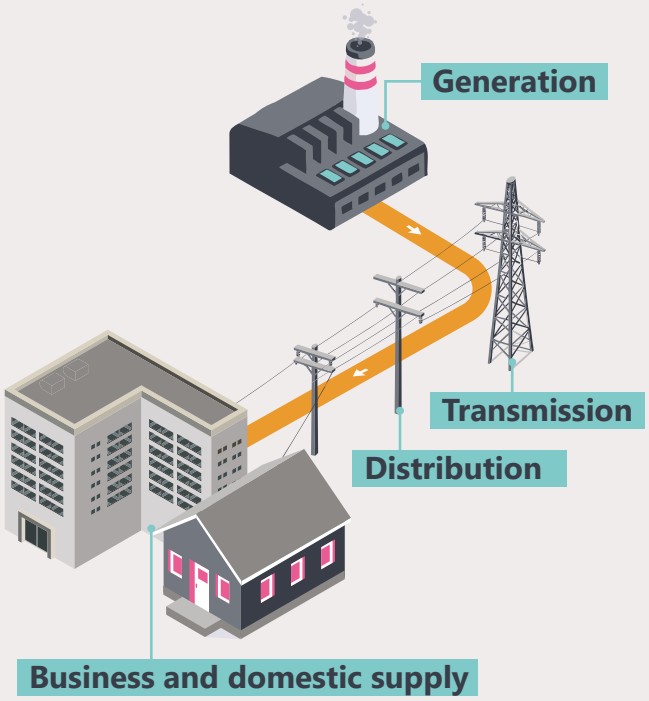
This is a huge systems challenge, particularly for the electricity system where balancing needs to happen in near real-time. It will require innovation from engineers, technology entrepreneurs, businesses with new consumer-facing products and services, as well as policymakers and regulators.

A smarter, more complex electricity system is emerging – flexibility will be essential to make it work

Hover over the titles for key characteristics of each energy system.

Centralised past

System operator

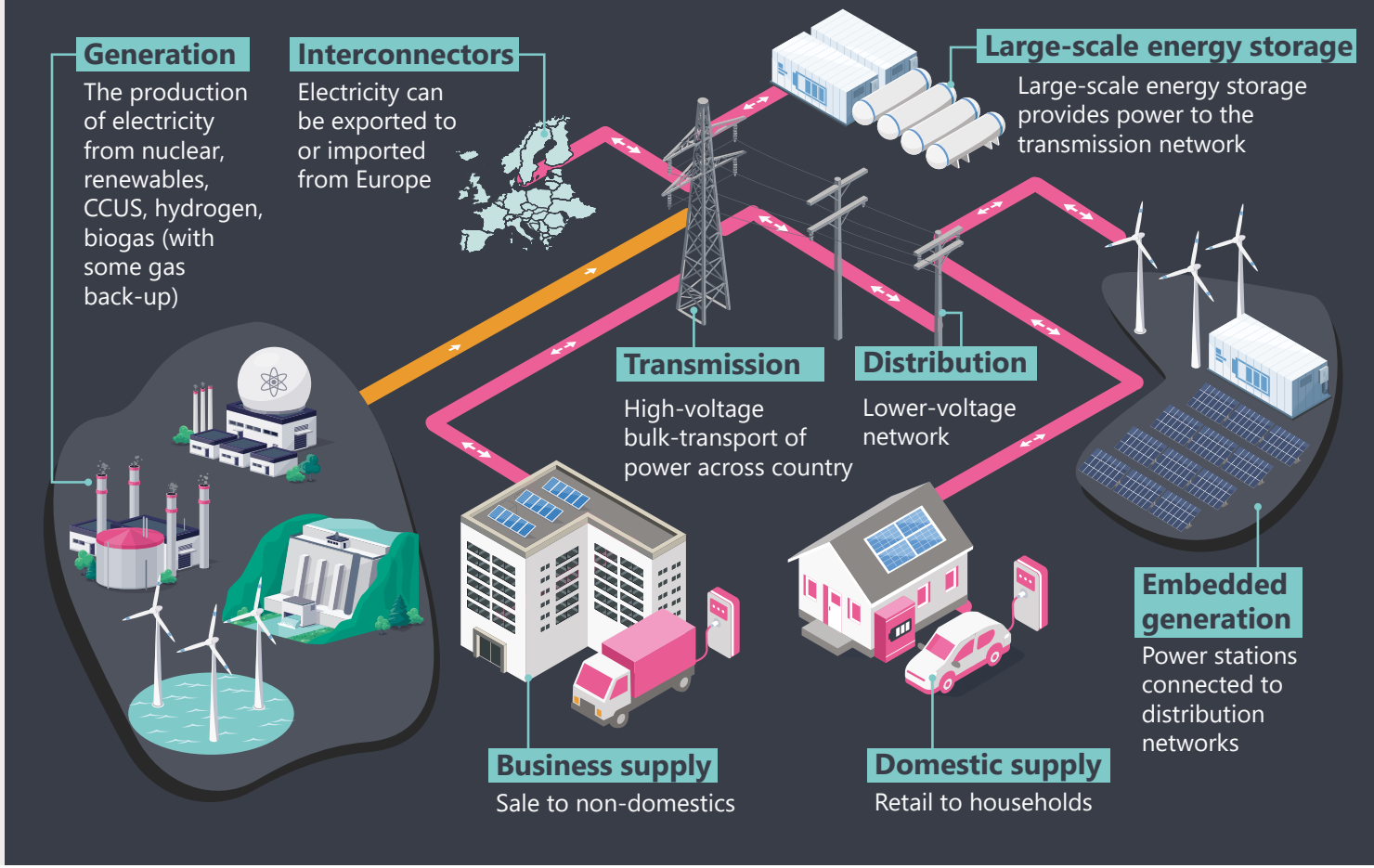


Energy flows in one direction

Energy flows in both direction

Distributed future

Transmission system operator | *Distribution system operator*



The scale of flexibility needed in a future energy system can be determined by a set of four 'peak gaps'

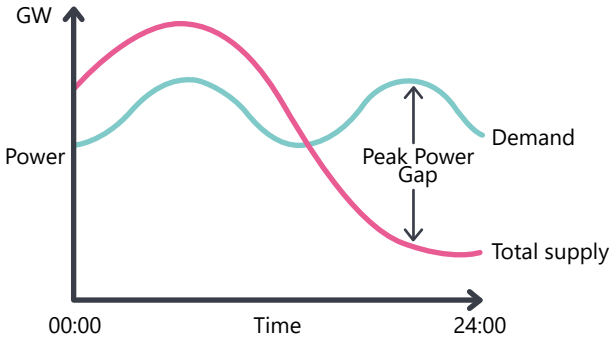
In exploring the requirements for flexibility, we found it instructive to consider the types of energy imbalances that can occur in the system. For electricity, we identified four peak gaps that quantify the amount of flexibility or storage we need to balance the system in both capacity (power) and volume (energy) terms. Peak gaps differ from the traditional peak demand in that they relate to the difference between supply and demand rather than an absolute value.

Technologies to meet these gaps fall into two groups: intra-day balancing and between-day balancing. The peak power and energy gaps set the intra-day needs (covered in the intra-day flexibility section), while the peak daily and duration gaps define the between-day needs (covered in the between-day flexibility section).

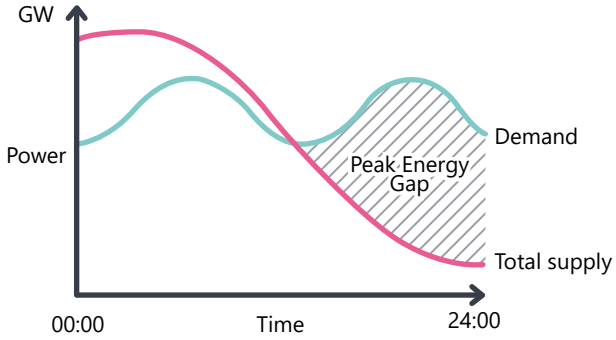
Different flexibility solutions are best suited to address different gaps, depending on three key metrics: £/GWh of storage, £/GW of capacity and %round trip efficiency.

Throughout the document, where we refer to peak gaps we mean both the worst case and similar stress events of a lesser scale that will occur more often.

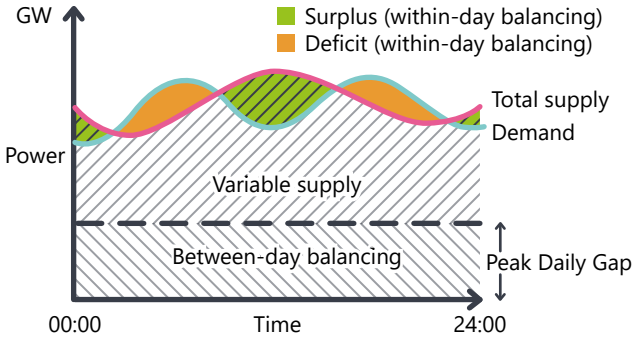
Peak Power Gap – the instantaneous maximum gap (in GWe) between supply and demand, driving the need for short-term capacity.



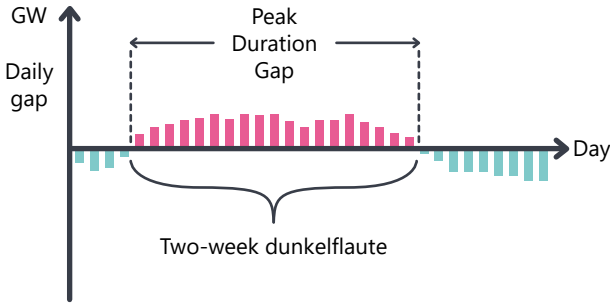
Peak Energy Gap – the maximum amount of energy (in TWhe) to be shifted during a single day to minimise the need for dispatchable power.



Peak Daily Gap – the maximum amount of extra dispatchable power (in GWe) that over the course of a day would bring low-carbon generation into balance with demand.



Peak Duration Gap – the volume of storage needed (in TWhe) to address prolonged periods of low renewables generation.



A fifth gap relates to the demand for heat during times of very cold weather – the 'Peak Heat Gap'

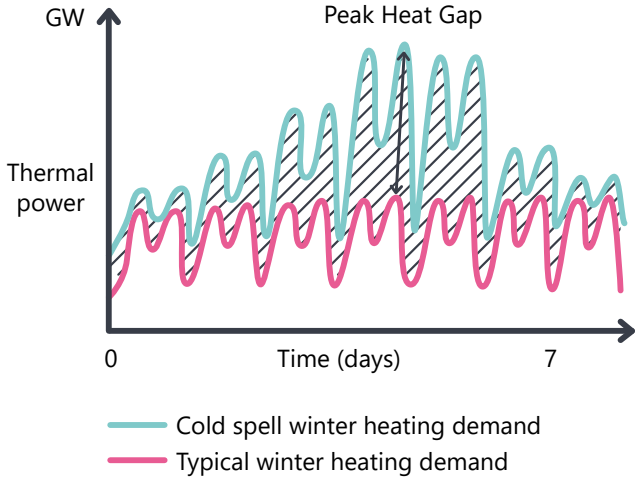
The UK's generally mild, wet winters are occasionally interrupted by severe cold snaps. For example, in December 2024 to February 2025 average temperatures were 4.6°C[3], but some areas saw daily averages drop to -7.5°C during this period[4].

Historically, electricity infrastructure has been sized to meet an average winter, as electric heating was not a significant driver of demand. The gas network, on the other hand, was sized to a 1:20 extreme cold spell, recognising gas demand is driven primarily by external temperatures.

Sustained periods of very cold winter weather can create an **additional 2.5 TWh_{th} of daily heat demand.** This puts severe strain on an electrified energy system and **presents probably the greatest unsolved challenge to the energy transition.**

This gives rise to our fifth gap – the Peak Heat Gap. This is the additional heat demand during a period of extreme cold weather that is not cost-effective to satisfy using electricity under current assumptions of technical cost and performance.

It differs from the other gaps in that it is a measure of heat rather than electricity. And because it occurs only very rarely, there are several alternative solutions to bridging this gap, which are explored in more detail later in the report.



Very cold winter weather can create an additional 2.5 TWh_{th} of daily heat demand.

Scale of the challenge

We used the Catapult's whole system models and a scenario-based approach to explore the need for flexibility

We developed and assessed four future scenarios for the energy system to understand how variation in supply and demand for energy might evolve to 2040 and beyond, particularly in light of the government's ambition around Clean Power 2030.

Crucially, we wanted to understand what effect different versions of the future energy system have on the scale of peak gaps and hence the future needs and market opportunities for flexibility.

Name	Scenario summary
Higher Dispatch	Clean Power 2030 is met with a rapid deployment of renewable generation although less than other scenarios, and with more generation from low-carbon dispatchable power by 2030.
High Renewables	Clean Power 2030 is met, largely through a rapid deployment of renewable generation and batteries. The installed capacity of some technologies is based on NESO's 'New Dispatch' scenario[5].
Further Offshore Wind	Clean Power 2030 is met in a similar way to the High Renewables scenario but with additional deployment of offshore wind and batteries. The installed capacity of some technologies is based on NESO's 'Further flex and renewables' scenario[5].
Steady Transition	Clean Power 2030 is not met, but deployment of low-carbon technologies continues at a pace that ensures Carbon Budget 6 and Net Zero 2050 are delivered.

Summary of whole system modelling scenarios

Electricity consumption increases as sectors, especially transport and heat for buildings, largely electrify

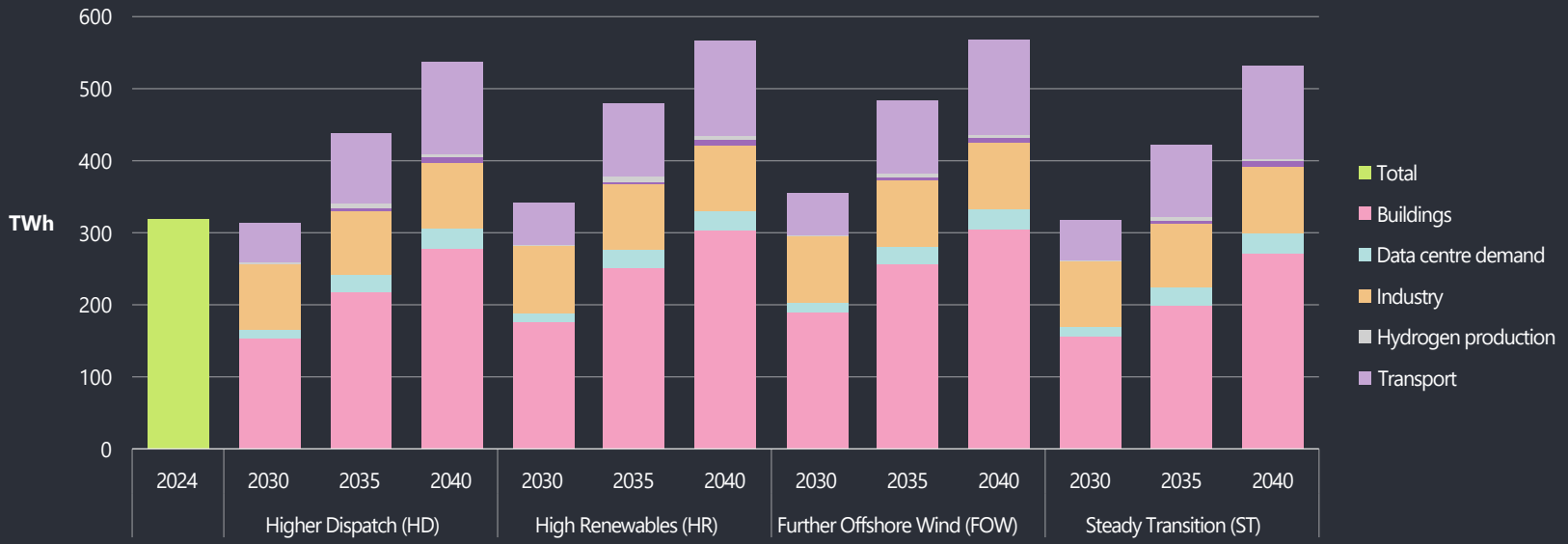
Electrification of transport and heat, and the growth in data centres drives a significant increase in electricity demand in all scenarios.

Data centres are assumed to require an additional 28 TWh in 2040, representing 5% of overall demand.

Electricity consumption increases from today's levels by as much as 10% by 2030 and 70-80% by 2040.

As carbon budgets tighten and more low-carbon electricity becomes available, the majority of surface transport and significant levels of building heat are electrified by 2040.

The overall demand for electricity for industrial processes shows little change after 2030. Wider electrification of industrial activity is countered by the increased efficiency of using electricity rather than fossil fuels. Although there is also a significant amount of fuel switching to other options such as biomass, hydrogen, and gas with CCUS.



Electricity consumption in 2024 and modelled electricity consumption for 2030-2040

80%

Electricity consumption increases by as much as 80% by 2040

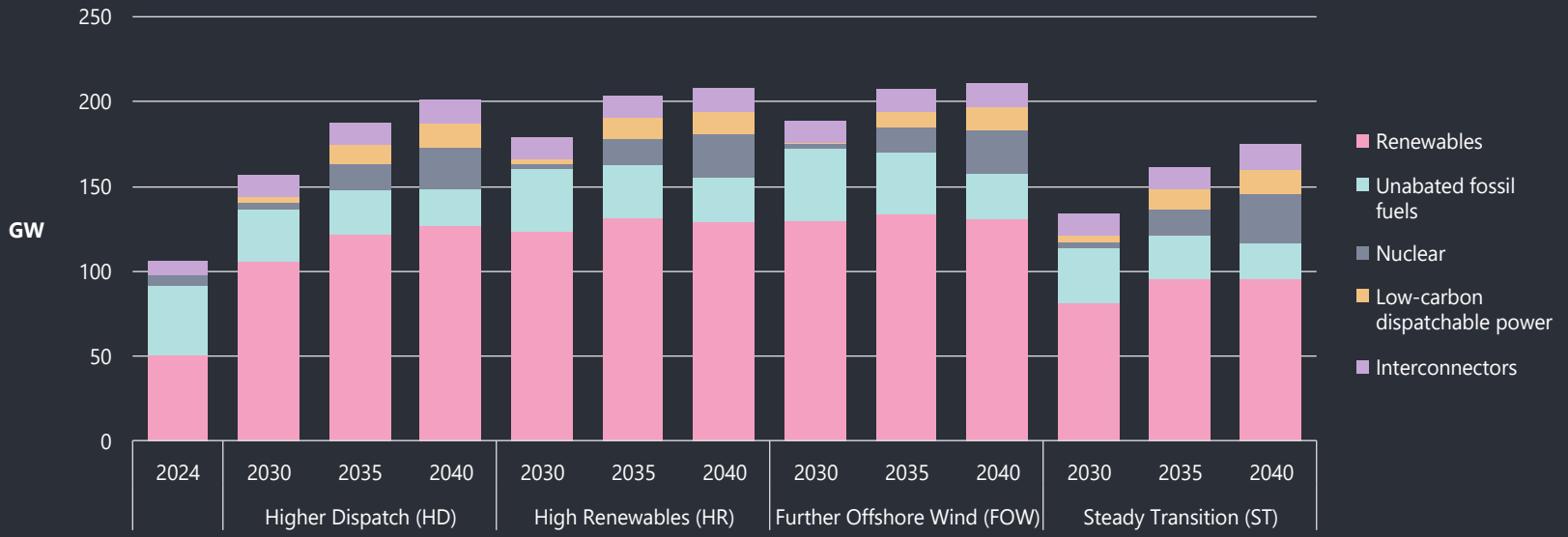
Renewable generation capacity increases rapidly to 2030 in all our scenarios. It will only realise lower system costs if partnered with flexibility

Renewable generation capacity increases between 1.5x and 2.4x by 2030.

In all scenarios, electricity generation capacity is increasing to meet the rising demand for electricity but also switching away from fossil fuels to low-carbon generation.

While this results in a significant increase in renewable generation from 2024-2030, it is greatest in High Renewables and Further Offshore Wind scenarios, where the NESO Clean Power 2030 pathways expect at least 43 GW of offshore wind and 47 GW of solar PV.

If this challenging level of renewable deployment can be achieved by 2030, alongside the necessary flexibility to 2030 and beyond, then these high renewable scenarios for Clean Power 2030 result in the lowest total overall system costs out to 2050.



Electricity generation capacity in 2024 and modelled electricity generation capacity for 2030-2040

2.4x

Renewable generation capacity to increase by as much as 2.4x by 2030

Electrification of demand and further renewable supply drives an increase in the need for flexibility

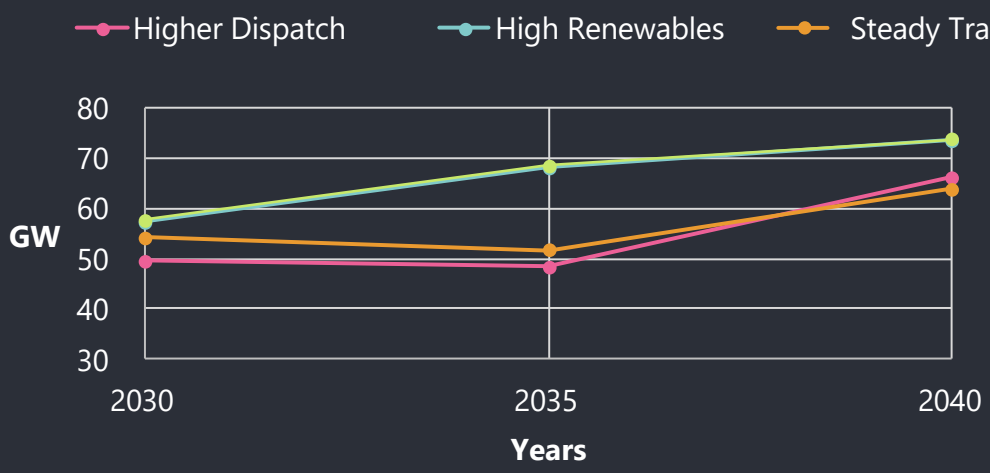
We analysed 44 years of historic weather data (1980-2024) to work out the potential size of each of the peak gaps under our four scenarios (see next page).

This allowed us to model hour-by-hour supply and demand in 2030, 2035 and 2040, allowing us to assess the impact of each peak gap on the future energy system.

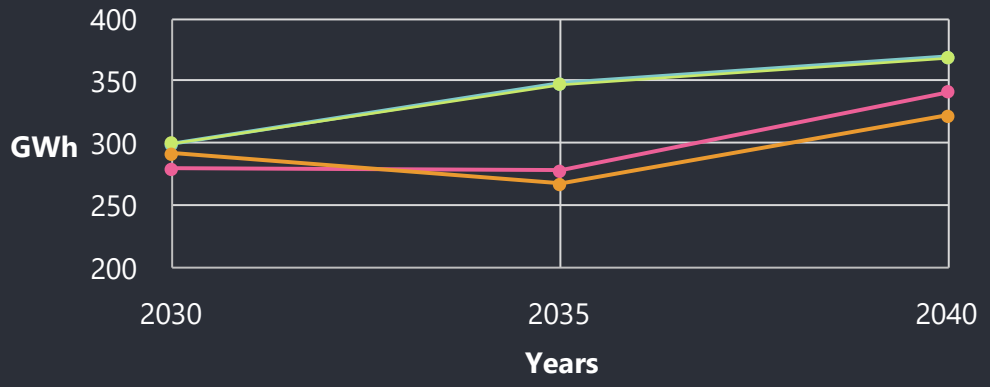
The size of the total gap provides insights on the requirements for flexibility.

1. The need for flexibility (i.e the size of the gaps) increases more across the scenarios with higher renewables.
2. The ratio between Peak Energy and Peak Power Gaps suggests each stack of batteries will need to spread their daily output over up to six hours compared to one to two hours today.
3. It is important to note that not all the peaking plant needed to meet the Peak Daily Gap runs continuously during the 14-day Peak Duration Gap. This means other technologies which cannot run for the entire length of the Peak Duration Gap could still contribute to providing within-day flexibility during this period.

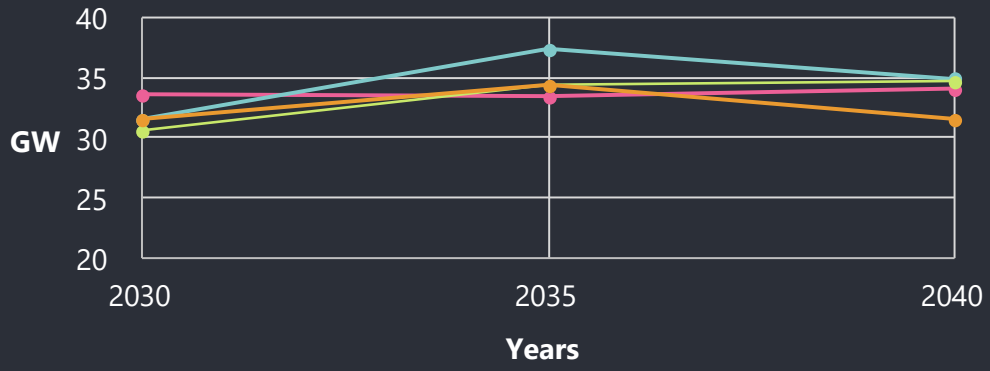
The peak gaps and therefore the need for flexible technologies will increase to 2040. Significant flexibility is needed in all scenarios



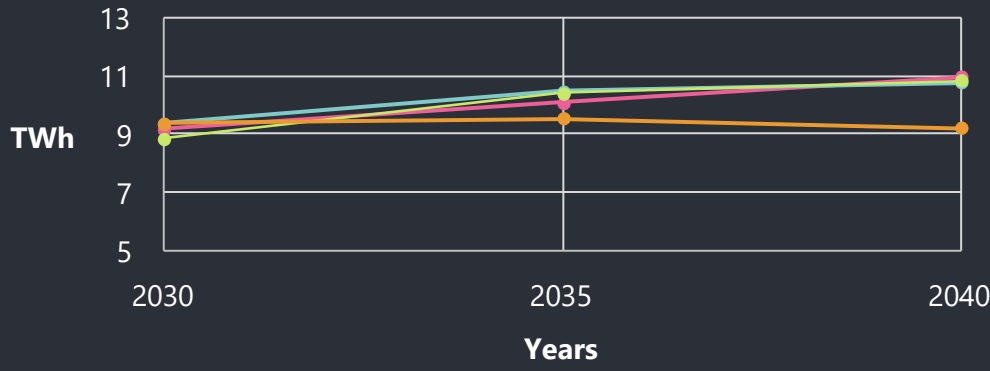
Peak Power Gap (GW) 2030-2040



Peak Energy Gap (GWh) 2030-2040



Peak Daily Gap (GW) 2030-2040



Peak Duration Gap (TWh) 2030-2040

Value of flexibility

Why is energy system flexibility so important?

Previous work by the Catapult[6] highlighted three important roles for flexibility:

Managing the delivery of network upgrades	The logistical benefits of deferring reinforcement of both distribution and transmission network infrastructure.
Reducing capital and operational costs of the energy system	The financial benefits of improving the utilisation of low-carbon, low-marginal-cost assets and avoiding investment into additional high-cost, lower-utilisation assets.
Supporting energy system resilience	The financial and social benefits of helping networks to mitigate and recover quickly from high-impact, low-probability events like black start as well as more probable but lower-impact events such as localised power cuts.

Flexibility is also a huge opportunity for UK innovators, where the UK is a world leader.

The need for flexibility in the UK and globally will increase significantly in the coming decades with one estimate suggesting the total flexibility market in Europe alone could be worth €12 billion by 2030[7].

UK innovators have already demonstrated their ability to raise investment and develop solutions which can meet this need.

With further support, they can continue to grow, capturing a valuable portion of this new and increasing global market, creating new jobs and growth.

Low-carbon flexibility alongside renewable generation can reduce energy system cost, but only if the necessary innovation happens to enable deployment

We found that those scenarios with the greatest and quickest deployment of renewable capacity enabled by low-carbon flexibility have the lowest system costs out to 2050.

Higher Renewables and Further Offshore Wind showed **total costs savings of 1.5% (~£70 billion)** compared to the most expensive scenario, Steady Transition, which has the lowest levels of renewables and low-carbon flexibility.

Scenarios with more flexibility and renewable generation find it easier to meet demand so spend less on alternatives such as the operation of unabated gas-fired generation.

This aligns with analysis we carried out for the Energy Systems Nexus Flex Mix project[8], which found scenarios with the highest level of flexibility saved around £125 billion out to 2050. This was because modelling in that work compared to a scenario with even lower levels of flexibility than Steady Transition.

Our system of systems mapping revealed that achieving flexibility's full potential requires innovation across all elements of the energy system. This includes:

- Technical innovation to scale up technologies and drive down fixed and operating costs.
- New ways to engage and support consumers.
- Creating an effective and supportive market, policy and regulatory environment.
- Accelerating roll out of networks that are fit for purpose.
- Harnessing deep-tech to deliver a step change in digitalisation.
- Novel approaches to support innovators, tailored to the nature of the flexibility challenge.

Higher Renewables and Further Offshore Wind scenarios showed

total cost savings of 1.5% (~£70 billion)

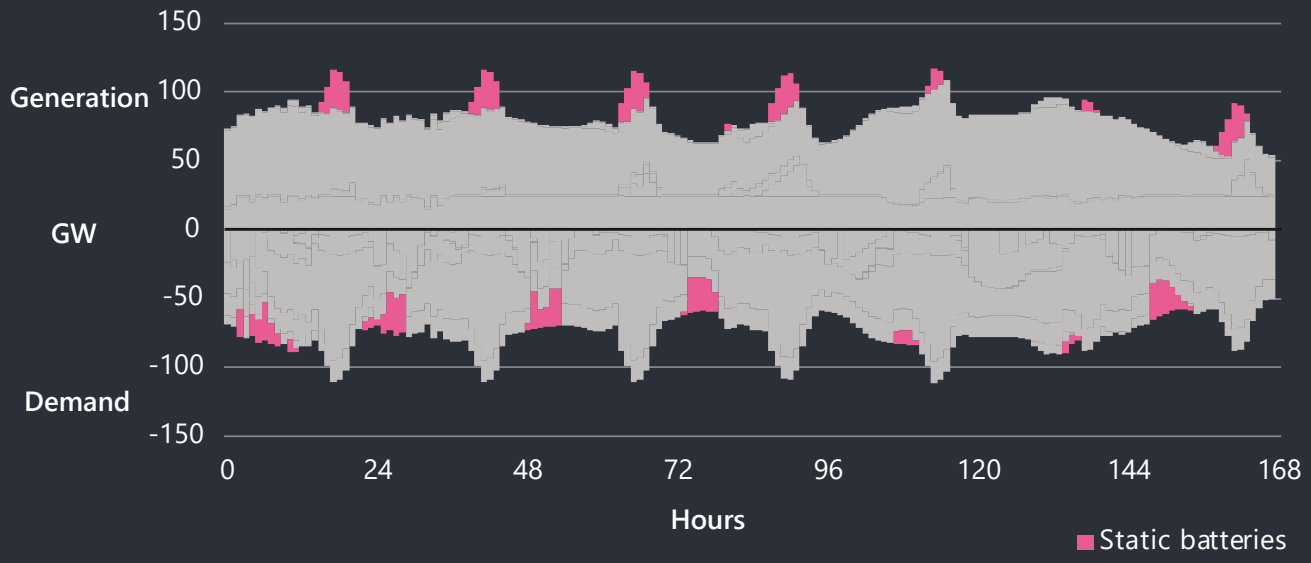
The Peak Energy and Peak Power Gaps – intra-day flexibility

Static batteries are important for balancing supply and demand, cycling daily to meet peak demands across all seasons

Static batteries help to reduce system costs by requiring fewer peaking plants to operate for longer periods of time. A 2 GW peaking plant running for four hours can deliver the same impact as an 8 GW plant running for two hours if the static batteries shift power to when it is needed.

Static batteries are recharged when demand is lower relative to supply, often overnight but also during the mid-day solar peak in summer.

They continue to be dispatched even during the Peak Duration Gap helping smooth demand to match a more stable level of generation.



Electricity generation and demand showing how static batteries reduce peak demand on a daily basis for the Further Offshore Wind scenario during a winter week in 2040

Static batteries meet up to 33% of winter hourly peak demand by 2030

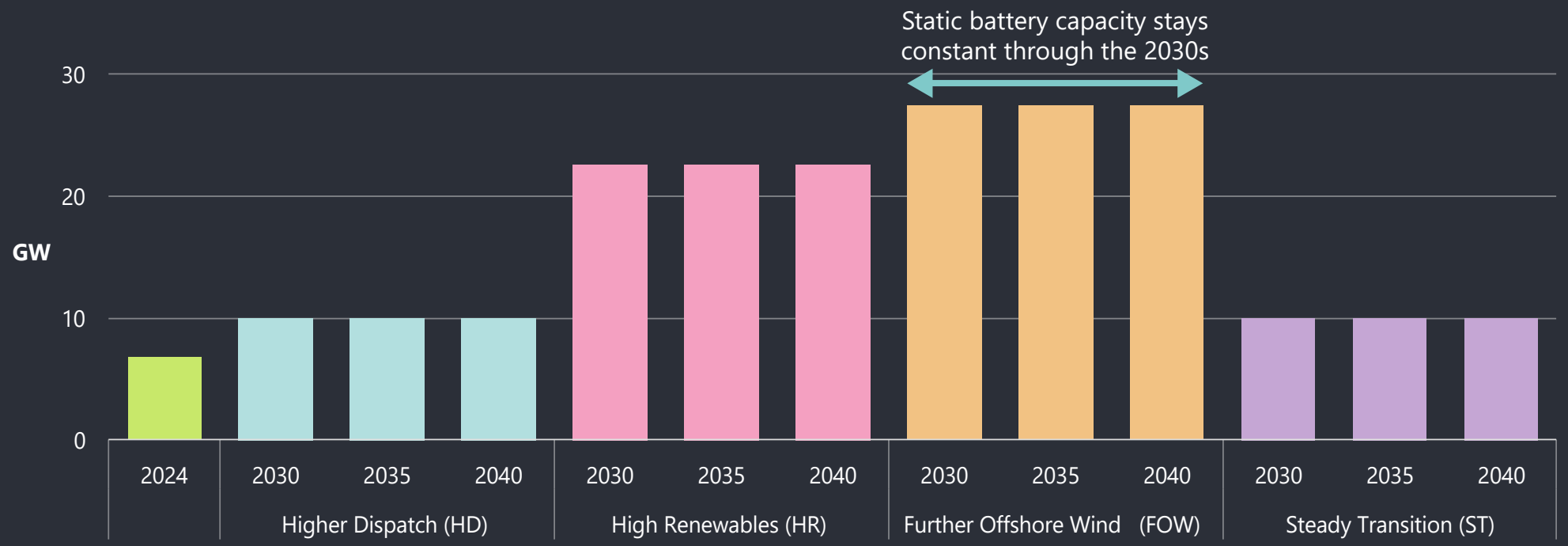
Static batteries meet up to 24% of winter hourly peak demand by 2040

The opportunity for static battery deployment appears time-limited

The deployment of static batteries out to 2030, including the 27 GW planned to be delivered under Clean Power 2030 provides intra-day flexibility out to 2030 and beyond.

Across all scenarios there is no additional static battery deployment from 2030-2040. EV smart charging and vehicle to grid (V2G) become increasingly available, providing the same services and are more cost-effective.

However, **this only holds if consumers can be convinced to allow their EVs to be used to benefit the system either through smart charging or V2G.** This depends on providing compelling consumer offerings.



Installed static battery capacity (2030-2040)

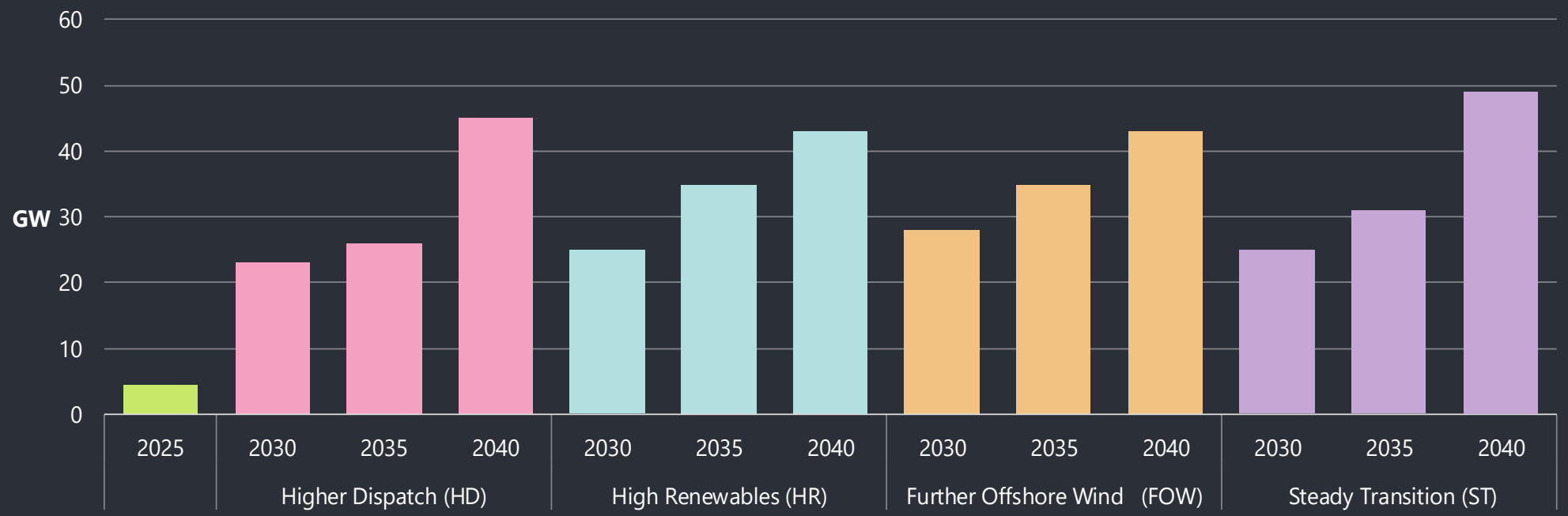
Flexibility provided by EV batteries is especially valuable to the energy system as the cost of the vehicle is not carried by the energy system

The mass roll-out of EVs can provide flexibility daily by 'smart charging'; shifting their own demand away from evening peaks to times of higher supply.

In 2030, with almost ten million EVs on the road, they could shift up to 23-28 GW in a single hour increasing to 43-49 GW by 2040.

However, realising this ambition will depend on compelling consumer propositions (including market signals).

EV flexibility is especially valuable to the energy system as consumers are adopting the technology independently, so the cost of the EV is not carried by the energy system.



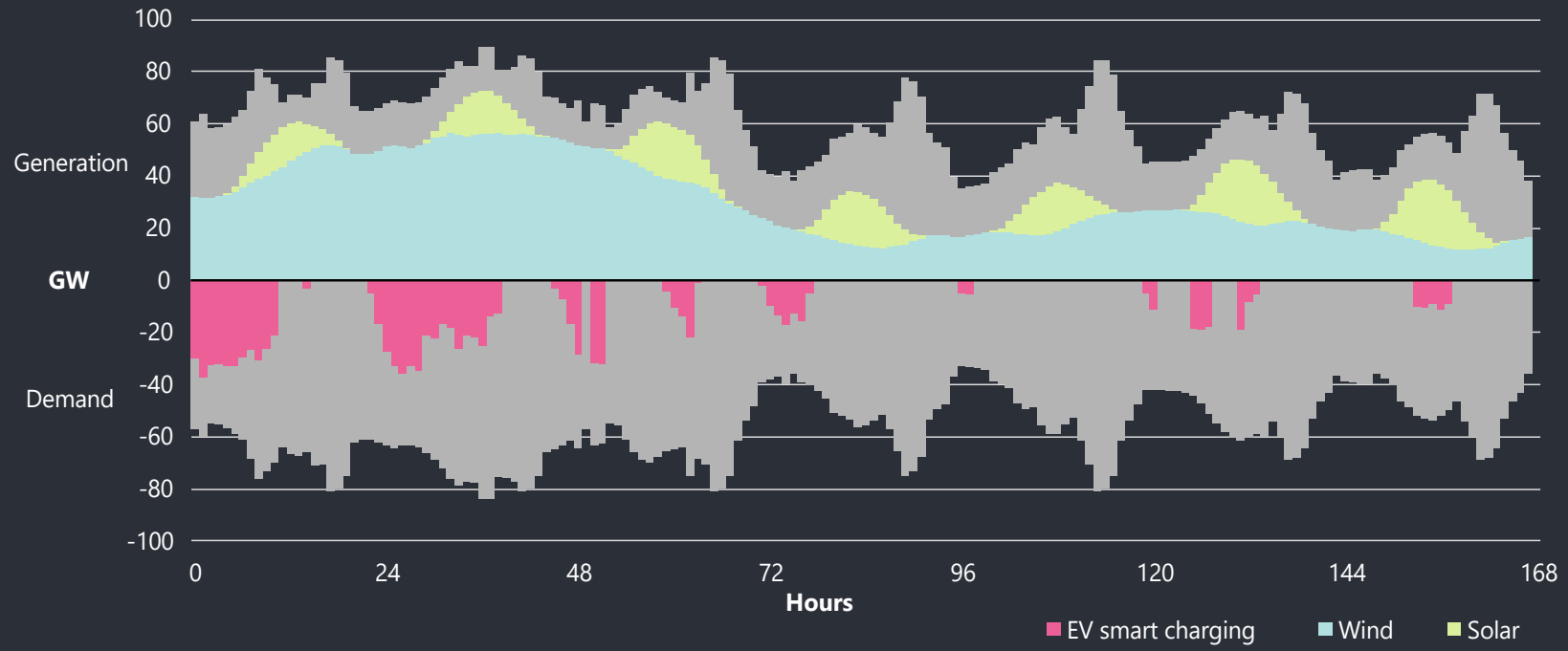
Change in maximum demand shifted for one hour by smart EV charging (2030-2040)

Smart EV charging fills troughs in demand (relative to supply) instead of charging when demand is high

EV smart charging fills troughs in demand relative to supply. This is typically charging in the middle of the night when demand is lowest, or in the middle of the day during the summer when solar generation is greatest.

Whilst some EV charging has to occur daily, within a given week smart charging also occurs most on days where wind generation is greatest.

With average daily mileage of less than 30 miles and a typical battery range of over 200 miles, most EVs require charging only once per week providing substantial opportunity for smart charging.



1 TWh

Over 1 TWh of EV demand shifted away from peak demand in a single summer week in 2040

Electricity generation and demand showing how EV smart charging reduces surplus generation for the Further Offshore Wind scenario during a summer week in 2040

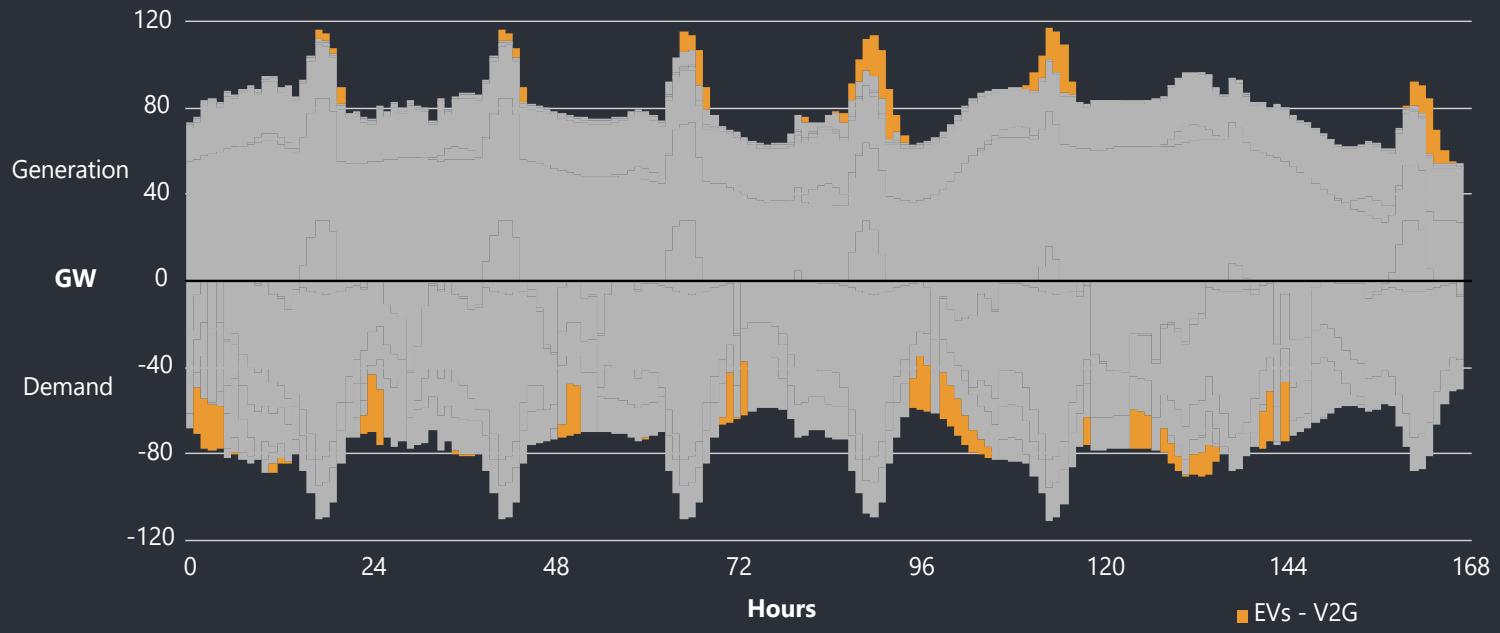
V2G could provide power to meet peak demands and both peak gaps making it especially valuable

V2G is starting to play a role in 2030 providing up to 5 GW across all scenarios for a small number of hours per week, including weeks containing both peak gaps when demand is high and generation is low.

By 2040, with many more EVs on the road and V2G technology more developed, it plays a much more prominent role. It discharges up to 26 GW in a single hour to meet peaks in demand, including to support meeting both peak gaps. It then recharges when supply is higher relative to demand.

Like smart charging, V2G is valuable to the energy system because the cost of the EV is not carried by the energy system, but its ability to meet demand and not just shift it provides an additional benefit compared to smart charging.

However, there is an urgency to develop the V2G infrastructure and vehicle standards needed to turn this potential into reality.



Electricity generation and demand showing V2G shifting peaks in demand to times of higher generation in the Further Offshore Wind scenario during a winter week in 2040

350 GWh

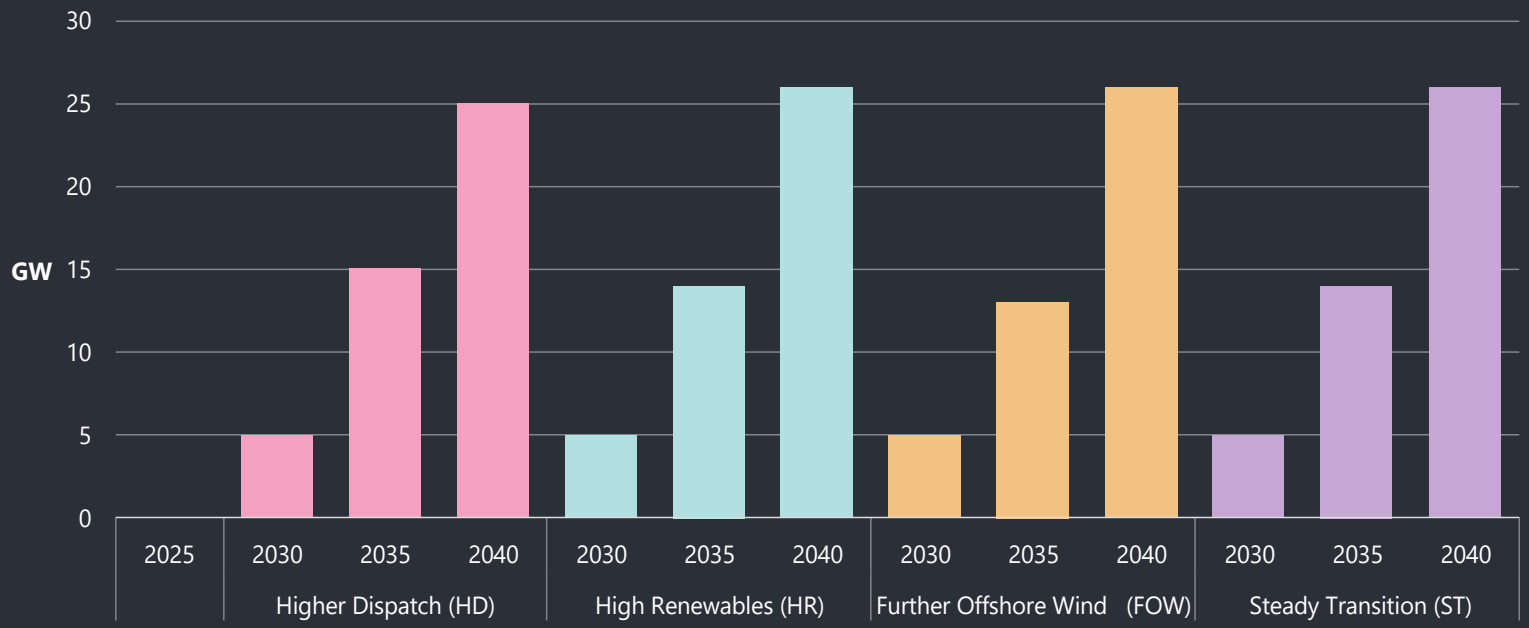
V2G provides 350 GWh of power to help meet peak demand during a single winter week in FOW in 2040

The potential of V2G will only be realised if challenges around consumer uptake and system integration are tackled

There are considerable barriers to realising the potential of V2G, including scale-up and consumer adoption which will have to be overcome. There are currently only a limited number of EV models in the UK that are able to provide V2G. Existing consumer uptake is mainly limited to trials and a single V2G tariff.

Improved integration and communication protocols between EVs and the electricity network are also needed to ensure V2G is taking place where and when it is needed. And market signals are needed to provide value to consumers.

These barriers are reflected in our modelling. While both V2G and smart charging exhibit steady growth, flexibility from V2G is limited to just over 26 GW by 2040 compared to 49 GW for smart charging.



Maximum V2G discharge capacity in one hour (2030-2040)

26 GW

Up to 26 GW of V2G smart charging capacity available by 2040

Innovation priorities for static batteries, EV smart charging, V2G and smart appliances to accelerate delivery of intra-day flexibility

Static batteries

- Innovations to address the main planning objections around large static battery systems including noise, fire and safety risks, and aesthetics.
- Develop battery refurbishment and reuse techniques so that EV batteries can be given a second life in static battery storage systems.

EV smart charging

- Improved control and scheduling of EV smart charging particularly around automated coordination with other chargers on the same feeder to manage demand within local constraints.
- Solutions for on-street charging, for example for the 30% (60% in London) of homes without off-street parking.
- Smart charging solutions at both depots and truck stops to ease the challenge of providing power for electrified heavy goods vehicles.

V2G

- How best to use V2G to improve battery lifetime and encourage adoption.
- Standardisation to help lower cost of V2G hardware, particularly V2G chargers.
- Improved consumer propositions for V2G.
- Improved integration and communication protocols between EVs and the electricity network.

Other smart energy appliances

- Testing the flexibility potential of heat pumps, particularly on the coldest day.
- Assessing what impact turning smart appliances on or off to deliver flexibility has on lifetime or performance.
- Trials to test what interruptions/ alterations of service consumers are prepared to accept and the value they would place on it.

The Peak Daily and Peak Duration Gaps – between-day flexibility

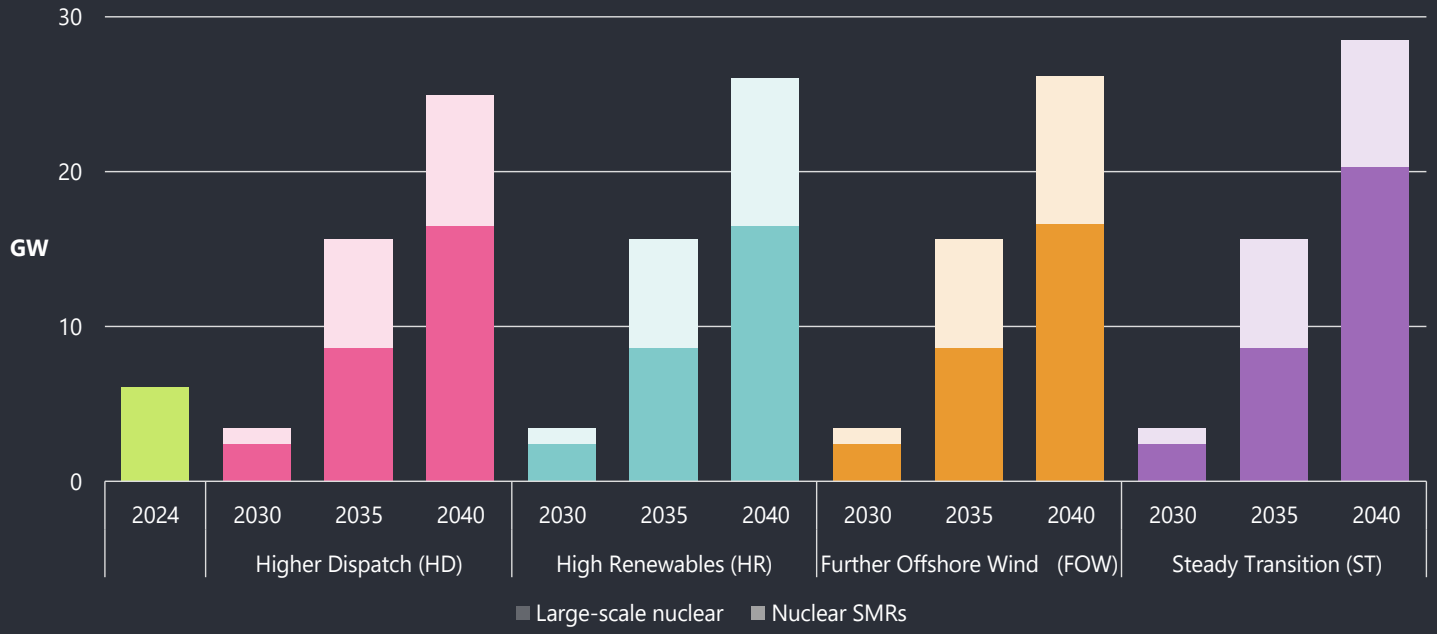
A rapid scale up in nuclear capacity (large scale and SMRs) is needed to provide firm, low-carbon baseload to help meet both peak gaps

Many existing nuclear plants are expected to close by 2030. This, plus new electricity demand, means it is urgent that new plants, including small modular reactors (SMRs), scale up deployment from 2030.

By 2040 we see a role for both large-scale nuclear and SMRs, totalling over 25 GW. This will run close to baseload for the majority of the time.

This could meet around 65% of the increase in peak electricity demand from 2030 to 2040.

Nuclear generation can also provide further whole system benefits, largely through cogeneration of heat, producing up to 96 TWh of heat per year for district heat networks by 2040 (around 17% of total domestic and commercial heat demand).



Nuclear capacity (2030-2040)

65%

An increase in nuclear capacity meets around 65% of the increase in peak electricity from 2030-2040

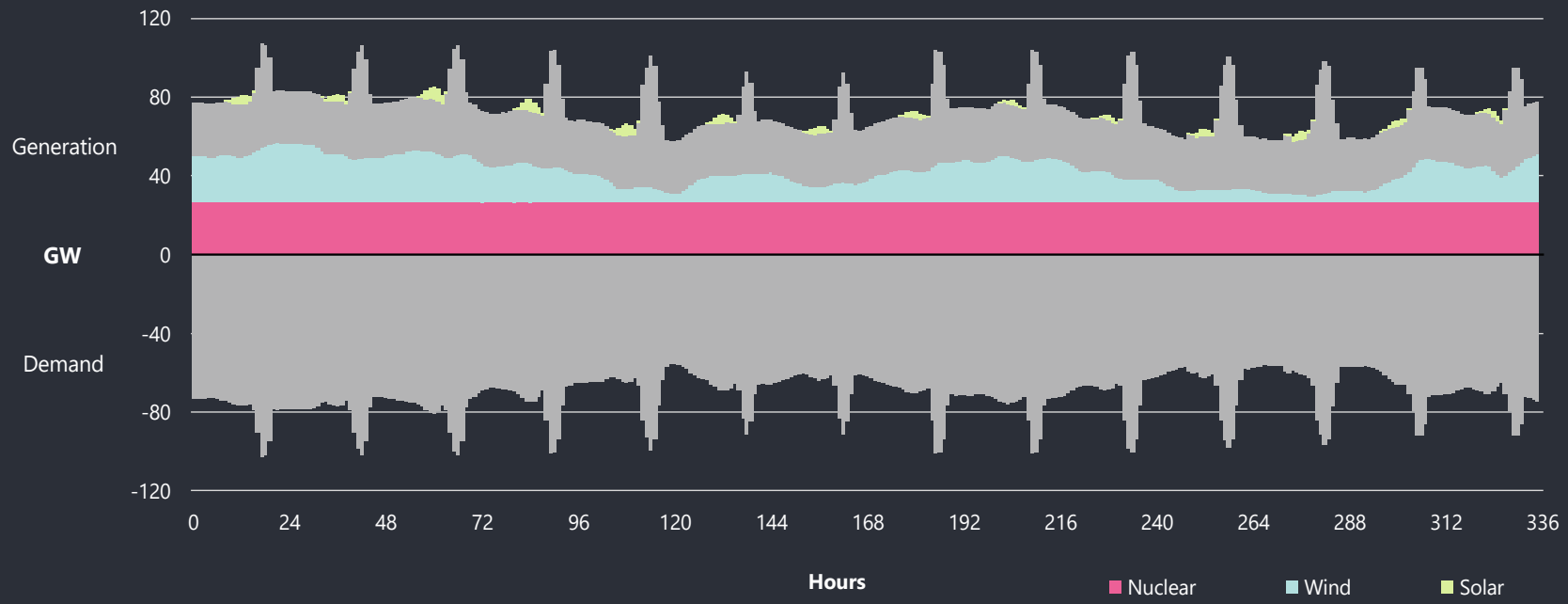
Nuclear and renewables complement each other, reducing flexibility needs versus renewables alone

This large amount of nuclear capacity helps limit any increase in the both peak gaps from 2030 to 2040, allowing flexibility technologies to meet the rest of the gap. Nuclear's ability to run consistently for long periods of time makes it particularly beneficial for meeting the Peak Duration Gap.

So, a combination of nuclear and renewable capacity reduces the total flexibility needed compared to a system with only renewable capacity and so lowers total system costs and improves resilience.

In our analysis the ratio of nuclear to renewable capacity ranges from 1:3 to 1:4 by 2040, with nuclear generation reducing the size of the Peak Duration Gap by up to 10 TWh.

Analysis with no new nuclear deployment led to additional gas with CCS (+10 GW) and offshore wind (+15 GW) by 2040, with an increase in system costs of 1.1% (£50 billion) by 2050.



Electricity generation and demand focusing on nuclear generation in the Steady Transition scenario during the two-week Peak Duration Gap in 2040

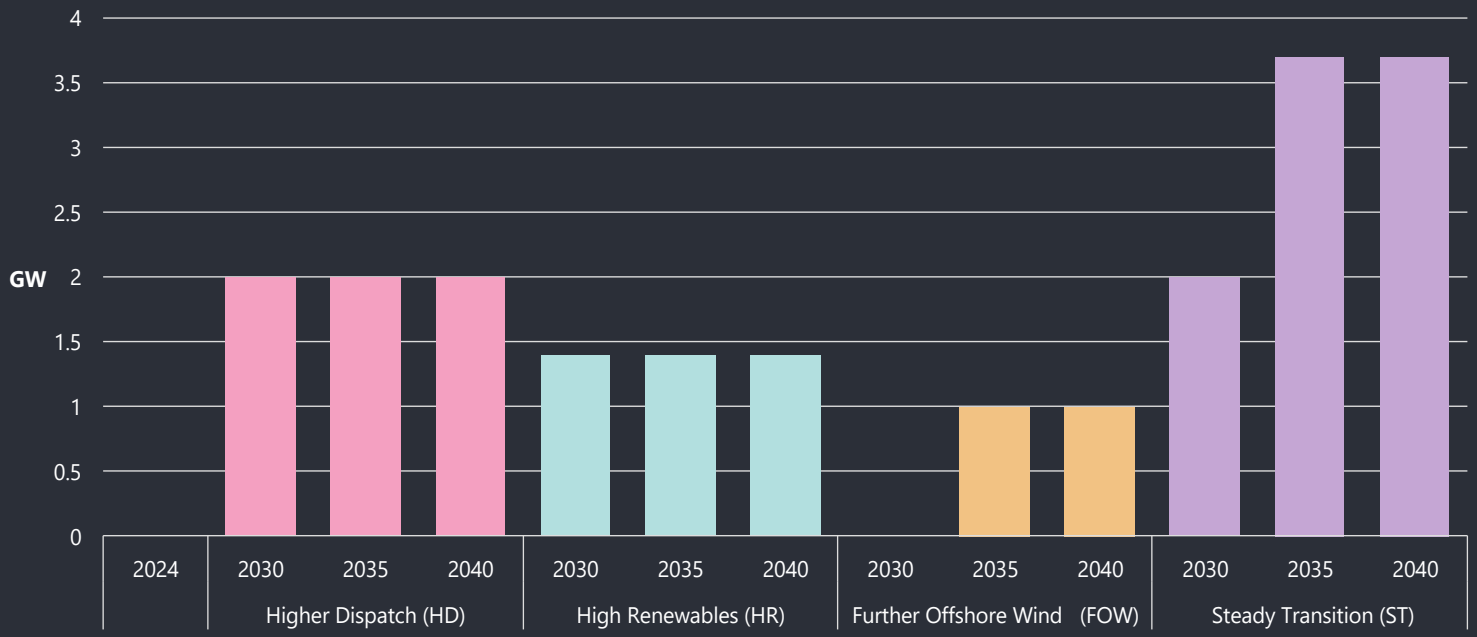
High capital cost means gas CCS runs close to baseload, but in limited volumes

Gas turbines with CCS deployment ranges from 0-2 GW in 2030 and then increases to 1-3.7 GW by 2040 to help meet increases in electricity demand.

Some scenarios do not deploy any gas CCS until 2035, instead relying on large increases in renewable generation and batteries, alongside existing unabated gas generation. Others are more favourable, if the renewable build out is slower.

Gas CCS is valuable to the system, especially during both peak gaps as it is both low carbon and independent of weather. Due to its high capital costs, it runs as baseload across all scenarios and both peak gaps to maximise its utilisation.

It displaces other plant which runs intermittently and so reduces the need for back-up capacity or displaces unabated gas generation, lowering carbon emissions.



Gas CCS capacity (2030-2040)

3.7 GW

Up to 3.7 GW of gas turbines with CCS are deployed by 2040

If gas CCS is not available to the power sector then system costs rise

Despite its value to the system, gas CCS for power is deployed at relatively low capacities, due to a combination of both its relatively high capital cost and fuel costs. Although its high utilisation does in part negate the high capital cost.

Gas CCS is still at early deployment worldwide so in sensitivities we explored the impact on the system if it is not available. We found that it made minimal difference to system costs in most scenarios as there was only 1-2 GW of gas CCS plant to replace, largely by a small increase in offshore wind (+1 GW) and a fractionally greater utilisation of unabated gas (+0.2 TWh per year) out to 2040.

But in Steady Transition where 4 GW of gas CCS plant was removed, there was a small additional deployment of biomass plant with CCS (up to +0.5 GW) a slightly larger increase in offshore wind (up to +3 GW) and the retaining of around 6 GW extra of unabated gas capacity. This results in a slightly larger impact on system cost of around 0.5% (£22 billion) and fractionally greater utilisation of unabated gas (+0.2 TWh per year) out to 2040.

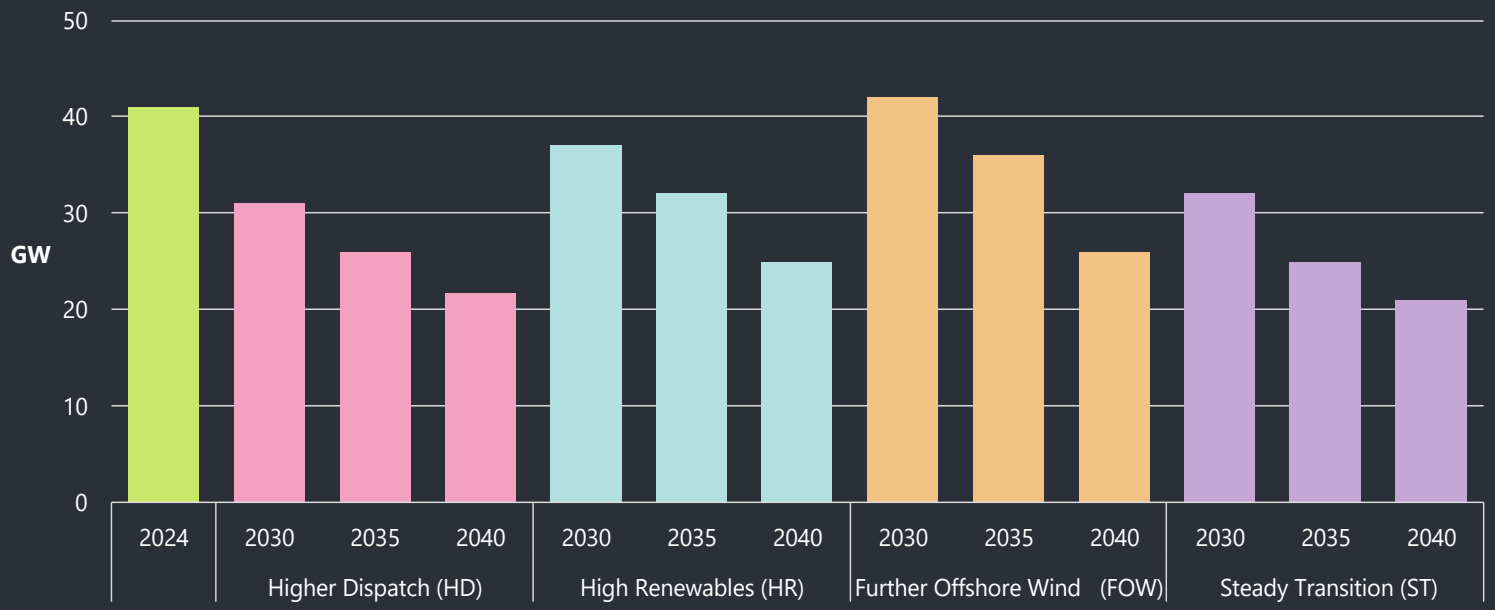
These sensitivities reflect CCS technology not being available only for gas-fired power plants. CCS plays a critical role in decarbonising industry. It produces up to 120 TWh of hydrogen by 2040 and is vital to the wider energy system.

Unabated gas generation will still be important in 2040 for energy security

Unabated gas capacity will continue to fall from now until 2040 and beyond although it will still be present on a small scale, even out to 2050.

In 2030, some unabated gas generation is used in typical summer or winter weeks but only when wind generation is low. This also occurs less in the scenarios with more renewable generation (i.e. Further Offshore Wind and High Renewables).

Unabated gas is a mature technology and so has limited technical innovation requirement. Innovation is needed to develop market mechanisms which ensure the technology is available to meet both peak gaps (see Policy section) and ensure resilience.



Unabated gas capacity (2030-2040)

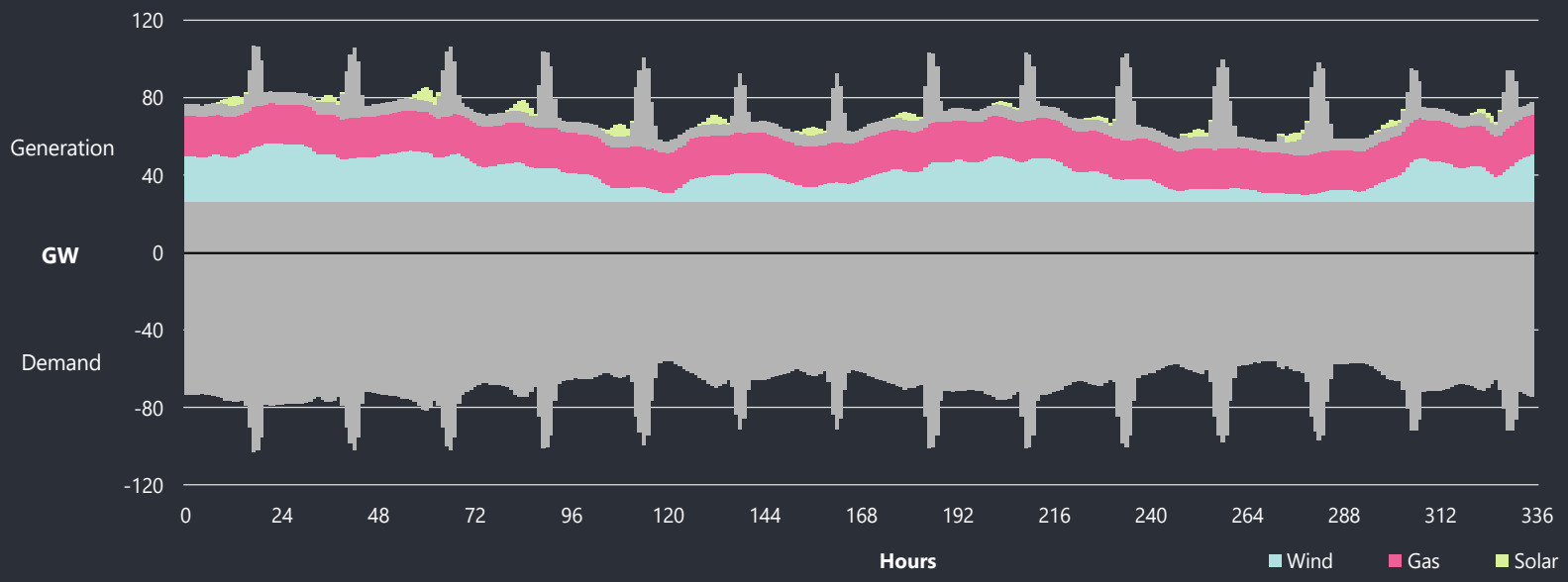
20 GW

At least 20 GW of unabated gas-fired generation remains in 2040, but is used very rarely

Unabated gas generation is only used to support both peak gaps by 2040

By 2040, unabated gas turbines are only used during both peak gaps. Although in these cases, they are used at close to full capacity meeting around 20% of the Peak Duration Gap.

This high use of unabated gas only occurs during a single week (or a fortnight in the case of the Peak Duration Gap). While it represents an extreme case of high demand relative to low renewable supply, it does not breach decarbonisation pathways.



20%

Unabated gas generation meets up to 20% of the Peak Duration Gap

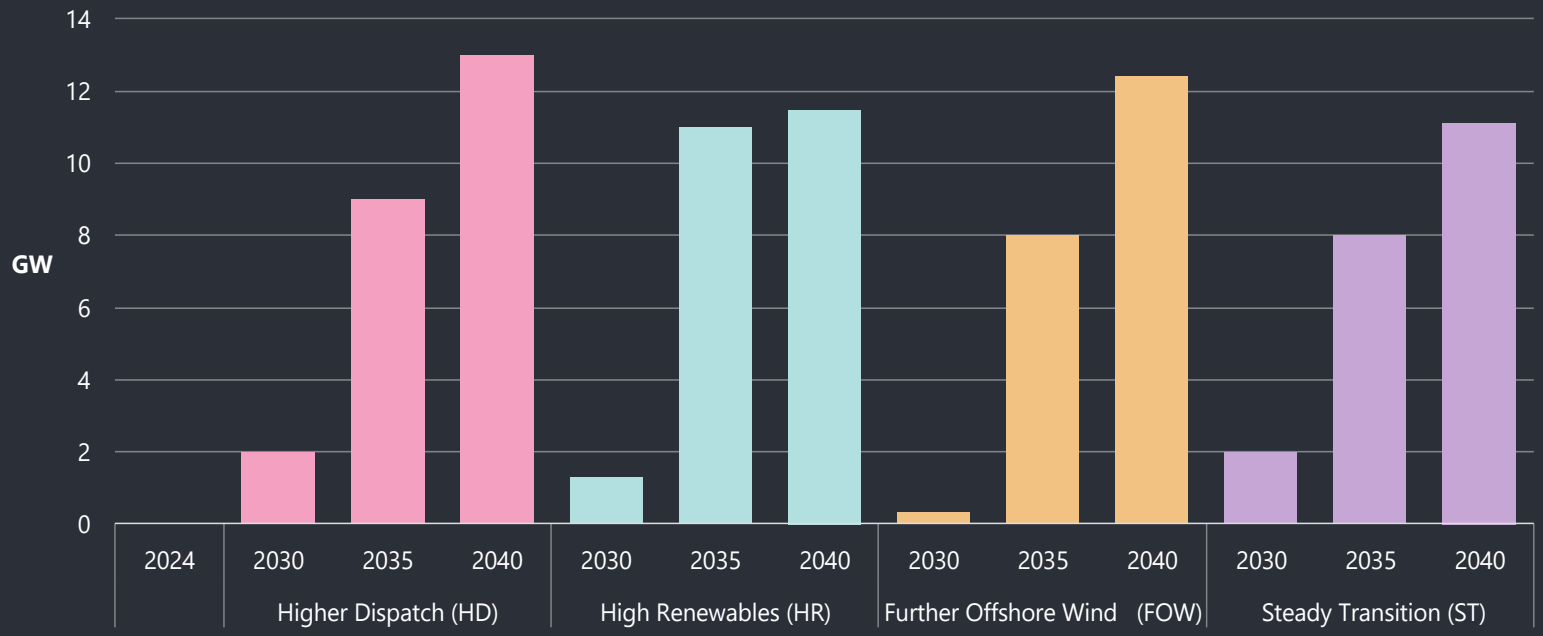
Electricity generation and demand focusing on unabated gas generation in the Steady Transition scenario during the two-week Peak Duration Gap in 2040

Hydrogen-fired turbine capacity could increase to help meet gaps through the 2030s, so scale-up needs to start soon

Up to 13 GW of hydrogen-fired turbines are deployed by 2040. Early uptake is slowest in Further Offshore Wind as the higher levels of renewable generation and batteries, combined with existing unabated gas, reduce the need for hydrogen-fired turbines.

Hydrogen-fired turbines are used sparingly during typical weeks in our scenarios. Most hydrogen is produced from steam reformation with CCS and so uses natural gas as a feedstock. This is because it results in the lowest whole system costs and avoids the low-round trip efficiency of hydrogen produced from electrolysis.

From an operational perspective, this means hydrogen-fired turbines are potentially more expensive than gas CCS which runs close to baseload. Furthermore, hydrogen production is often prioritised for other demands, with industry assumed to use 65-75 TWh[9] by 2040.



Hydrogen turbine capacity (2030-2040)

13 GW

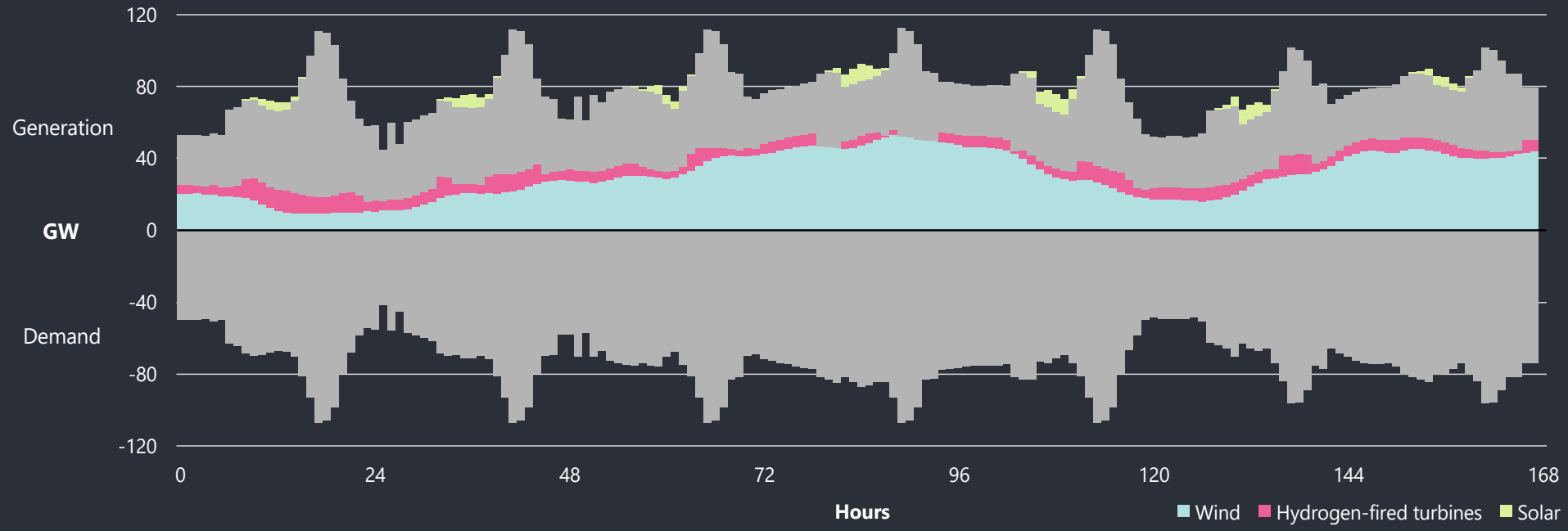
Up to 13 GW of hydrogen-fired turbines are deployed by 2040

Hydrogen-fired turbines are vital to meeting demand during peak gaps

During all peak gaps (including the Peak Energy Gap and Peak Duration Gap) hydrogen-fired turbines play a key role in ensuring demand is met.

This is particularly the case by 2040 when their cost has reduced and they have had time to scale up. The exact role changes across each peak gap and scenario, but they typically run for at least 20 hours at a time (albeit at varying capacities) and sometimes for over 100 hours.

During the week containing the Peak Daily Gap, hydrogen-fired turbines run almost constantly for the entire week although they ramp up and down to some degree, providing up to 35% of the capacity required to meet this gap.



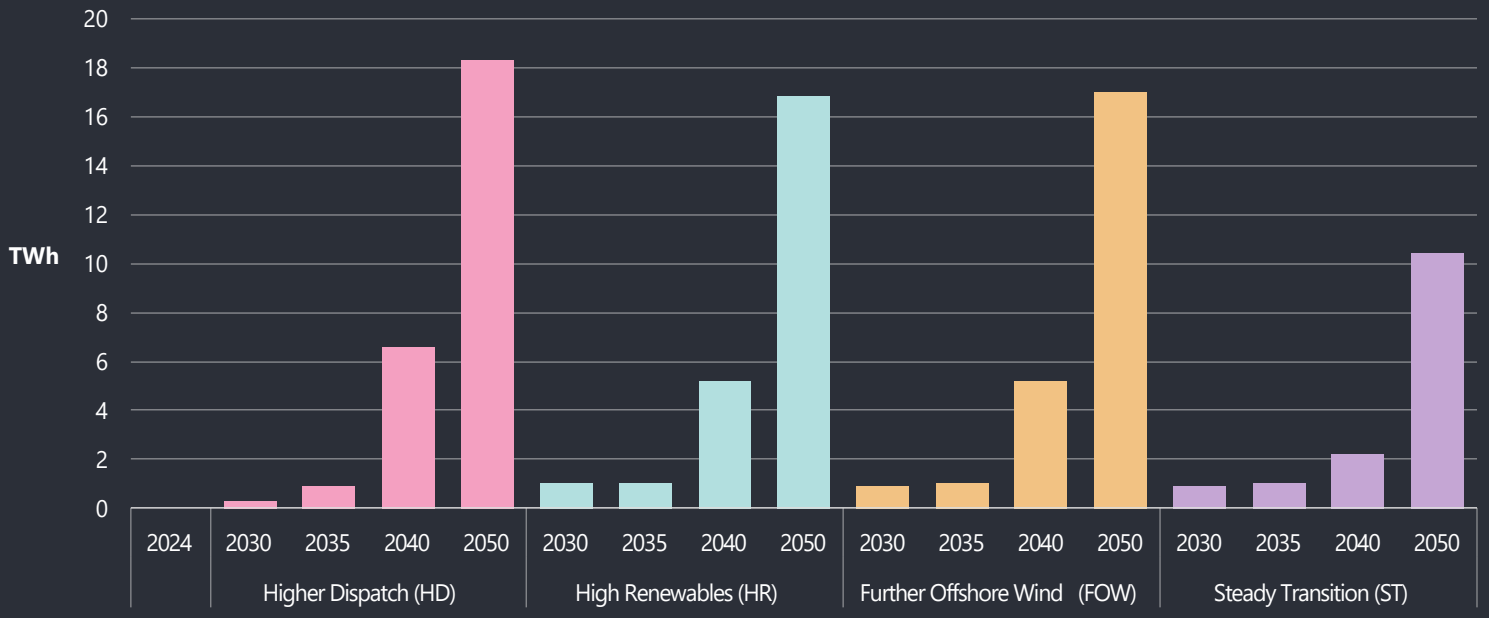
Electricity generation and demand showing how hydrogen turbines run continuously to fill the Peak Daily Gap in the Further Offshore Wind scenario in 2040

Up to 6 TWh of hydrogen storage is deployed by 2040

As we approach 2040, the role of hydrogen and therefore hydrogen storage increases. First sites deployed from 2030. Producing up to 6 TWh by 2040 and 18 TWh by 2050. Our Steady Transition scenario has the lowest deployment at around 2.5 TWh by 2050 due to lower levels of renewable generation and hydrogen turbines.

Hydrogen storage does not deploy more quickly out to 2040 as there is still a significant amount of unabated gas capacity available for peak gaps up to this point. But by 2050 this capacity is largely retired to meet carbon restrictions which contributes to the tripling in hydrogen storage capacity from 2040-2050.

Hydrogen is stored in salt caverns with shallower caverns cycling over shorter durations and deeper caverns cycling over longer periods; both acting as ultra-long duration storage[10].



Hydrogen storage volume (2030-2050)

6 TWh

Up to 6 TWh of hydrogen storage by 2040

18 TWh

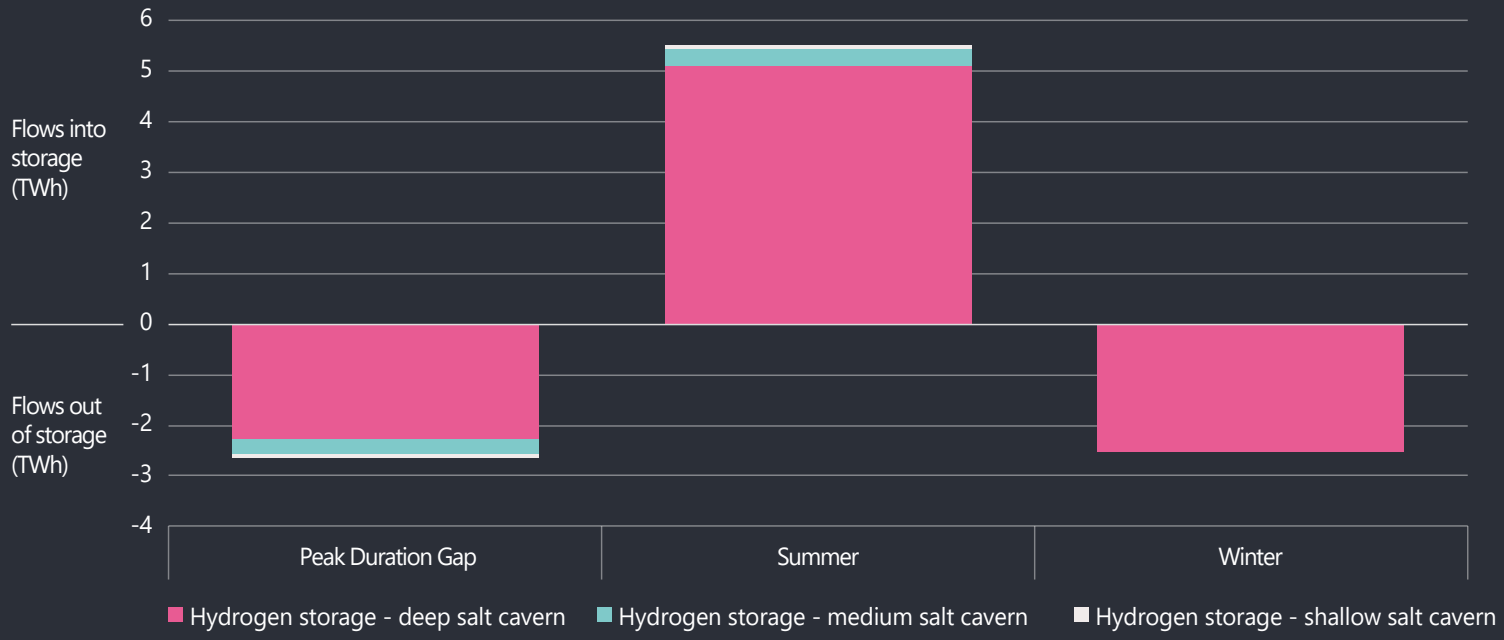
Up to 18 TWh of hydrogen storage by 2050

Hydrogen storage can support hydrogen turbines during peak gaps

There is a seasonal trend where hydrogen storage is charged over the summer (up to 6 TWh in 2040) and used through the winter. Most hydrogen is produced from natural gas with CCS, so this seasonal trend ensures that most gas is imported in the summer when it is cheaper.

During the peak gaps, especially the Peak Duration Gap, hydrogen storage discharges continuously for many hours (up to 164 hours in Further Offshore Wind in 2040). This results in around 3 TWh being emptied from the cavern storage over the single Peak Duration Gap fortnight in 2040, compared to a further 3 TWh across the rest of the winter.

This highlights the role of hydrogen storage during peak gaps but especially the Peak Duration Gap, where it is mainly used to support the industry demand for hydrogen and the operation of hydrogen-fired turbines.



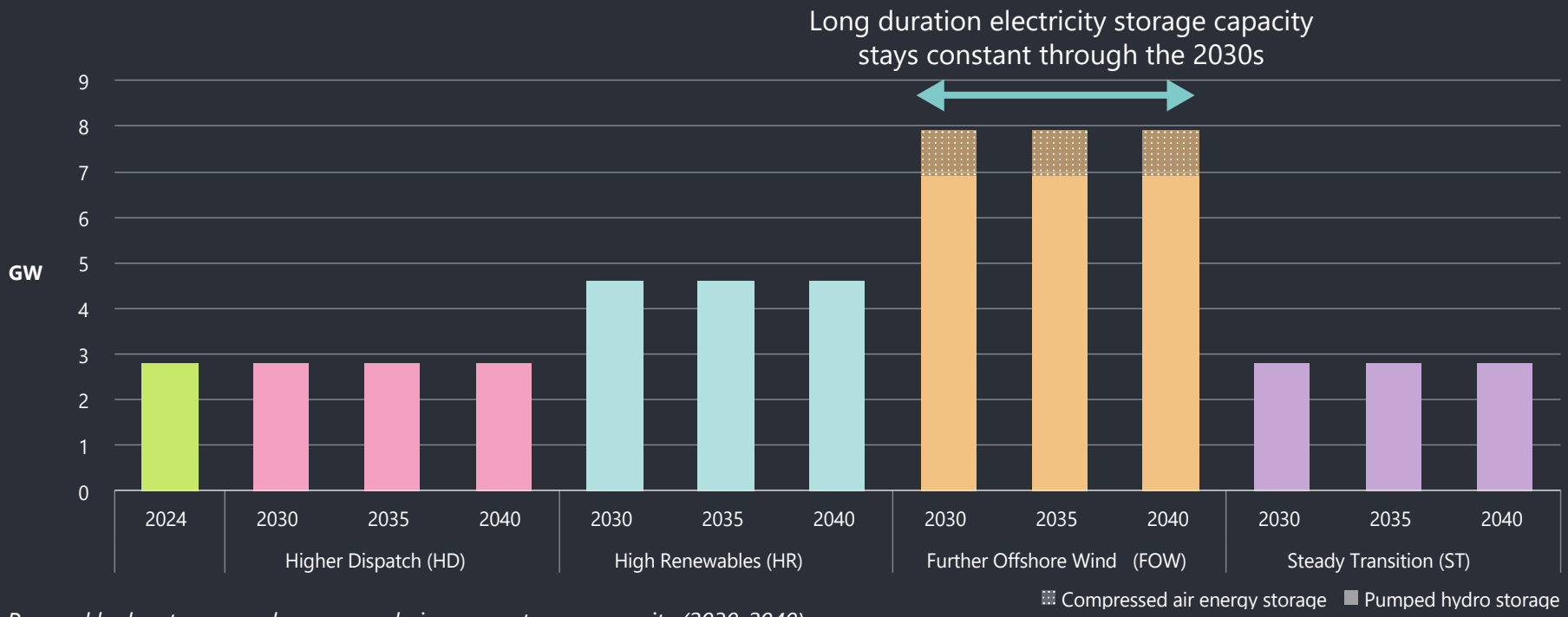
Net flows of hydrogen storage in summer, winter and Peak Duration Gap in the Further Offshore Wind scenario during 2040. Positive values represent flows into storage and negative values show stores being depleted.

Innovation is needed to drive down the cost of long duration electricity storage technologies if they are to scale up and provide greater value to the system

We assume in Further Offshore Wind and High Renewables that **pumped hydro storage and compressed air energy storage** increase their capacity by 2030 to align with long duration electricity storage[11] capacities in the NESO Clean Power 2030 pathways. So this capacity is "forced" into these scenarios.

In our modelling, no additional long duration electricity storage (LDES) capacity is deployed out to 2040. The existing LDES capacity is utilised, discharging up to 23% of the time in 2030 and 13% in 2040.

This highlights that whilst LDES could provide value to the future energy system, this will only happen at scale if the cost of these technologies can be driven down. Innovation will be required to support this.

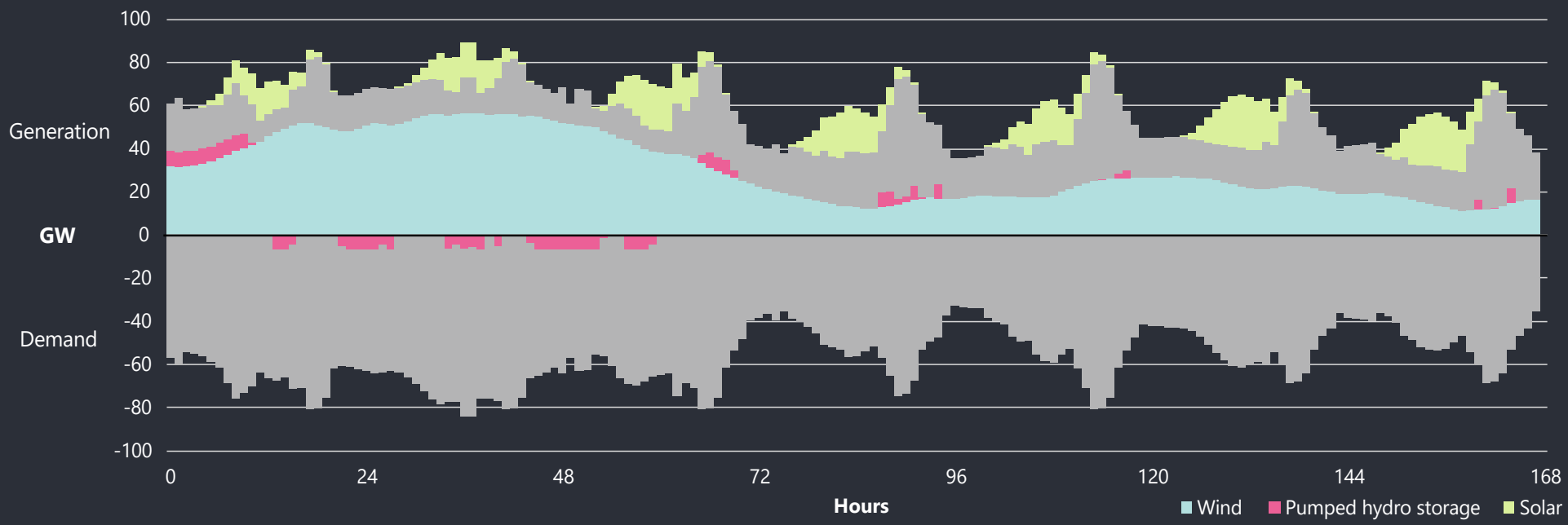


Pumped hydro storage and compressed air energy storage capacity (2030-2040)

If deployed, long duration electricity storage supports across all periods when wind generation is low

Pumped hydro storage and to a lesser extent **compressed air energy storage** help balance supply and demand up to their full capacity in summer and winter (up to 6.9 GW for pumped hydro storage and up to 1 GW for compressed air energy storage), and the peak gaps for 2030 and 2040. These technologies are not used every day but instead support during periods of lower wind generation.

Their longer discharge duration and larger storage volume means that during the duration gap where wind generation is low across a whole fortnight they can discharge intermittently without recharging. This provides more flexibility to the system when wind generation is low.



Electricity generation and demand focusing on pumped hydro storage in the Further Offshore Wind scenario during a summer week in 2040

Innovation is needed in nuclear, gas CCS, hydrogen and LDES to maximise the value of between-day storage

Nuclear

Large-scale nuclear requires faster deployment and lower capital costs and construction risks. This can be supported by streamlined planning and stronger supply chains.

The deployment of the first nuclear SMRs should be accelerated to as early in the 2030s as possible.

Gas CCS

Improve capture rates by advancing different technologies, and chemical and regeneration processes.

Start the process of large-scale trials of CCS to allow for deployment from the early 2030s onwards.

Hydrogen-fired turbines

Test, demonstrate and lower costs of technologies that produce hydrogen from natural gas and biomass with CCS, electrolysis and nuclear. This will in turn lower the cost of running hydrogen-fired turbines.

Test hydrogen-fired turbines at scale in real-world demonstrators to prove viability and boost efficiency.

Hydrogen storage

Large-scale demonstrators are needed to:

- Improve business case uncertainty
- Improve supply chain readiness
- Reduce social and environmental impact
- Better understand the risks of cycling regimes on salt cavern integrity.

Reduce the cost of repurposing existing salt caverns or solution mining of new caverns.

Demonstrate end-to-end, whole system solutions for hydrogen power (production, storage and generation) is urgently needed.

LDES

Utilise waste heat and/or waste cold sources to improve efficiency of compressed air energy storage or liquid air energy storage.

Continue the scale-up of new LDES technologies, such as high-density pumped hydro storage and liquid air energy storage, building on existing pilot and demonstrator plants.

The Peak Heat Gap – managing heat demand

Energy efficiency remains an important way to narrow all the peak gaps, particularly in buildings where reducing heat demand is essential to address the Peak Heat Gap

Energy efficiency of electrical devices has been on an improving trajectory for several decades. This has driven a reduction in overall demand even as the number of devices increased. Our analysis shows that by 2040 up to 9.5 million houses will have received insulation retrofit packages including a combination of wall, loft and floor insulation, draught stripping, and door and window replacements.

As transport and heating electrifies, primary energy demand will also fall significantly. EVs are three to four times more efficient than vehicles with an internal combustion engine, as are heat pumps compared to gas boilers. But both will drive up overall electricity demand and the size of the peak gaps.

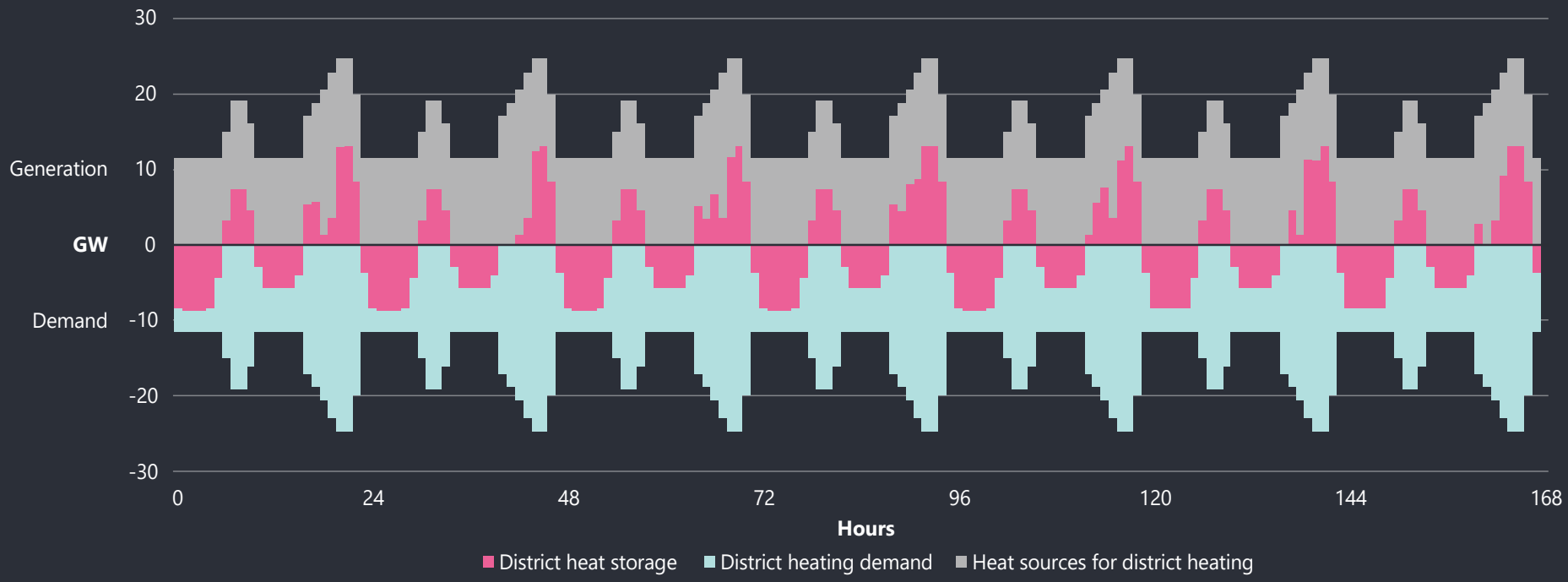
Innovation for continued improvement of energy efficiency remains important. This is especially true in homes where space heating accounts for about 60% of their total demand[12]. Reducing the energy loss from buildings' fabric by improving insulation has the potential to cut overall heat demand by 15-20%.

Currently the quality of insulation installs is inconsistent, while costs are high for hard to treat and solid wall homes. Innovation is needed to develop insulation measures that are more cost-effective, easier to install and less prone to poor quality installs. Technologies and approaches to measure in-situ energy performance of the home exist (e.g. SMETERs[13]) but need to be integrated into policy and matched with attractive pay for performance-based customer propositions.

Large heat networks with thermal stores help overcome the Peak Power and Peak Energy Gaps, lowering whole system costs

Thermal storage in heat networks (including large-scale hot water tanks) is a relatively low-cost way to store energy, helping to mitigate whole system costs associated with meeting peaks in heat demand. Novel technologies such as molten-salt, phase-change materials and sand batteries also show promise if their costs can be reduced.

'Baseload' heat sources, including geothermal and 'waste heat' from processes such as nuclear cogeneration, are of most value to the system when paired with thermal storage systems. That is because they provide a continuous heat source, which can be flexed depending on the wider pressure on the electricity system. This helps avoid costly network reinforcement.



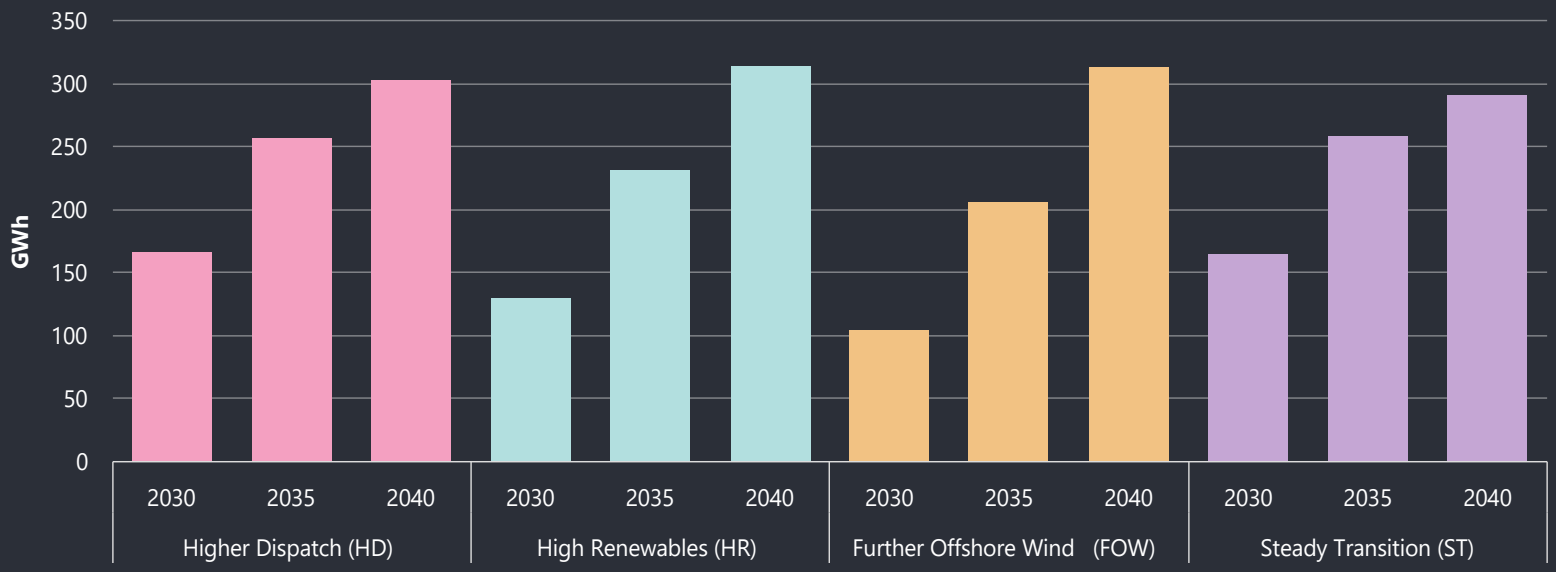
District heat network hot water generation and demand in the Steady Transition scenario during winter in 2030

Heat networks combined with thermal storage technologies could provide 300 GWh of flexibility by 2040

District heat networks will be an essential part of the UK's future energy system, meeting up to just over 20% of residential and commercial heating demand by 2040.

They also have potential to be a valuable and flexible asset on the system, helping to reduce strain on electricity networks, electricity storage and low-utilisation electricity peaking assets.

We see the potential for heat networks to provide more than 300 GWh of thermal storage – largely through existing heat storage technologies, such as large water tanks. Potential alternative and complementary technologies are emerging but must reduce costs to become competitive.



District heat network thermal storage volume (2030-2040)

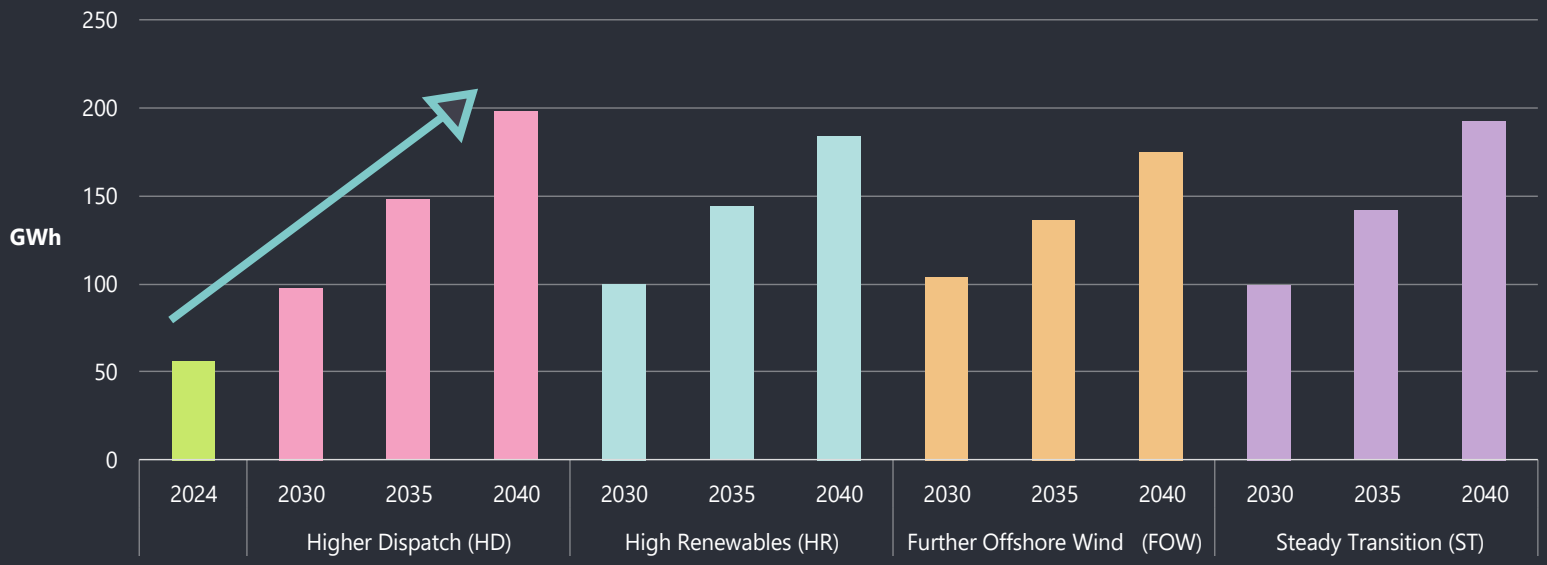
300 GWh

Around 300 GWh of thermal storage support from district heat networks by 2040

For buildings without access to a heat network, thermal storage can still help to reduce daily peaks in heat demand

Technologies that can reliably reduce the electricity demand of non-heat-networked buildings during peak heat periods, whilst maintaining outcomes for the occupants, will be valuable to a system that seeks to minimise high-cost, low-utilisation electricity assets.

In our analysis this results in thermal storage in houses and commercial buildings increasing from around 50 GWh in 2024 (mainly through hot water tanks, although these have historically not operated in a 'smart' way) to almost 200 GWh of fully-connected, smart thermal storage by 2040 as heat is electrified.



Domestic and commercial thermal storage volume (2030-2040)

+150 GWh

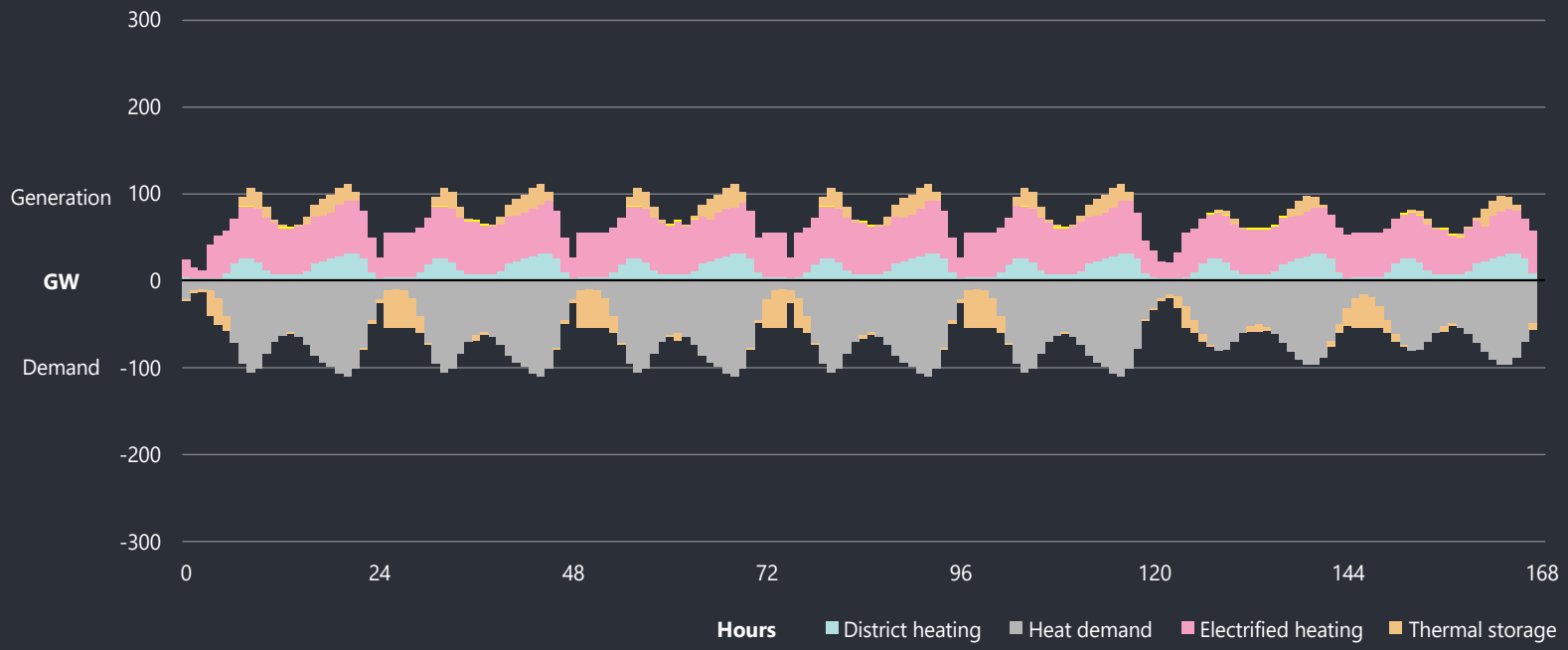
Up to a 150 GWh increase in thermal storage in domestic and commercial buildings by 2040

Thermal storage capacity cycles daily, but has little role in addressing the Peak Daily and Peak Duration Gaps

Thermal storage is charged when heat demand is lower overnight and then discharged to meet the morning and evening peaks in heat demand. This allows electrified heating (particularly heat pumps) to be smaller, reducing whole system costs.

Hot water tanks offer the cheapest domestic thermal storage, but they are limited by space (many lofts have now been converted). Their ability to offer their full potential value to the system will inevitably be constrained by their primary function to provide hot water.

Alternatives such as phase-change materials, thermochemical storage and the thermal mass of buildings could provide similar benefits. Batteries minimise space requirements but are the most expensive option once higher heat pump capacity is included.



Space heat and water supply and demand in the Steady Transition scenario during a winter week in 2040

Cold winter spells create a significant Peak Heat Gap which will require innovation to meet

Cold and calm extremes can push heating demand sharply higher (up to 2.5 TWh per day). This creates a Peak Heat Gap, straining an electrified heating system at the very moment heat pump performance drops and renewable output is low.

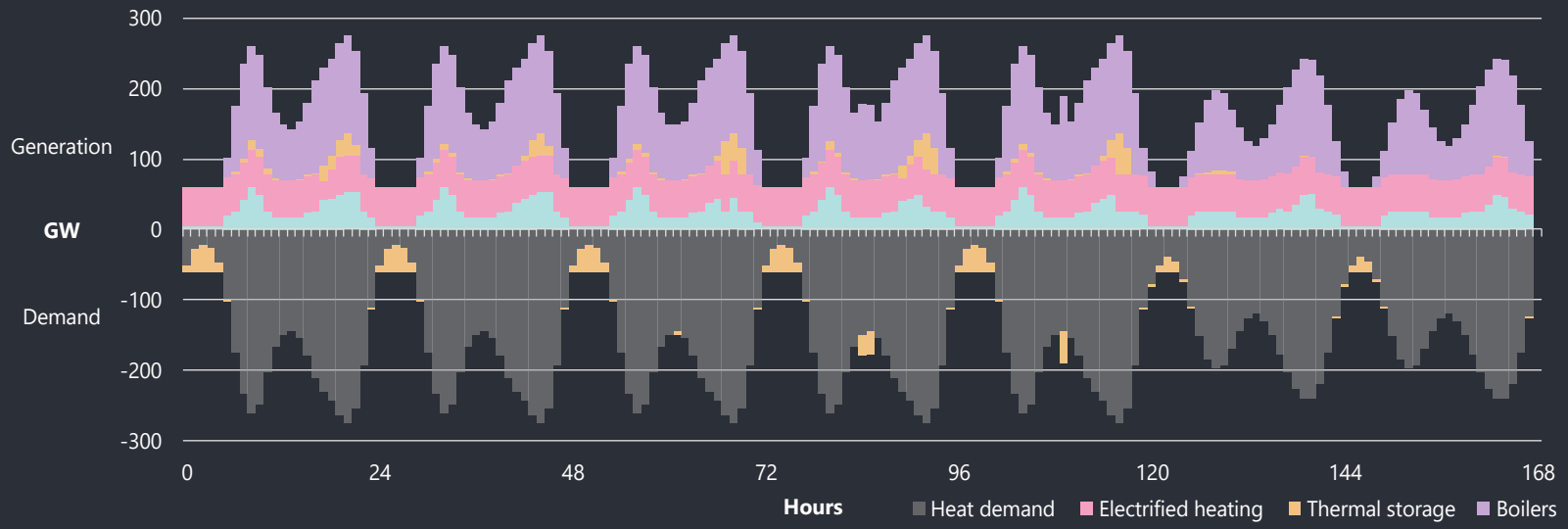
This presents probably the greatest system challenge to the energy transition – and the greatest flexibility opportunity.

Cutting this peak will require innovation, such as heat pumps that perform better in very cold weather; large-scale energy efficiency upgrades that could lower demand by around 20%; heat-network expansion and significant industrial flexibility.

If this is not achieved, then a series of difficult options remain:

- Provide up to an additional 50 GW of peaking plant.
- Retain the gas grid and a fallback gas boiler in most homes (hybrid heating).
- Rely on behaviour change and manage the impact of colder homes.

Our analysis uses gas boilers to meet this peak gap but there are positive and negative implications of this approach.



Space heat and water supply and demand in a cold and calm extreme period during 2040

The potential for hybrid heating in a future energy system is extremely uncertain

Our whole system models deploy heat pumps and gas boilers together in a way that suggests many of them are operating as a hybrid system – using both technologies to heat a single building.

For example, ramping up gas boilers only during peak gaps to reduce the costs of delivering peak demand through electricity alone.

Our modelling suggests that hybrid combinations offer lower whole system costs for meeting peak heat demand than deploying either technology alone.

Whilst hybrid systems are commercially available today, there are potential challenges which our modelling does not fully account for. These include:

- Will consumers accept larger dual-fuel systems?
- Can the potential system-value of hybrids be reflected in the capital cost consumers would pay for them?
- Is maintaining an extensive gas network at very low levels of utilisation cost effective.

On the other hand, there are potential benefits to hybrid systems that are not represented in the modelling either. This includes the transitional benefits of accelerating the deployment of low-carbon technology in advance of electricity network reinforcement to cope with the most severe peaks.

With heat pumps meeting the majority of heat demand on typical winter days by 2040 the priority should be for innovation to lower the Peak Heat Gap and avoid the need for hybrids at all. But further exploration of the other options including hybrid heating is needed.

Our modelling sees the current gas grid still being in place for 2040, with a reduced utilisation. By 2050, the gas grid has been reduced in scale and is more regionally targeted, but is still providing important system benefits.

Innovation is needed across thermal storage, insulation measures and heat pumps

Thermal storage for heat networks

Support rapid scale-up, cost reduction and space-efficient deployment of large heat stores for urban heat networks. Phase-change, thermochemical and sand-based systems also show promise and merit exploration.

Develop low-temperature district heat and storage solutions that operate efficiently at temperatures of around 50°C, enabling the use of lower-grade heat sources whilst minimising draw on the electricity system.

Thermal storage in commercial and domestic buildings

Support scale-up and drive reduction in costs of advanced thermal storage technologies with lower footprints, such as phase change materials, thermochemical storage and sand-based systems.

Investigate through trials the value of pre-heating houses making use of their thermal mass during peak heat periods, and the barriers to this approach.

Automation of integrated heat pumps and thermal storage to respond to price signals that represent whole system costs.

Innovation priorities – Peak Heat Gap

While heat networks and thermal storage themselves help reduce the Peak Heat Gap additional innovation is needed.

Improve heat pump coefficient of performance in cold temperatures, potentially via higher-efficiency refrigerants and weather-responsive system controls.

Develop insulation measures which are easier to install and less prone to unintended consequences, alongside policy measures which encourage more energy efficient homes.

Further research to identify the most effective solutions to meeting the Peak Heat Gap and then a targeted programme of innovation to ensure their readiness for implementation by 2040.

Integration

New tools are needed to determine how to integrate all aspects of the whole system to enable flexibility. We developed the System of Systems Map to support this

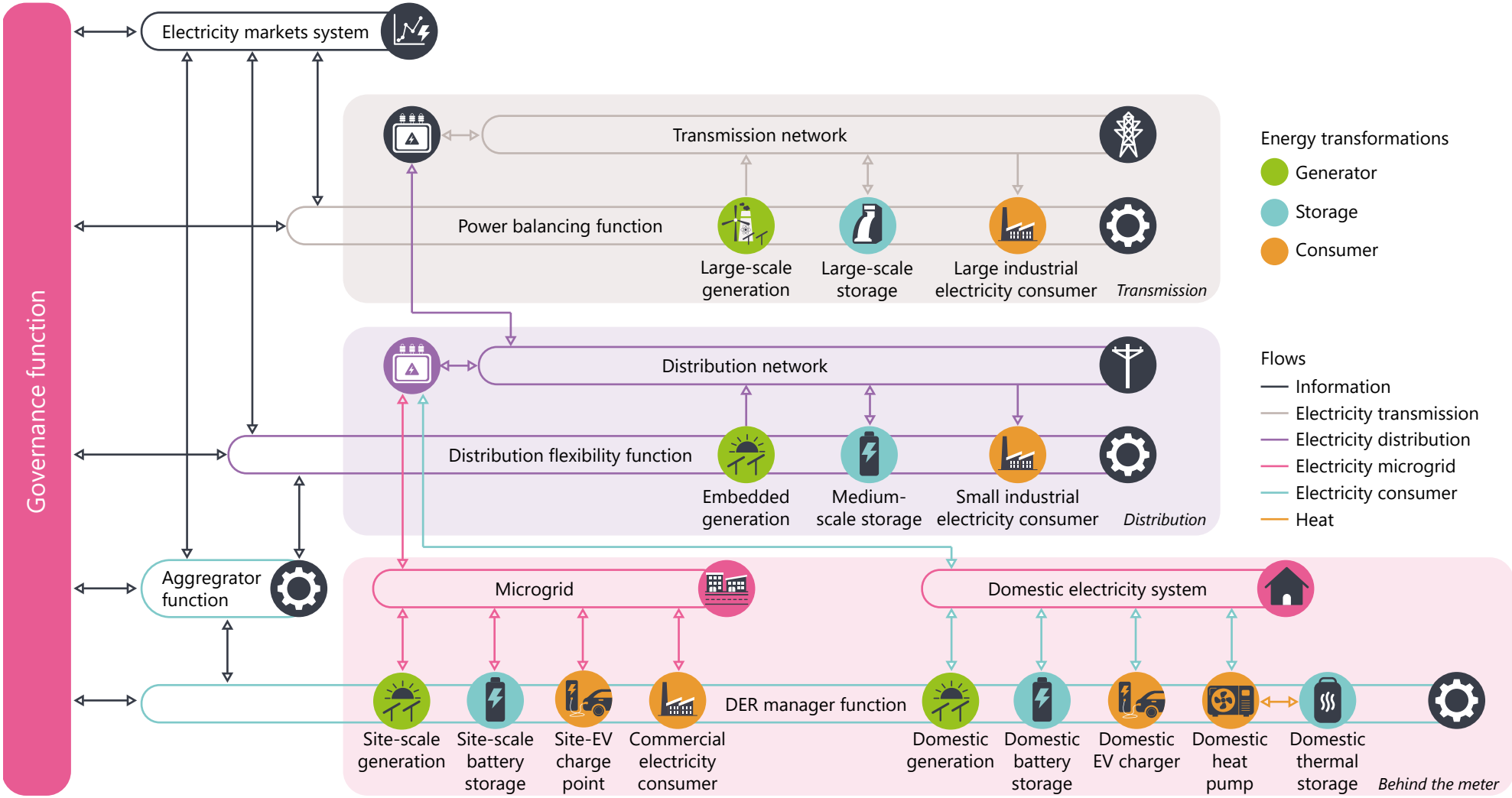
Modelling has been the historical tool of choice to understand the shape and scale of the energy transition. It is less helpful in understanding how best to orchestrate the different components of the energy system so they can transition to a more complex, digitalised energy system.

This is where our System of Systems Map comes in. System maps can be powerful toolsl for understanding the architecture of the current and future system, exposing critical system dependencies and identifying priority areas to make changes to the system design.

Our System of Systems Map allows users to visualise how technologies, markets and organisations interact across the energy system and the information that flows between them. This allows more effective solutions to be developed that operate smoothly together for the benefit of all consumers.

A high-level overview of the System of Systems Map is shown on the following page.

The System of Systems Map shows how technologies, markets and organisations interact across the energy system



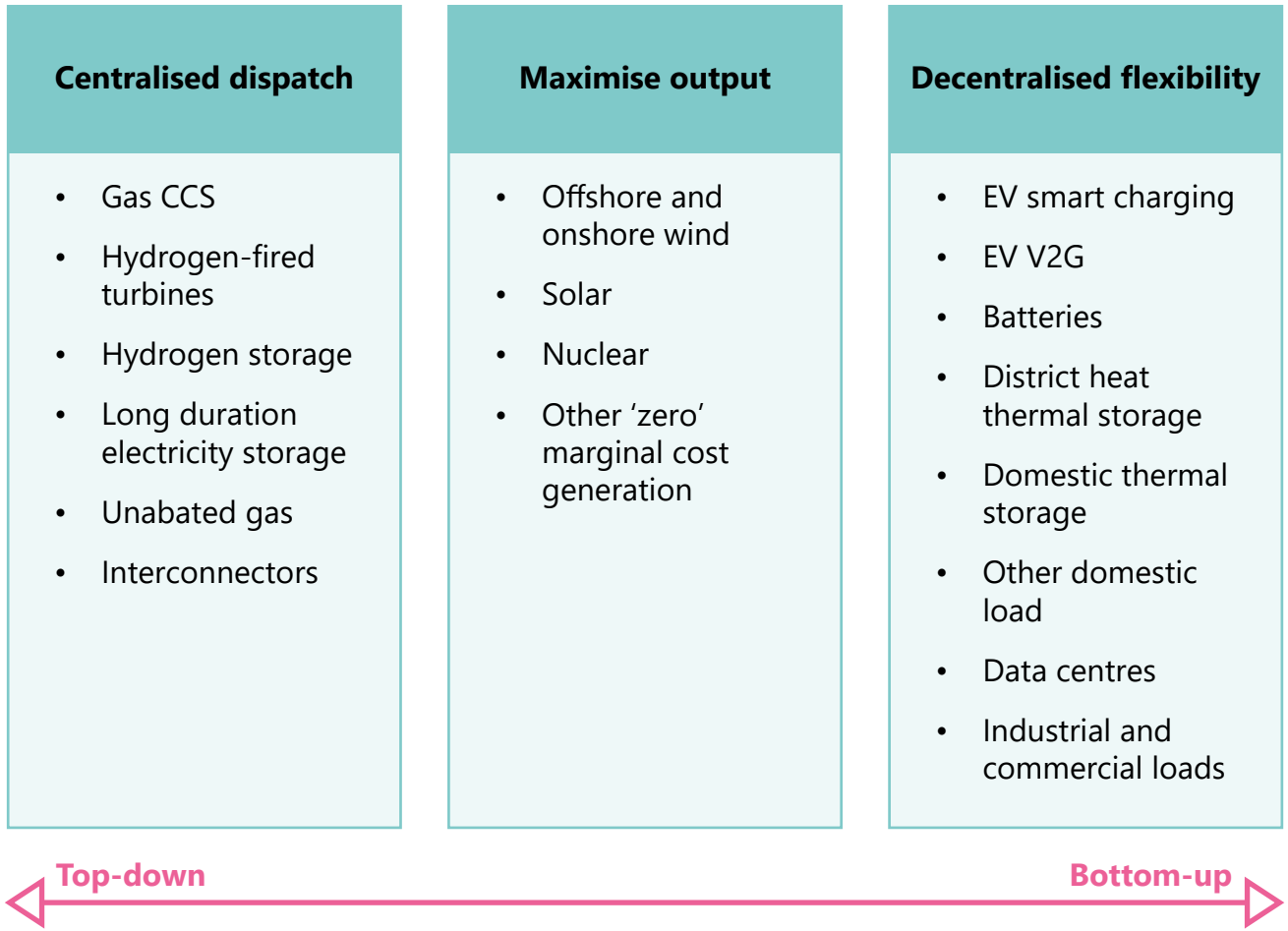
The System of Systems Map highlights we need to shift from commanding generation to orchestrating flexibility

Historically, a few large fossil-fuel plants with low capital and high operating costs were centrally dispatched to follow predictable demand. This is a top-down approach to flexibility.

As the System of Systems Map shows, today's system is much more complex, dominated by high capital, low operating cost-generation such as wind, nuclear and solar. Much of this is invisible to central dispatch as it sits on the distribution network or behind the meter. Most of it is run to maximise return on capital.

Coordination needs to shift to the local level, where EV charging, batteries and heating systems flex in real time.

In the future, every smart device on a feeder will need to negotiate its energy needs with other local devices, staying within local constraints and the national availability of electricity. This requires a bottom-up approach.



Technologies best suited for top-down or bottom-up control

The System of Systems Map shows the energy transition enablers that need to be integrated to benefit customers

The generation, storage and energy-using assets that make up any energy system need to be effectively integrated to deliver useful services to consumers.

The System of Systems Map highlights four system innovations that we need to enable these assets to work together flexibly:

- **Networks must move energy from where it's available to where it's needed**
  The transmission network handles large-scale flows while the distribution network takes care of local generation and storage. Power must move both ways to allow businesses and homes to increasingly contribute through technologies like solar, batteries, and V2G.
- **Digital infrastructure and AI must enable system visibility and operation**
  Allowing faster and more accurate flows of information will enable a smarter, and lower-cost energy system. For example, this would support aggregation of distributed energy resources or controlling signals to EVs.
- **A deeper understanding of consumers and their behaviour within the system**
  We need to understand how end-users consume energy and how this may be changed; how they provide power back to the system; and how their consumption and generation impacts the broader system.
- **Policy, regulation and markets underpin how energy is created and used**
  A framework is needed that enables energy to be generated, used and shifted affordably and reliably across time and place.

Networks

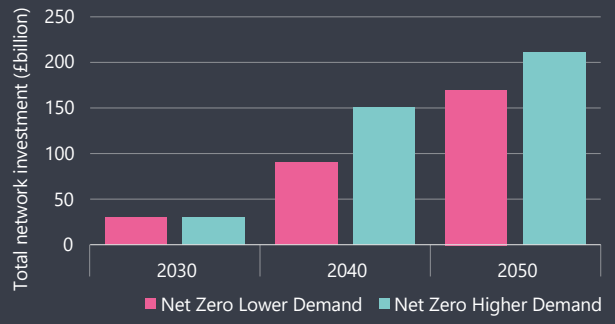
The electricity network is changing and will need reinforcement

The shift from dispatchable generation to renewables and the electrification of energy demand, combined with a slow roll-out of network build over the past 15 years, has led to significant network congestion, where renewable power, often generated in the north of Great Britain, cannot be transported by the network to centres of demand in the south.

This congestion makes it difficult to connect new capacity, including flexible resources, to the network. It also forces NESO to take costly operational measures, curtailing (or limiting) the output of low-marginal-cost and low-carbon renewable energy and instead dispatching more expensive, often fossil-based, power generation closer to consumption areas.

Network reinforcement to strengthen and upgrade the grid is needed to reduce congestion and ensure that electricity generating assets, including those which provide flexibility, and new sources of electrical demand, such as data centres, can connect to the network when and where they are needed. The Department for Energy Security and Net Zero (DESNZ) estimates £170–£210 billion of network investment will be needed by 2050. This should help keep electricity supply as low-carbon as possible, and could help to reduce constraint costs.

Flexibility has helped manage network reinforcement and saved consumers around £410 million over the past two years[14]. But flexibility cannot defer network reinforcement indefinitely as demand grows. As ageing or constrained network assets are replaced, the low marginal cost of adding extra capacity makes it worthwhile to do so from a resilience perspective[15].



Total onshore transmission and distribution network reinforcement needed by 2050. Data taken from the DESNZ analysis 'Electricity Networks: Enabling the Transition to Net Zero' for the lower-demand and higher-demand scenarios. Costs are in 2020 prices[16].

DESNZ estimates £170–£210 billion of network investment will be needed by 2050

Even with the 'Great Grid Upgrade' there is still likely to be electricity network congestion in some areas by 2040

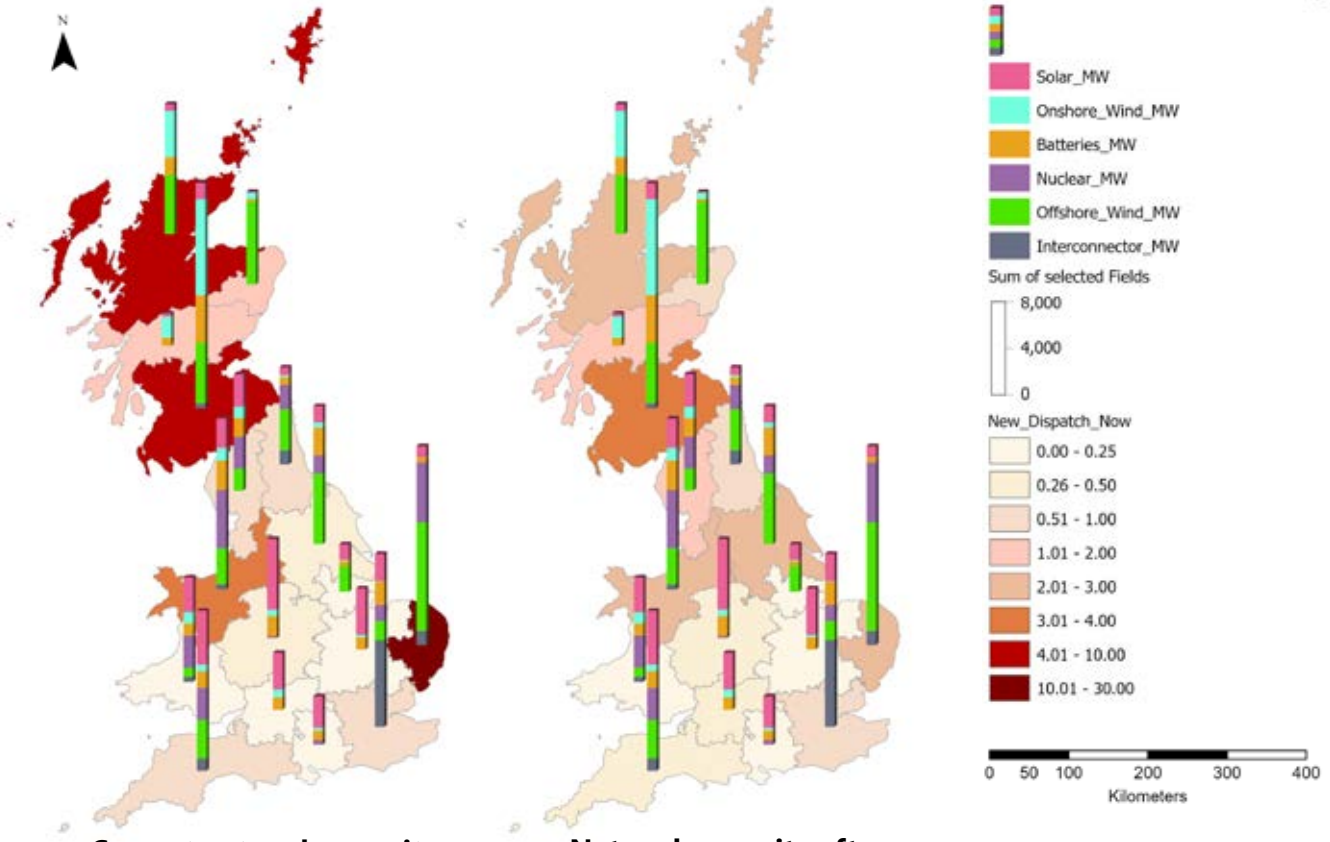
The UK's electricity transmission network is currently undergoing an extensive programme of network reinforcement, which aims to reduce network congestion.

We have modelled regional redispatch volumes[17], an approximation for network congestion, and show those for 2040:

- under current network capacity; and
- as they would be after planned network upgrades are implemented.

Whilst major investment including these upgrades will significantly reduce congestion, some network constraints will remain (areas of darker red), particularly in southern Scotland.

This means innovation is essential to help further reduce network congestion, for example: improved network demand forecasting; technologies to get the most out of the existing grid; and improved network planning and coordination.



Current network capacity

Network capacity after planned upgrades

Regional capacity and redispatch volumes for Strategic Spatial Energy Planning (SSEP) zones before and after network reinforcement – Further Offshore Wind 2040. The methodology for developing this figure can be found in the Technical annex

Gaseous networks retain a role. The natural gas network will have to adapt to run at lower utilisation but is still important for meeting peak demand in 2040

Natural gas and biomethane

Our analysis shows natural gas consumption in 2040 will reduce by as much as 50% from today's levels and 68% by 2050. But by 2040 it will still be essential for providing flexibility, especially during periods of low-wind generation and high demand, where unabated gas turbines and gas boilers still fill the gaps.

A key challenge to the natural gas network will be understanding how to run and maintain the same network when it is used less often or at lower utilisation. This includes exploring new ways of paying for the natural gas network or decommissioning or repurposing parts of the network. In a recent study we carried out with the Hydrogen Innovation Initiative[18] programme, many stakeholders stressed the need for a stronger evidence base to support decisions on whether to decommission or repurpose parts of the natural gas network.

The gas network will play an increasing role in the transport of biomethane produced from energy crops and waste. Estimates vary but a 2025 report for the Green Gas Taskforce[19] identified the potential for the UK's annual production of biomethane to reach 120 TWh by 2050. This compares to 220-230 TWh of expected UK gas demand in 2050. Driving down the cost of biomethane, reducing fugitive emissions and simplifying gas grid injection will help increase uptake and improve UK energy security.

Natural gas consumption in 2040 will reduce by as much as 50% from today's levels, and by 68% by 2050

2040

2050

A hydrogen network may be needed to distribute hydrogen to industrial clusters and to support hydrogen-based flexibility

Hydrogen

We expect to see growth in hydrogen demand from around 27 TWh today (most of which is not clean hydrogen) to between 65 TWh and 145 TWh[20,21] by 2040.

For this analysis, our scenarios result in a more narrow, centralised range of 115-120 TWh. This reflects the significant uncertainty about the extent of hydrogen's role in the future economy.

Most of this demand (~60%) is for industry, but some of it provides system flexibility through energy storage and hydrogen turbines providing back-up power. A network would be needed to transport the hydrogen from where it is produced to where it is used.

The development of this network has already started with a number of initiatives planned including Project Union[22] led by National Gas Transmission.

Smooth development of the hydrogen network requires overcoming several key barriers: technical challenges in repurposing gas networks, public acceptance issues, and investor uncertainty.

Innovation is needed across electricity, natural gas and hydrogen networks

Electricity networks

New tools and modelling approaches: these support network planning across different geographical scales and voltage levels to improve network capacity and grid operability.

Enhanced data and information sharing: better sharing across planning bodies and deeper stakeholder engagement to align national and regional policy and local delivery.

Automated constraint management: using AI and machine learning to enable real-time control of the network, allowing it to operate safely closer to thermal limits.

Improved demand forecasts: this should include short-, medium- and long-term energy demands at high spatial resolution to support network planning.

Network coordination: innovative approaches for network coordination and primacy frameworks that give commercial and operational clarity, enabling efficient use of distributed flexibility to manage constraints across voltage levels.

Natural gas networks

Infrastructure readiness: evolving asset management to ensure gas network infrastructure remains able to operate efficiently even at lower utilisation.

New market mechanisms: to ensure the gas network is appropriately remunerated for being available to provide energy during peak gaps for as long as it's needed.

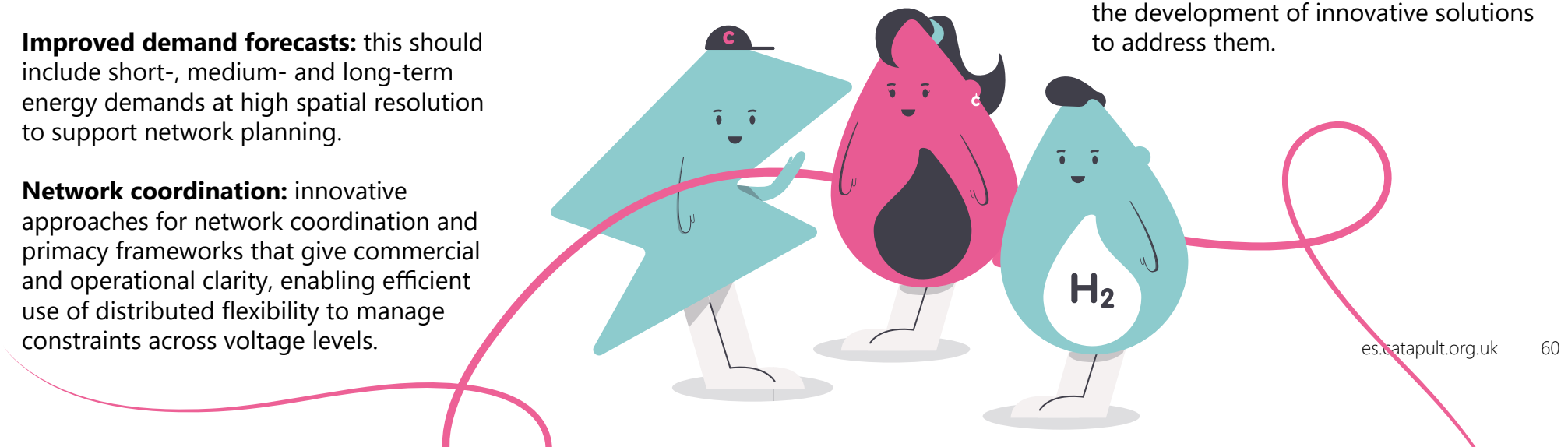
Repurposing: develop robust tools and business cases for safely repurposing redundant assets for hydrogen.

Hydrogen networks

Whole system coordinated energy system planning: highlighting the role of hydrogen assets, supporting the case for investment and deployment of a hydrogen network.

Targeted innovation and demonstration funding: to support the development of a network, leveraging private funding and building on existing business models and allocation rounds.

Improved stakeholder and public engagement: a better understanding of the public's safety and environmental concerns around hydrogen will support the development of innovative solutions to address them.



Digital infrastructure and AI

Digitalisation is essential to enable a smarter, more efficient energy system, and we have identified three areas where it delivers most value

We define digitalisation in the energy sector as: "**the coordinated use of digital technologies, data, and processes to enable smarter, more efficient, and customer-focused energy system.**" This allows for energy generation, transmission, storage, and consumption to become more flexible and therefore more balanced, optimised and autonomous.

There are three broad areas of the energy system where digitalisation can deliver most impact by improving information flows:

1. Real time visibility and control;
2. Smarter forecasting and decision making;
3. Coordination across distributed assets.

AI advances, in particular in advanced data processing, machine learning and accurate forecasting, are essential tools that will enable the shift from top-down control of 60 power stations to bottom-up orchestration of 60 million distributed, smart, flexible assets.

While the technologies needed to process data at the required scale have been proven in other sectors, there is still much development and innovation needed to apply them across the energy sector.

We can use our System of Systems Map to highlight how further improvements in these areas will enable flexibility to deliver the services needed by the wider energy system.

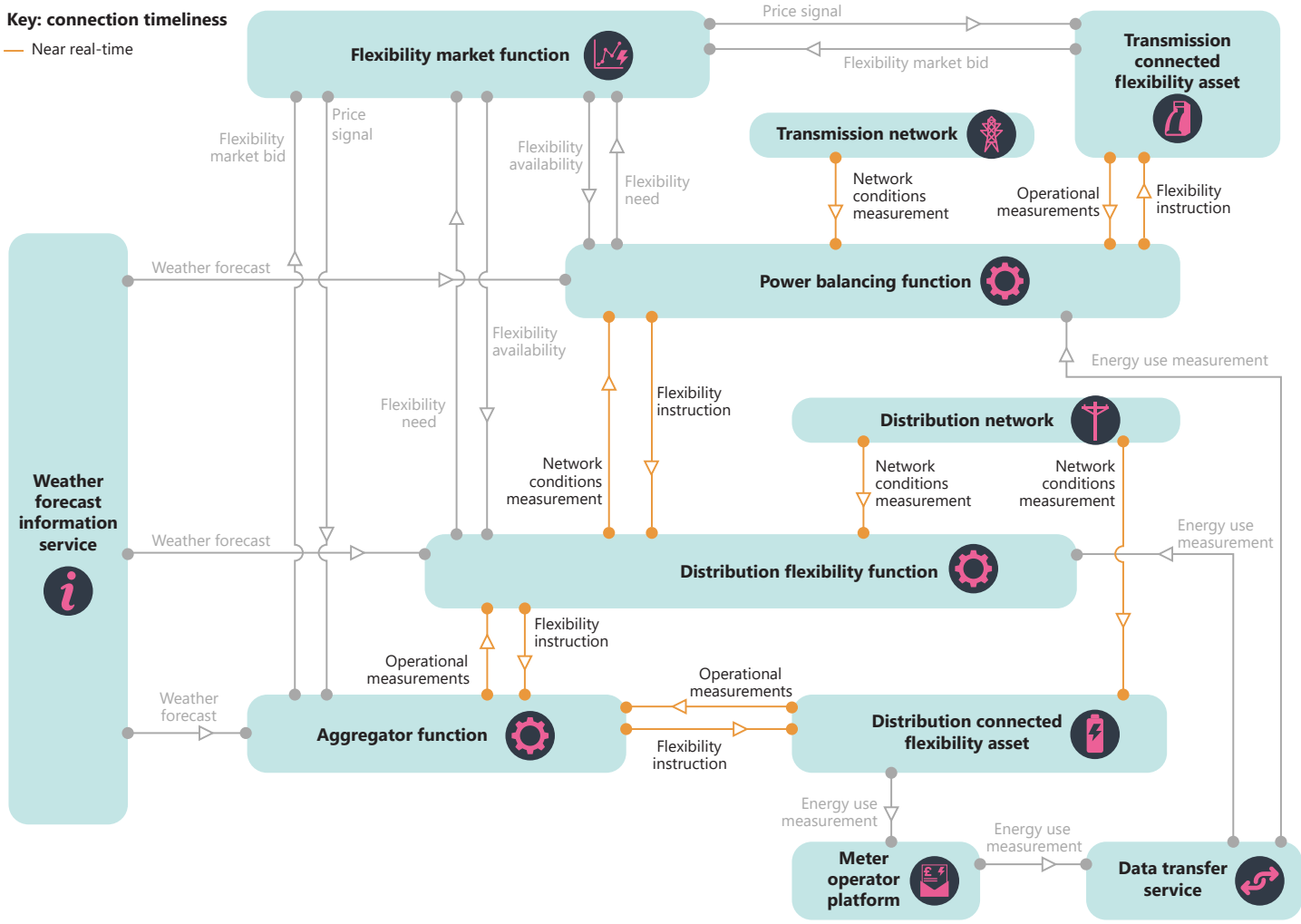
Real-time visibility and control, across all levels, is essential for managing the energy system most effectively

Digitalisation provides the connectivity to deliver real-time visibility and control.

Much of this control and decision making within the future energy system will need to happen automatically, distributed across the entire grid with central controllers maintaining oversight.

Locally, at either a substation or feeder level, individual smart energy assets will need to connect with each other for visibility of demand, and to help control their behaviour and optimise it within local constraints.

Similarly, central interventions made by transmission and distribution system operators will require clear visibility and control of power flows and constraints, potentially down to a local level, to ensure the whole system remains stable and resilient.



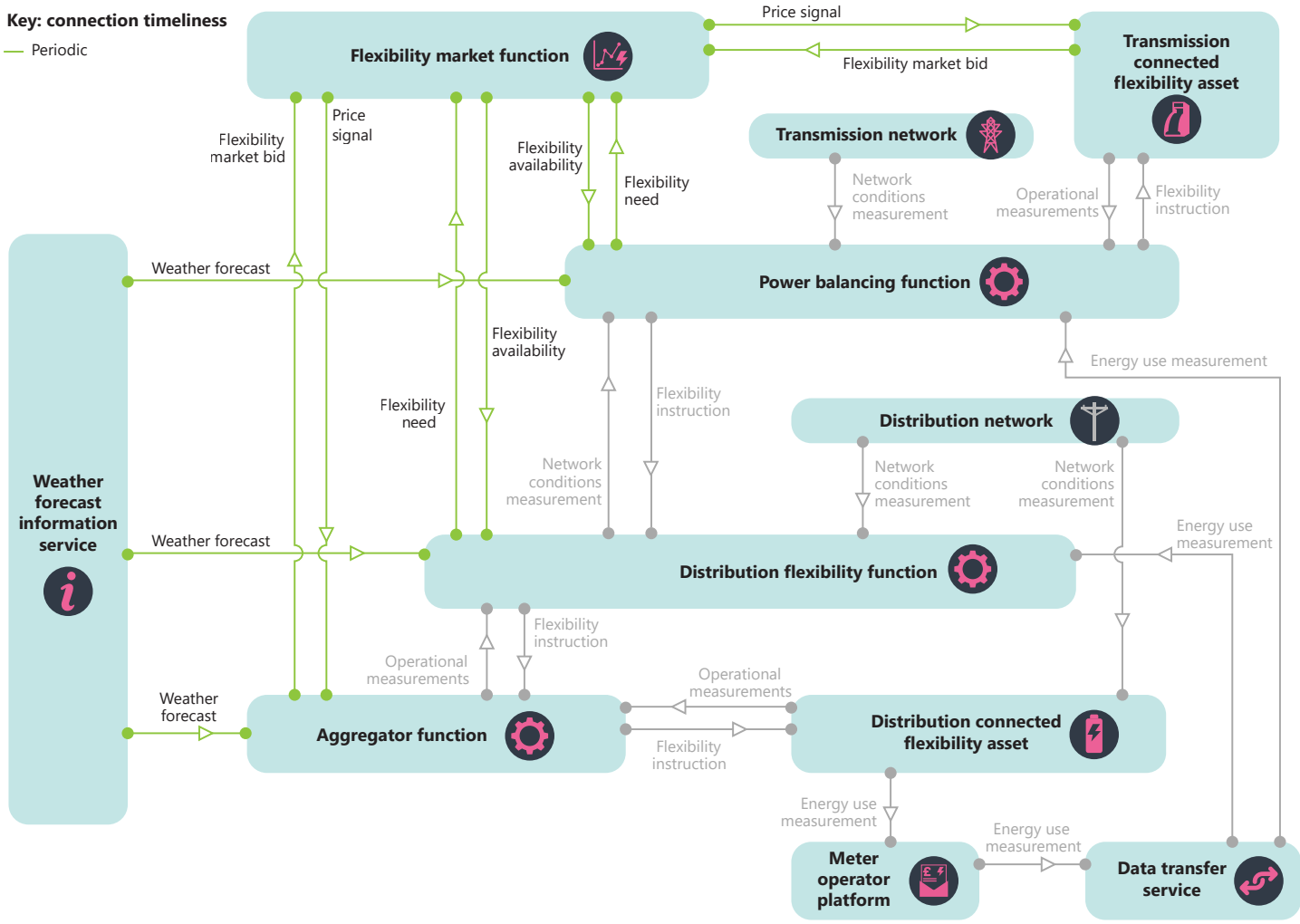
Smarter forecasting and decision making helps optimise the energy system

Digitalisation provides the automation to support smarter forecasting and decision making.

AI-based models are helping us to better predict weather patterns, energy demand and energy generation.

This means improved forecast data can be sent to control rooms, aggregators and flexibility assets, as well as inform market signals. This enables operators and assets to respond earlier and more effectively.

This allows smart energy assets to make best use of the available energy and reduces the need for last minute balancing actions, like starting up a gas-fired power plant.



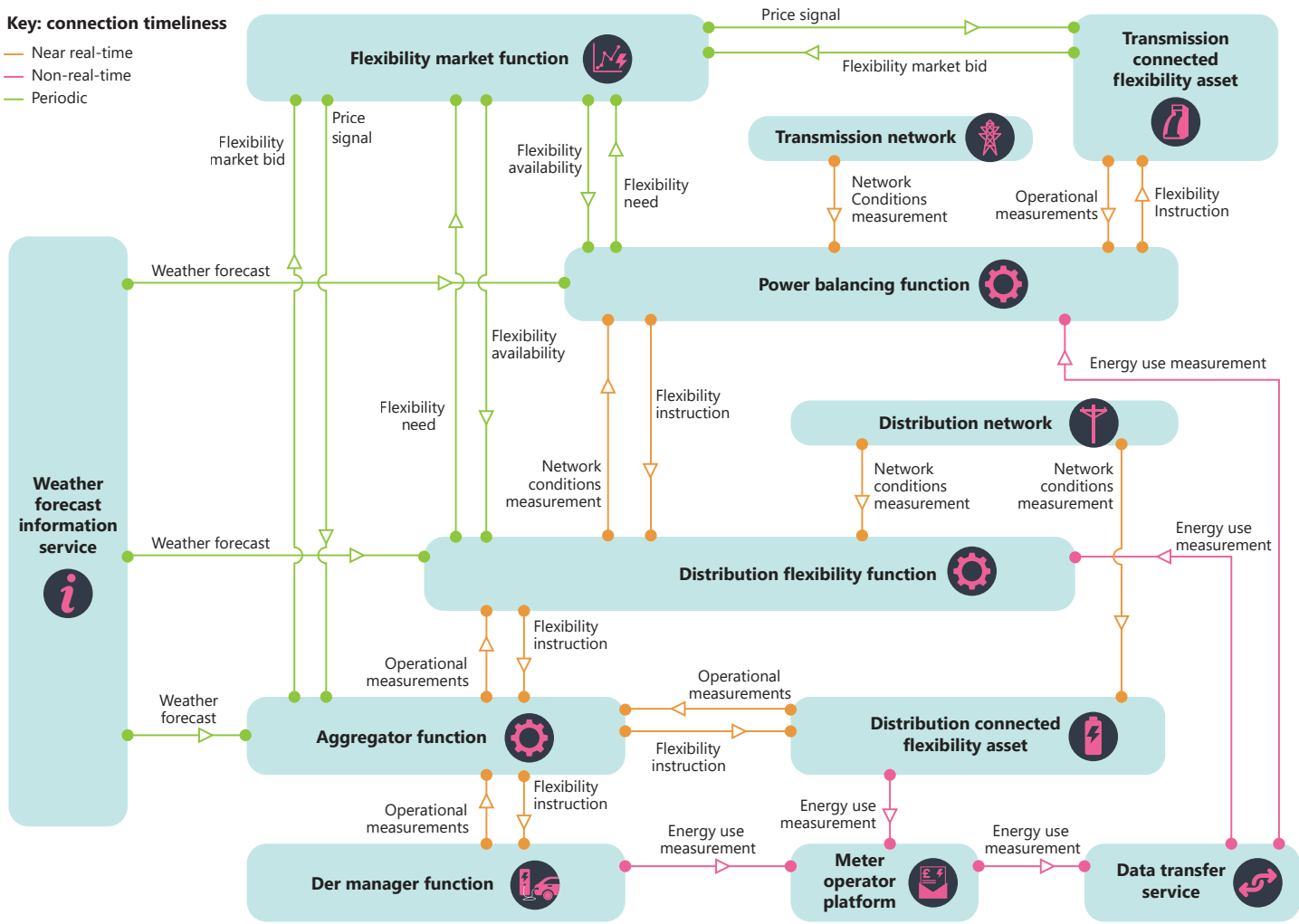
Coordination across distributed assets is essential to flex demand, to balance supply and manage constraints

Digitalisation provides the information to enable coordination across distributed assets.

It enables millions of smart energy assets (e.g. batteries, EVs and heat pumps) to act autonomously together to deliver the same effect as controlling a single large power station.

It also allows aggregators to access near real-time network information, assess the operational status of connected or behind-the-meter assets, and dispatch instructions to many at once, delivering far more flexibility than any single asset.

Digitalisation unlocks new sources of flexibility and allows for decentralised, automated responses to our energy system's needs.



Further innovation is required to unlock the full potential of digitalisation, deep tech and AI across the energy system

Building on the progress that has already been made, further innovation is required if we're going to unlock the full potential of digital solutions.

Priority areas for innovation include:

- **Scalable control systems** that use AI to improve control and coordination of millions of smart energy assets. This would support the provision of reliable and scalable balancing services, for example by enabling virtual aggregation of buildings to deliver consistent, system-level balancing and constraint management.
- **High-quality, interoperable data infrastructure** with real-time access across the system, supported by better data-sharing, standardisation and cyber-security. Internet of Things connectivity strengthens this by linking devices that can share and collect operational data.
- **Advanced forecasting and simulation tools** that can model complex, uncertain scenarios. This includes AI-driven models that deliver forecasts using a tiny fraction of the energy required by traditional numerical weather prediction methods.
- **Seamless integration of consumer technologies** enables EVs, heat pumps and other devices to connect to the grid in ways that support flexibility and work across both current and legacy systems.
- **Integrated control systems** enable smart buildings that work effectively and seamlessly with the wider energy system.
- **Adoption of open energy data** supports digitalisation of the energy system, enabling interoperability and avoiding technology lock-in.

The AI for Decarbonisation's Virtual Centre of Excellence (ADViCE) project provides more details on the potential applicability of AI to flexibility

ADViCE[23] identified where innovative AI technologies could be applied to decarbonisation challenges to support the transition to Net Zero. The programme is delivered by Energy Systems Catapult and Digital Catapult, alongside the Alan Turing Institute on behalf of DESNZ. It has identified two specific grand challenges where AI can support innovation in flexibility:

- GC3 – Maximising flexibility in energy networks
- GC8 – Optimising EV infrastructure.

Together these grand challenges outline 20 innovation priorities where AI can help address flexibility in energy networks and smart EV charging.

Enabling consumer flexibility

Enabling household consumer flexibility requires smart flexible solutions that are controllable, reliable and low-cost; more than behaviour change

Households could provide around 76 GW of electricity flexibility by 2040, as well as over 350 GWh of thermal storage (including that combined with domestic district heat networks).

Our 'Enabling Distributed Flexibility for Net Zero report' found that delivering consumer-led flexibility at the point it is needed will be far easier through smart flexible solutions via automation, rather than relying on consumers to change their behaviour throughout the day or week. This will enable consumer flexibility to be controllable, reliable and low-cost[24]:

- **Controllable:** devices can be influenced or adjusted by the energy system when needed.
- **Reliable:** devices respond as expected when needed.
- **Low-cost:** doesn't require expensive incentives to enable flexibility when it's needed.

But automation does not mean consumers are removed from the process of flexibility entirely. Most of the flexibility solutions selected by our modelling (i.e. batteries, EV smart charging or V2G, and domestic thermal energy storage) require consumers to do "something" to enable this flexibility. This includes installing a battery, plugging in their EV, or opting into a service.

Finding the right consumer propositions and tools to encourage uptake remains an exciting innovation opportunity.

These could be relatively simple solutions such as an app to support flexible energy use, like the equiwatt proposition trialled in our Inclusive Smart Solutions programme[25] (ISS), or something more complex such as the heat-as-a-service offer trialled in our Smart Systems and Heat programme[26].

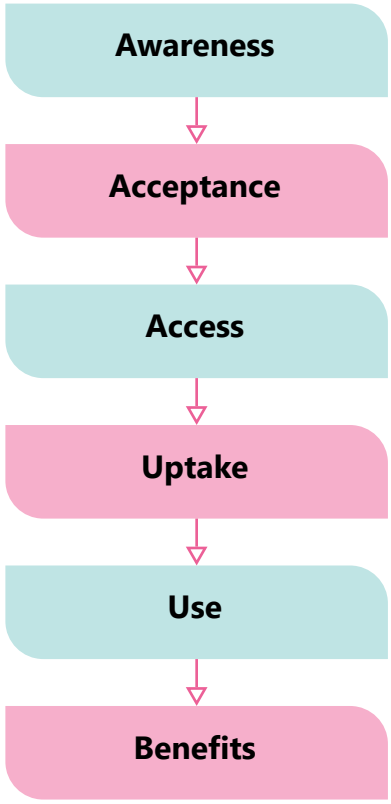
Household consumers need support to adopt and benefit from providing flexibility

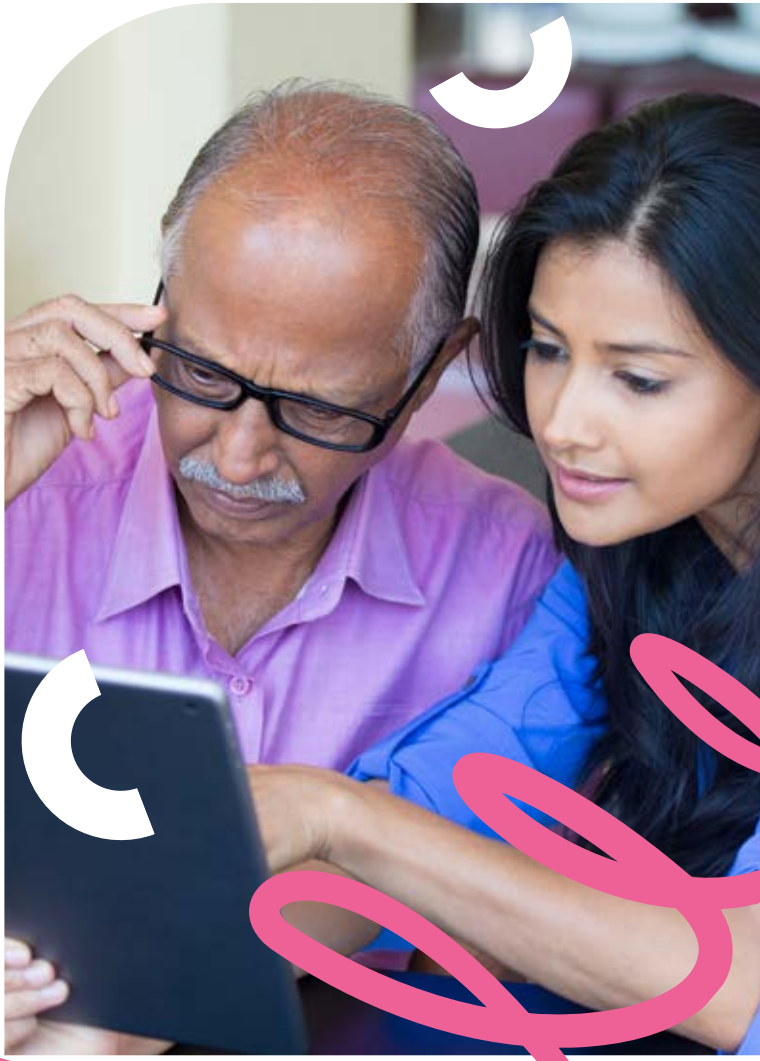
Uptake and use of smart, flexible solutions will depend on consumers navigating potential barriers (see diagram). Barriers at any one of these stages can reduce the system-wide benefits of consumer flexibility driving up energy costs for all. Innovators who can come up with products and services that make it easy and more affordable for consumers to provide system flexibility through their assets, or in how they use energy, will thrive.

Some of the many barriers consumers face in engaging with flexibility include:

- difficulty finding out about energy flexibility;
- difficulty accessing smart solutions;
- disproportionate barriers to purchasing smart products and services;
- lack of means to use energy in a flexible way;
- disproportionately lower rewards and benefits from flexibility.

Our ISS programme[27] identified several groups most at risk of being impacted by these barriers. They include: households in receipt of benefits, tenants, those over the age of 65, and low-income households. This highlights that these barriers are not a niche issue. They impact large proportions of the population. For example ~19% of the population is over 65[28].





Equity will be important if consumers are to have confidence in flexibility services

Even when consumers adopt a technology, they must still engage with it as intended to provide flexibility

Even if consumers adopt a potentially flexible technology, they must still use it as intended to deliver the flexibility required.

For example, V2G consumers must be willing to plug their vehicle in when flexibility is needed and allow the network to withdraw power from it. A consumer that acquired their V2G solution to provide energy security in case of a power cut may not be prepared to plug in when flexibility is needed most and the chance of a power cut is highest.

Such behaviours may slow uptake or could result in consumers exploiting or manipulating how services are used. Inevitably, this will see service providers tinkering with their offer as they learn more about consumer behaviour[29]. Clarity of the full proposition and clear and fair rules will be essential to avoid these unintended consequences.

Equity will be important if consumers are to have confidence in flexibility services and this may require a new approach to regulation and consumer redress.

Consumers will need to be able to choose from solutions that offer relevant benefits and work for their needs and circumstances.

Care needs to be taken to manage a market where consumers who have the means (i.e. technology and the ability to pay) are effectively able to buy their way out of participating in flexibility. For example, by taking up a V2G proposition that costs more but minimises the risk of disruption during peak duration gaps.

Consumers tend to stick with a technology they are familiar with so given the advantages of V2G over smart charging from a system point of view it is important that the roll out of V2G, and particularly bi-directional chargers is accelerated. Otherwise, many consumers installing EV chargers in the next five years will choose models which aren't bi-directional and which, once installed, are unlikely to be replaced just for V2G functionality.

Innovation for household flexibility should focus on developing consumer-friendly propositions, including for low-income and vulnerable consumers

To remove barriers and allow consumer flexibility to meet its potential by 2040 there should be a focus on:

Smart flexible solutions delivered via automation: this could include apps to support flexible energy use, or more complex consumer propositions such as heat as a service. These solutions help consumer flexibility rely less on behaviour change and be controllable, reliable and low-cost.

Supporting the consumer journey: develop a coordinated approach to design, implement and integrate actions that address barriers to consumer flexibility at each stage of the consumer journey. This would ensure that innovations and support measures delivered at each stage of the consumer journey facilitate subsequent stages.

This will require collaboration between innovators, consumer-facing organisations, all tiers of government and others, including those providing consumer redress.

Clear messaging and incentives: incentives and clear, trusted messaging are needed to gain and maintain participation, especially among consumers required to shift or reduce usage during prolonged events.

Further real-life trials: these are needed to better understand what consumers value and what influences their interactions with flexibility. Key areas to consider are:

- **Essential vs discretionary needs:** what is the minimum level of service that must be maintained for consumers throughout the Peak Duration Gap?
- **Impact on well-being:** how do we ensure that providing flexibility does not negatively impact well-being and health?
- **Fairness and equity:** how do we ensure decisions don't disadvantage low-income or vulnerable households or disproportionately benefit others? How is flexibility paid for and how is it rewarded?

The commercial sector could provide 8 GW of flexibility by 2040 with building management systems being vital enablers

Commercial flexibility can take the form of peak reduction (i.e moving processes such as smart charging of EV fleets to periods of lower demand) or using energy storage to shift energy consumption without changing processes and behaviour.

Our modelling sees the commercial sector providing around 8 GW of electricity flexibility alongside 150 GWh of thermal storage by 2040. The commercial sector currently represents 19% of energy consumption and 30% of electricity consumption so has strong potential to provide even greater levels of flexibility. It could be two to three times higher than modelled, but barriers need to be overcome.

Barriers to commercial flexibility include uncertain revenue and therefore payback periods for investments, as well as organisations naturally prioritising their core commercial business rather than flexibility. These could be removed by many of the innovations discussed elsewhere in this report. These include improved digital infrastructure and smart controls to improve integration, and markets which value flexibility correctly and are easy to access.

The Innovate UK-funded GridFlex programme[30] examined the commercial flexibility value chain and how innovation can support its growth. It found that multiple actors influence a commercial organisation's decision to provide flexibility, including facilities managers, building management system (BMS) providers, aggregators, suppliers and market operators. Navigating across all these actors can be complex, time-consuming and often leads to disengagement. GridFlex also highlighted the critical role of BMS in enabling automated, smart participation in flexibility markets. To unlock commercial flexibility at scale, innovators, BMS providers and commercial organisations need to work together to create simple, accessible flexibility offerings.

Industrial consumers have the potential to provide flexibility but substantial barriers to uptake means it may lag domestic uptake

Industry is responsible for 26% (82 TWh) of UK electricity demand[31] and this may rise to around 90 TWh by 2040[32].

Individual sites can be huge consumers of electricity, used for a diverse set of processes and site uses. Even those sites which currently do not have significant electricity demands may see this change in the future as they seek to electrify their processes.

This means there is potentially significant untapped flexibility that could be unlocked from industrial sites, with one study[33] suggesting up to 3.9 GW of industrial flexibility by 2050, compared to 0.8 GW in 2023[34]. But substantial barriers need to be overcome to realise this potential, particularly:

- **Lack of awareness and capability to pursue flexibility**
  Understanding of flexibility in the industrial sector is generally low. Offers are limited and seen as confusing, overly technical, and poorly aligned to business needs.
- **No clear customer journey**
  It is not always clear to non-domestic customers how to provide flexibility, for example, how to access flexibility markets.
- **Little visibility of likely benefits**
  Unclear and unreliable flexibility revenues make it difficult to identify a path to investment for flexibility. There is also often a concern that providing flexibility will detract from the company's main revenue stream.

Novel solutions aimed at accelerating deployment of flexibility are required to unlock capacity from industry customers. For example, propositions that provide clarity on risk and reward; or demonstration projects that derisk the technologies and highlight revenue streams.

Industrial consumers lag the domestic sector in both awareness of flexibility and opportunities to provide it.

Untapped flexibility could be unlocked from industrial sites

New data centres will increase electricity demand substantially, potentially accounting for 5% of all UK demand in 2040. They also offer opportunities to provide flexibility

One fast-emerging specific sector that could provide substantial system flexibility benefits is data centres.

We expect data centres to add substantial new load to the energy system, representing around 5% (26-28 TWh) of total electricity demand by 2040. Put in context, this would be equivalent to around one third of expected industrial electricity consumption in 2040.

Data centres could provide flexibility by:

- **Load shifting**
  They move non-urgent computational workload (e.g. AI training or batch processing) to periods of high generation and low electricity demand. Activities could be transferred between data centres geographically to lower demand in specific locations.
- **Onsite energy storage or electricity generation**
  On-site battery systems can be used to store electricity when supply is high (and electricity is cheap) and then discharge onsite when electricity demand is high. Onsite backup generation, typically gas or diesel generators, could provide a similar service. In the future, this generation could be repurposed to replace aging gas-peaking plants and provide a wider system benefit (although with accompanying carbon emissions).
- **Reduce cooling load**
  Up to ~30%[35] of a data centre's demand can be for cooling. This can be temporarily turned down. Or it can be shifted entirely by using cooling provided by cold water or ice that was cooled previously during times of lower energy demand. Alternatively, the heat being cooled could be used in a district heat network, possibly via a local heat store.

Innovation priorities for industry and data centres should include improved awareness of the value of flexibility

Industry customers

- **Demonstrator projects**
  These would help demonstrate revenue streams from flexibility and show industry customers how to access flexibility markets.
- **Education and awareness**
  Further work is needed by market designers and operators to ensure industry segments are aware of the benefits of providing flexibility and want to enter flexibility markets.
- **Enhanced market signals**
  Market signals which represent the true value of flexibility would help provide longer-term revenue certainty.

Data centres

As well as these priorities, to enable data centre flexibility there should be a focus on trialling and demonstrating:

- **Greater flexibility in cooling systems**
  This could be from development of local thermal heat stores, or reuse of waste heat in a heat network.
- **Repurposing of onsite gas generation**
  Gas plants attached to data centres could be repurposed to provide peaking plant. The impacts and cost implications of this need further exploration.
- **Geographical load shifting**
  Further work is needed to understand the impacts of moving activities between data centres and to ensure the control and integration mechanisms are in place to enable this.
- **Improved telemetry and control standards**
  These will enable data centres to respond more effectively to electricity network signals for flexibility.

- **Integration**
  Legacy data centre infrastructure (power and cooling systems, control and monitoring systems) and some software weren't designed with flexibility in mind. Future data centre infrastructure and software should be designed to allow flexible operation.

Policy and regulation needed to enable the rapid take-up of flexibility

What do innovators want? A more agile regulatory and policy system – and better access to data

We spoke to a set of promising innovators at an expert roundtable and engaged with a wider group through a survey, helping us identify the following reforms we believe are needed to accelerate innovation and the deployment of flexibility solutions:

- **Policy, regulation and market reform** – simplification of regulatory frameworks and flexibility markets will make it easier for new entrants to understand and thrive in the sector. Policy needs to adapt in a timeframe that more closely follows the speed of technology innovation and progress.
- **Value of flexibility** – greater clarity and simplicity on revenue streams. Design markets that recognise the value flexibility brings to the system.

- **Targeted demonstration funding** – to show the benefits of new approaches that can increase confidence for buyers of innovation and for investors in new technologies. This aligns with the proposals in the Energy Networks Innovation Taskforce.
- **Data access** – more open access to data, especially real-time generation and consumption data, would help to speed up product development and deployment.
- **Transparency around system operation** – increased transparency around why certain assets are or are not dispatched at a given time will help to build trust among market participants and network/systems operators.
- **Consumer engagement** – pressing need to increase awareness, simplify the offer and demonstrate a compelling return on investment.

We agree existing electricity markets, policy and regulation do not sufficiently incentivise the deployment of flexibility technologies

A patchwork of policy interventions and inconsistent effective carbon prices distorts signals for flexibility
The government has over the years introduced a number of policy interventions that have created a patchwork of effective carbon prices across the economy (see next page). Some of these measures interact with and distort the price formation mechanism in the wholesale electricity market. For example, the capacity market distorts price signals by shifting the capacity costs power plants need to recover from the wholesale market into the capacity market. This blunts the price signals in the wholesale market and reduces the value flexible technologies can reap from the wholesale market.

The Long Duration Energy Storage (LDES) cap and floor scheme together with bespoke business models for CCUS and hydrogen-to-power risks locking in an inefficient allocation of flexible technologies that are not sufficiently guided by market forces that can drive innovation.

This patchwork of policies is compounded by a messy, inconsistent set of effective carbon incentives across the wider energy system (see next page).

Wholesale pricing lacks granular locational and temporal signals
The current wholesale market does not provide locational signals for efficient siting and operation of assets. The government ruled out zonal pricing in favour of keeping a single GB wholesale price. Instead, siting decisions are dependent on central planning to direct the location of investments, through the strategic plans, TNUoS charges and a connections queue that reflect those plans. The lack of localised operational signals, batteries and longer-duration energy storage will need frequent re-dispatching through the Balancing Mechanism (BM) to ensure power flows in the right directions for system stability, adding costs to consumer bills.

Small non-BM assets have limited opportunity to access NESO markets outside of Scotland's Local Constraints Market. Current primacy rules do not go far enough in addressing efficient coordination between NESO and DSO markets. There are barriers to demand turn-up that holds back local flexibility. Temporal price signals are currently hourly or half-hourly, which limits the opportunity for batteries and consumer-led flexibility to respond to more granular temporal signals based on very short-term variations in demand and supply.

The capacity market risks locking in higher-carbon assets in the technology mix for years to come
The current capacity market rules do not differentiate between low-carbon generation capacity and unabated gas generation, which risks locking in gas generation capacity for years to come, without considering the whole system costs of different generation technologies.

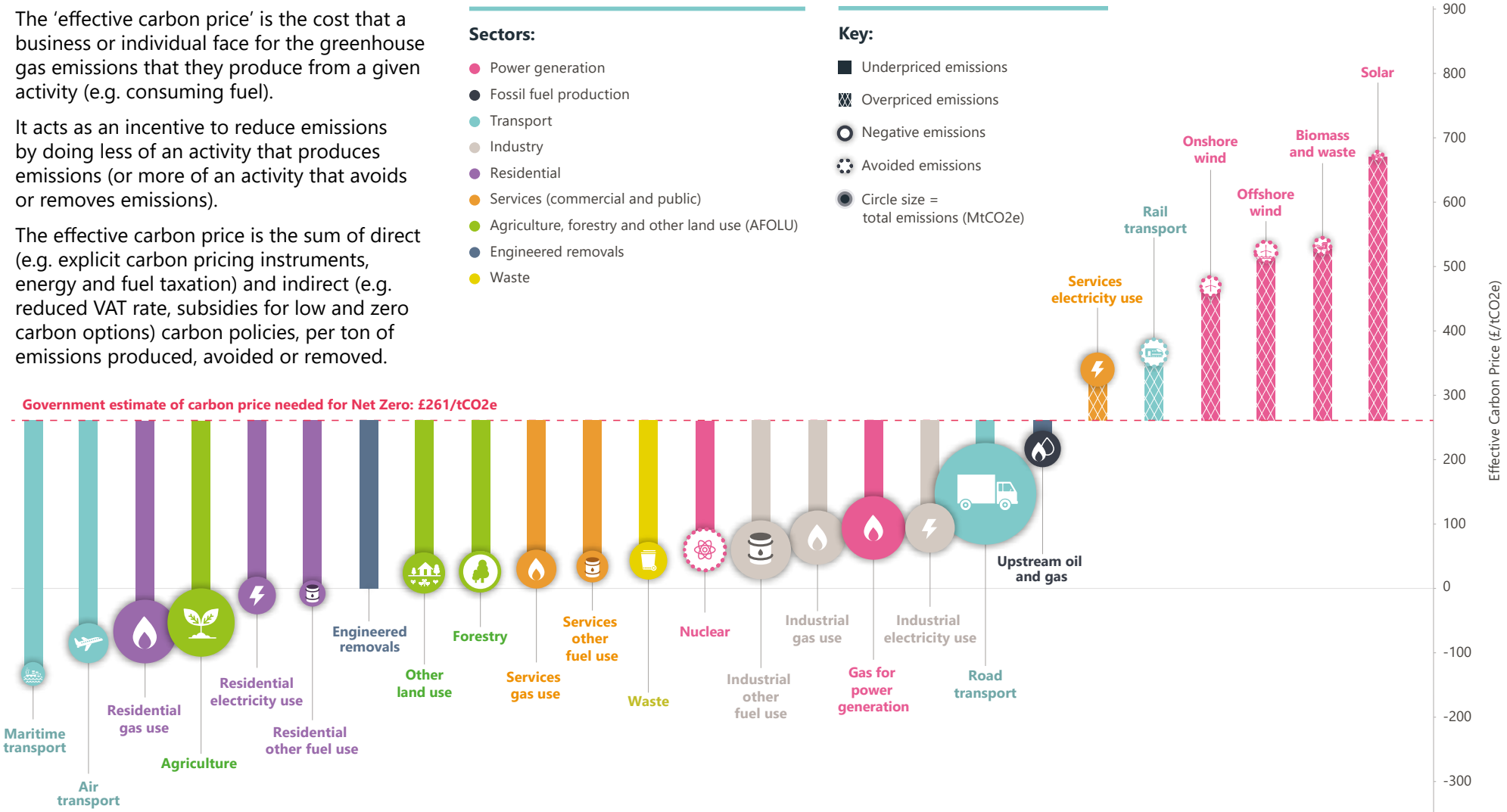
The LDES cap and floor scheme does not sufficiently incentivise 'long duration' energy storage
Our analysis highlights that low carbon dispatchable power will play a critical role from 2030 to 2040. The government's LDES cap and floor scheme risks muting the incentive for truly long duration energy storage by rewarding projects with a minimum dispatch requirement of only eight hours.

Effective carbon prices across the wider energy system are inconsistent, stifling innovation and investment

The 'effective carbon price' is the cost that a business or individual face for the greenhouse gas emissions that they produce from a given activity (e.g. consuming fuel).

It acts as an incentive to reduce emissions by doing less of an activity that produces emissions (or more of an activity that avoids or removes emissions).

The effective carbon price is the sum of direct (e.g. explicit carbon pricing instruments, energy and fuel taxation) and indirect (e.g. reduced VAT rate, subsidies for low and zero carbon options) carbon policies, per ton of emissions produced, avoided or removed.



Effective carbon prices and emissions in the UK by sector
(Our analysis calculates 2022 figures, as this is the latest year for which complete data is available)

Existing price signals and outdated regulation stifle progress in key technologies, ranging from nuclear to V2G

Current carbon prices fail to incentivise low-carbon flexibility, serving only to raise consumers' bills
While pricing through the UK Emissions Trading System (ETS) and Carbon Price Support (CPS) increases the cost of unabated gas generation and wholesale prices when gas sets the marginal price, it remains too low to properly value some key flexible low-carbon technologies, such as batteries and long duration energy storage.

As a result, the government relies more heavily on direct support schemes, with costs recovered through policy levies on consumers' bills. Because these charges are largely fixed and do not vary by time of use, consumers have limited ability to shift demand away from high-carbon periods, weakening price signals and incentives for both consumers and investors.

Unless the UK ETS price rises enough to make low-carbon dispatchable power cheaper to operate than unabated gas, batteries, long duration energy storage and other flexible low-carbon technologies will remain at a disadvantage in the market.

The current state of retail regulation does not allow for differentiated supplier tariffs for different assets and technologies
There is a lack of regulatory diversity in electricity retail that can allow consumers to have different tariffs for different home appliances. For example, some consumers may prefer a flat tariff for their general household consumption, but a dynamic tariff for their heat pump or EV charger, where they can capitalise on heating or charging during periods with low prices.

V2G remains limited in scale without a mandate for bi-directional EV charging capability
There is currently no regulatory requirement that EV charge points must be capable of bi-directional charging and the Clean Flexibility Roadmap[36] cautions that V2G bi-directional charging will only grow significantly past 2030. However, our analysis shows that V2G needs to begin scale-up by 2030. Not growing V2G opportunities by 2030 risks missing important consumer flexibility that EVs are increasingly capable of providing.

Government policy for SMRs is not yet focused enough on unlocking innovation and competition
The government has committed funding to develop the technology, but it has not set out a clear route-to-market, particularly the long-term revenue and deployment support needed for early commercial projects. This creates a risk that support remains ad hoc and design-specific, which could entrench technology lock-in, create subsidy dependency, and produce unintended market and supply-chain consequences.

Moreover, regulation remains a key driver of higher costs for new nuclear power stations. The **recent Fingleton Review** identified risk aversion, unnecessary process and complex procedures, and a lack of incentives to minimise social costs. **Urgently implementing those recommendations in full is essential** if we are to unlock the system benefits of low-carbon technology as a crucial part of the future energy system.

We should develop markets to reveal the best combination of flexible technologies to address the peak gaps, rather than picking technologies

Let market dynamics reveal the size of the peak gaps and equip consumers to thrive in a volatile market. Market dynamics should reveal the scale of the five peak gaps and incentivise participants to deliver the most cost-effective solutions. Each gap reflects a different system stress, and the wholesale market should be the primary mechanism for sending efficient price signals – provided consumers are equipped to respond to them.

The **Peak Power** and **Peak Energy** Gaps occur within a day and are best addressed by flexible technologies, including batteries and consumer-led flexibility. As prices become volatile, consumers must have access to dynamic tariffs, smart assets, and automation tools that allow them to optimise their energy use behind-the-meter.

The **Peak Daily Gap** requires between-day balancing. While no dedicated multi-day market exists, participants, including storage operators, respond to price expectations across days, charging during periods of high renewable output and discharging when supply is tight. The LDES scheme supports this by providing revenue certainty for longer-duration storage investments.

The **Peak Duration Gap** is rare and hard to predict, limiting the ability of the wholesale market alone to deliver sufficient capacity. This suggests the need for a targeted mechanism to ensure adequate backup capacity, while ensuring that assets used to address shorter-term gaps remain available when these rare events occur.

A capacity remuneration mechanism pays electricity resources for being available to generate electricity or reduce demand when the system needs it, rather than paying only for the electricity they actually produce. Examples for a capacity remuneration mechanism include a capacity market and a strategic reserve where the system operator procures capacity that can be used during periods of system stress.

Strengthen locational and temporal signals so flexible assets can address the peak gaps at a lowest whole-system cost: The current wholesale market design does not adequately address the locational challenges posed by the our peak electricity gaps, particularly while major network bottlenecks remain unresolved. In situations where transmission capacity is constrained, the ability to respond to peak gaps is limited by the physical network. Although the Balancing Mechanism (BM) helps manage these constraints, it does so after the wholesale market has locked in prices, resulting in higher system cost. To improve local balancing, NESO should extend the Local Constraints Market beyond Scotland to expand flex opportunities for non-BM assets, improve coordination with DSO markets beyond primacy rules, and work with Ofgem and DESNZ to remove barriers to demand turn-up.

Government decided not to go ahead with zonal pricing at this time, and so it is important that network tariffs reflect the actual conditions of the network. Strategic Spatial Energy Planning (SSEP), Centralised Strategic Network Planning (CSNP) and Regional Energy Strategic Planning (RESP) should be genuinely strategic and not overly specific to individual projects. Beyond 2030, nodal pricing should be explored again as the most effective tool to site the right technologies in the right locations.

Temporal signals are currently captured at 30-minute or one-hour blocks in the wholesale market, while settlement is half-hourly. To encourage better matching of supply and demand in real time, five-minute settlement periods should be introduced so generation, storage and consumer-led flexibility can respond more quickly to short-term changes in system needs.

Government and regulators should reform price signals, the capacity market and how it supports nuclear, as well as increasing 'regulatory diversity' for behind-the-meter technologies and support for long duration energy storage technologies

Enhance market signals to crowd in low-carbon flexible technologies, rather than relying on technology-specific support schemes.

The government currently supports power sector decarbonisation through capacity targets and technology-specific schemes. Some schemes, like the Dispatchable Power Agreement (DPA) and Hydrogen to Power Business Model (H2PBM), promote low-carbon flexible technologies over unabated gas but risk locking in specific technologies instead of letting market signals identify the most cost-effective options.

To unlock the full potential of low-carbon flexibility, the government should signal a move away from technology-specific schemes (beyond kick-starting the development of strategic technologies) to avoid locking in solutions and instead rely on stronger market signals.

Enhanced carbon pricing through the UK ETS or a rising Carbon Price Support (CPS) levy would incentivise low carbon flexibility to compete with unabated gas, but additional income from carbon pricing should be recycled directly back to consumers. A Clean Electricity Standard, where suppliers are obligated to buy an increasing proportion of their power from low-carbon sources, should replace Contracts for Difference (CfDs) over the medium term. Sharper wholesale price signals would increase the value of storage and flexibility, and encourage consumers to shift demand via dynamic tariffs.

Reform the capacity market in the short term to ensure low carbon capacity is cost-efficiently secured. Once sufficient low-carbon capacity is built out, replace the capacity market with a strategic reserve that provides capacity, but only during extreme system events.

It remains necessary to secure sufficient dispatchable generation capacity but we must avoid lock-in of high-carbon generation assets. Reforming the capacity market to procure capacity through two pots – a main pot for low-carbon technologies and a residual pot for unabated gas – would let the government balance decarbonisation and cost, while also avoiding rushed and costly investment in first-of-a-kind low-carbon technologies.

Our modelling suggests some unabated gas will still be necessary even in 2050. To stop gas from setting the marginal price in the wholesale market – and avoiding exposure to gas price shocks – the capacity market should be replaced in the longer term by a strategic reserve, which serves as the only use of gas in the power system. This would only be used during system stress events by NESO, where the wholesale market itself is not able to deliver the capacity. The transition to a strategic reserve should be managed carefully to avoid prolonged scarcity pricing while low-carbon capacity barriers remain.

Implement a competitive revenue support mechanism for the deployment of first-of-a-kind SMRs that can reduce the magnitude of the peak gaps.

Our modelling suggests that SMRs can provide important baseload power to the system, helping to reduce peak gaps. The urgency bringing them online means that support is likely to be necessary, but it should be targeted and time-limited. Site selection should be aligned with SSEP and CSNP and focus on the proximity to demand centres as well as the potential for SMRs to serve heat networks. The recommendations from the Fingleton Review should be implemented in full as a matter of urgency.

Implement the enablers that would maximise consumer-led flexibility including from EVs and heat pumps combined with thermal storage.

New business models are key to driving innovation, competition and flexibility in the energy system but new innovators often struggle to enter the market due to high regulatory burdens. Removing retail market access barriers can create opportunities for innovators to bring new products and services to consumers and stimulate competition to drive down prices and make consumer-led flexibility more attractive.

This could be addressed with greater 'regulatory diversity', allowing different rules for different assets and business models. Our consumer testing shows households are open to a 'secondary supplier' model if it delivers clear savings. A secondary supplier model, allowing households and businesses to choose different suppliers and tariffs for services, such as EV charging versus general consumption, is one practical way to deliver regulatory diversity. To make it easy for consumers to benefit from low-carbon technologies that are smart-enabled, standards for bi-directional smart EV chargers should be developed to encourage manufacturers to offer smart energy products that unlock their full flex potential.

Increase the minimum storage duration requirement gradually in future LDES cap and floor rounds so that future LDES increasingly capture longer spells of high renewables output and discharge for longer. As the duration requirement increases, ensure the LDES scheme procures genuine needs and does not crowd out market-led investments in low-carbon dispatchable power technologies.

LDES will play a key role in storing abundant wind and solar power for times when renewable output is low. As the first rounds of the current LDES cap and floor scheme with eight-hour minimum discharge are being procured, the need for even longer duration storage will increase as more renewables come online over time. The government should explore how procuring increasingly longer-duration energy storage through the LDES cap and floor scheme can reduce total system cost by displacing more expensive forms of flexibility.

As the duration requirements increase, it will be important to ensure that LDES procurement does not artificially crowd out new market-led investments in low-carbon dispatchable power that have a lower total cost to the system. This could happen if the government sets procurement targets for LDES too high, where low-carbon dispatchable technologies that could lower whole system costs do not have a viable route to market without support schemes.

And we need as much innovation in how we do policy and regulatory change as we do in technology

We know from our work with innovators over the past ten years (confirmed by the expert roundtable and survey we did as part of this piece of work) that **energy policy and regulation, designed for a world of a limited number of power stations and a predictable load needs to adapt.**

In particular, **if we are to unlock the potential of flexibility to reduce costs, we need to develop processes for policy and regulatory change that more closely follows the speed of technology innovation and progress.** The emergence of digitalisation, data and AI makes this even more urgent.

That means a more agile approach – real-world testing of policy and regulatory reform with domestic and non-domestic consumers; rapid testing and sand-boxing of new approaches; and the bravery to encourage innovation rather than stifle it, while maintaining high safety and security standards.

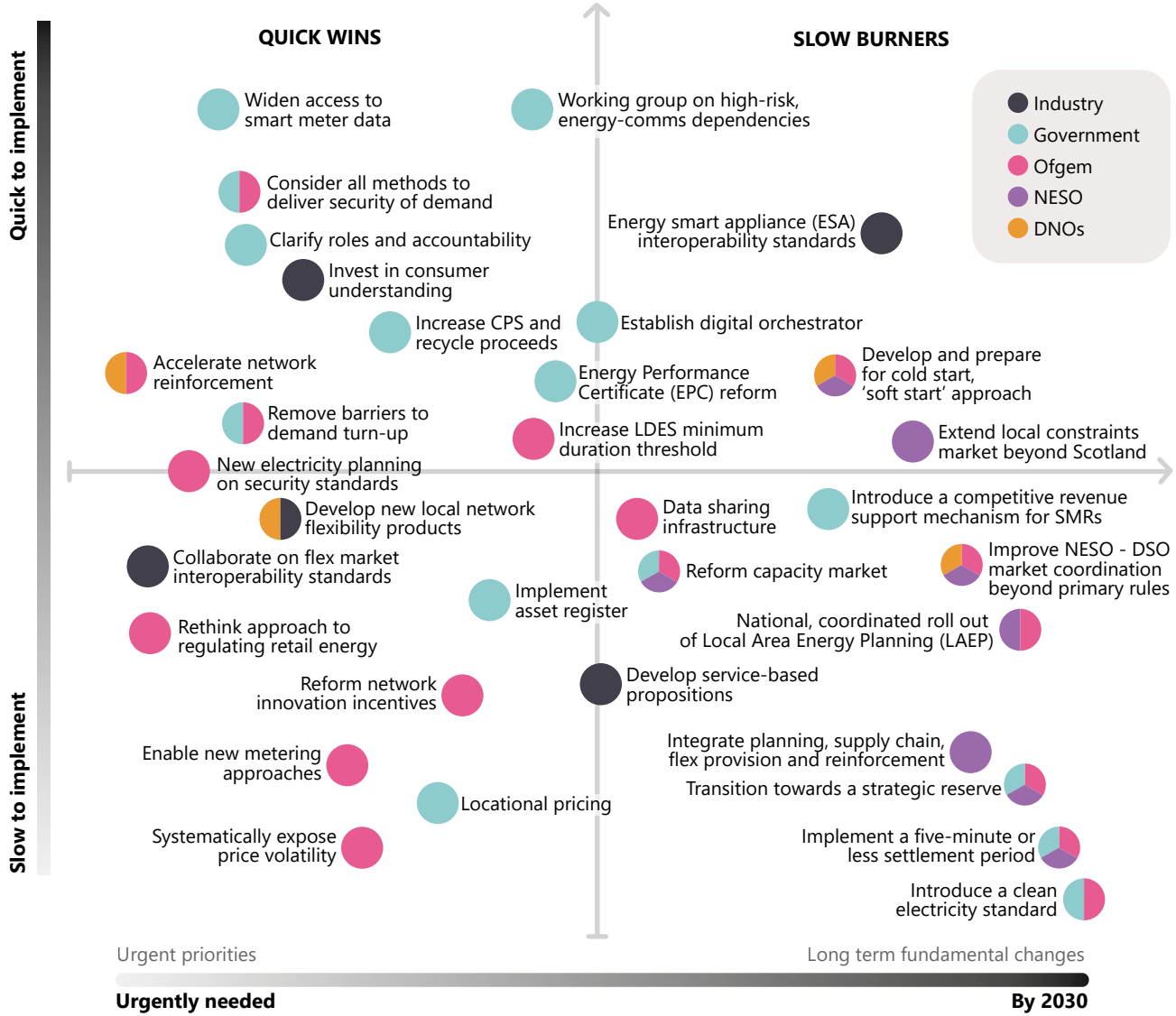
Energy Systems Catapult designed our Living Lab, including its collaboration with the Power Networks Demonstration Centre at the University of Strathclyde, to advance such an agile approach. This is supported by our suite of whole system models and our System of System Map (see the *Integration* section).

Our recent work exploring 'secondary suppliers' in the domestic sector demonstrates the power of this approach in trialing new policy initiatives.

To unlock flexibility, we need coordinated actions and cross-sector collaboration

In our Enabling Distributed Flexibility for Net Zero project we consulted across the sector to identify a set of actions needed to unlock flexibility. They build upon existing progress and direction of travel, rather than reinventing the wheel. They do not include the delivery of ongoing processes (e.g. market-wide half-hourly settlement and smart meter roll-out).

We identified lead stakeholder(s) for each action, but they will often involve collaborative approaches across industry. The lead stakeholders are identified in this plot along with the urgency and time to implement each action.



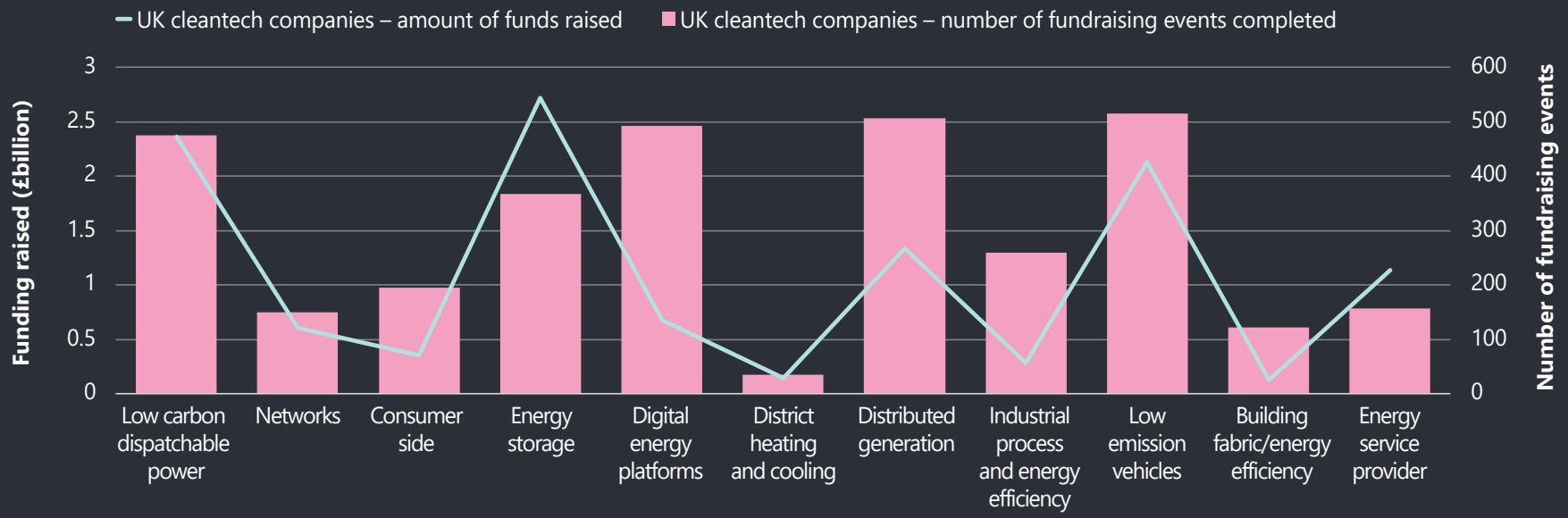
Innovators

Flexibility is a new and growing market opportunity that UK flexibility innovators, having already raised £12 billion, are well placed to exploit

The UK is a global leader in innovation around flexibility. Since 2000, there have been over 1,200 UK innovators active in sectors relating to energy system flexibility. They have raised funds over 3,000 times with a total amount of almost £12 billion raised.

This highlights the UK's strength in areas like digital energy platforms, but also the potential for growth in areas like district heating innovation.

The need for flexibility both in the UK but also globally will increase significantly in the coming years. The total flexibility market size in Europe alone is expected to reach €12 billion a year by 2030[37]. This presents a significant business growth opportunity for the UK to tap into.



Funding raised by UK innovators in sectors related to flexibility (data source: www.beauhurst.com)

Flexibility innovators still face many barriers including uncertain revenue streams and complex regulations

To understand the real challenges energy innovators are facing and the barriers they need removing, we spoke to a range of innovators at a roundtable event and through a survey. This highlighted that uncertain revenue streams and the complexity and fragmentation of regulations were the biggest commercial barriers they faced.

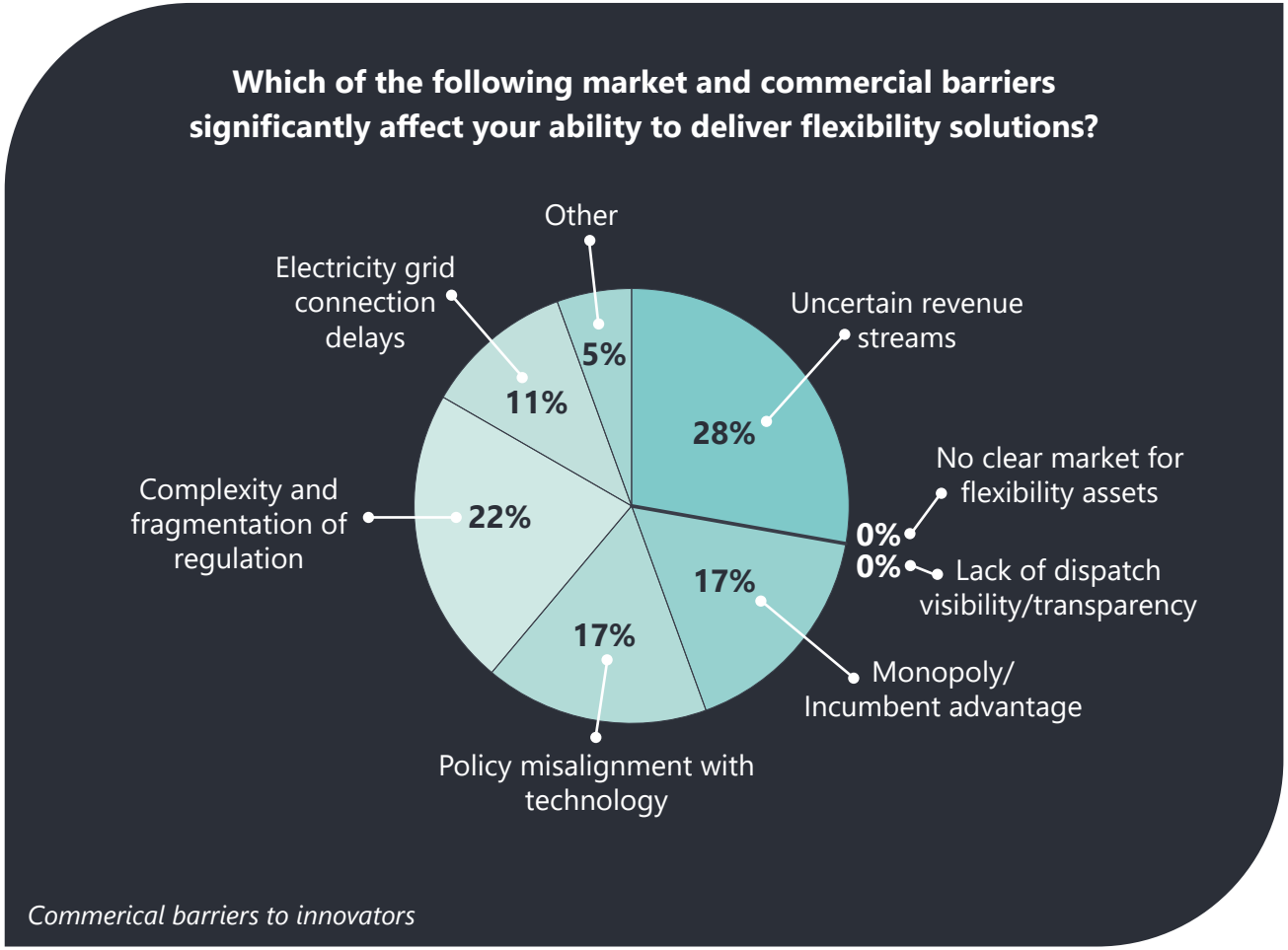
Full details of the roundtable event and survey results can be found in the Technical annex.

"Without consistent, transparent value signals, it is hard to finance or invest in new flexibility assets"

Innovator comment at roundtable event

"[Regulation is] overly complex and not harmonised across regions, making innovation risky and raising technical costs"

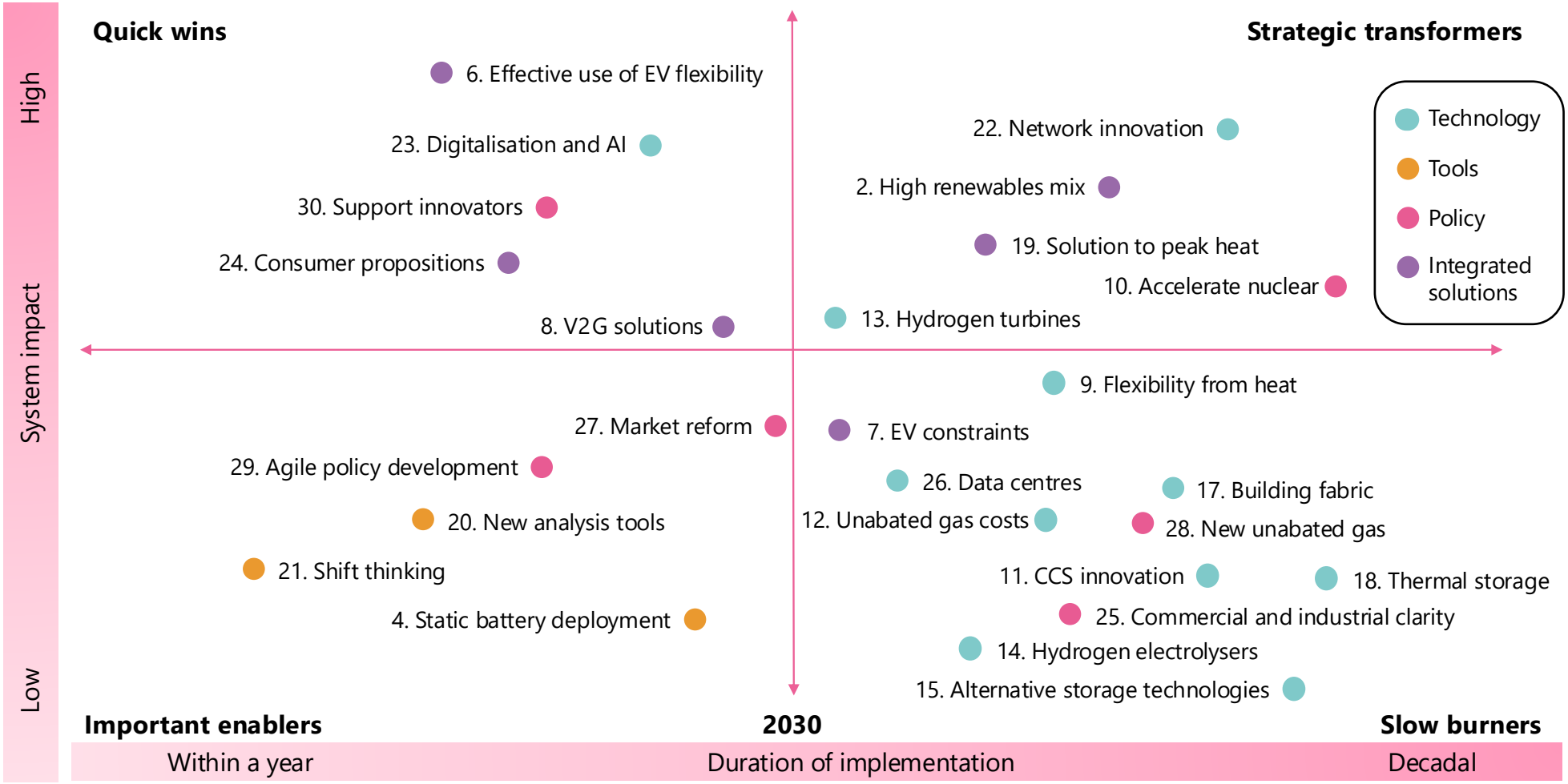
Innovator comment at roundtable event



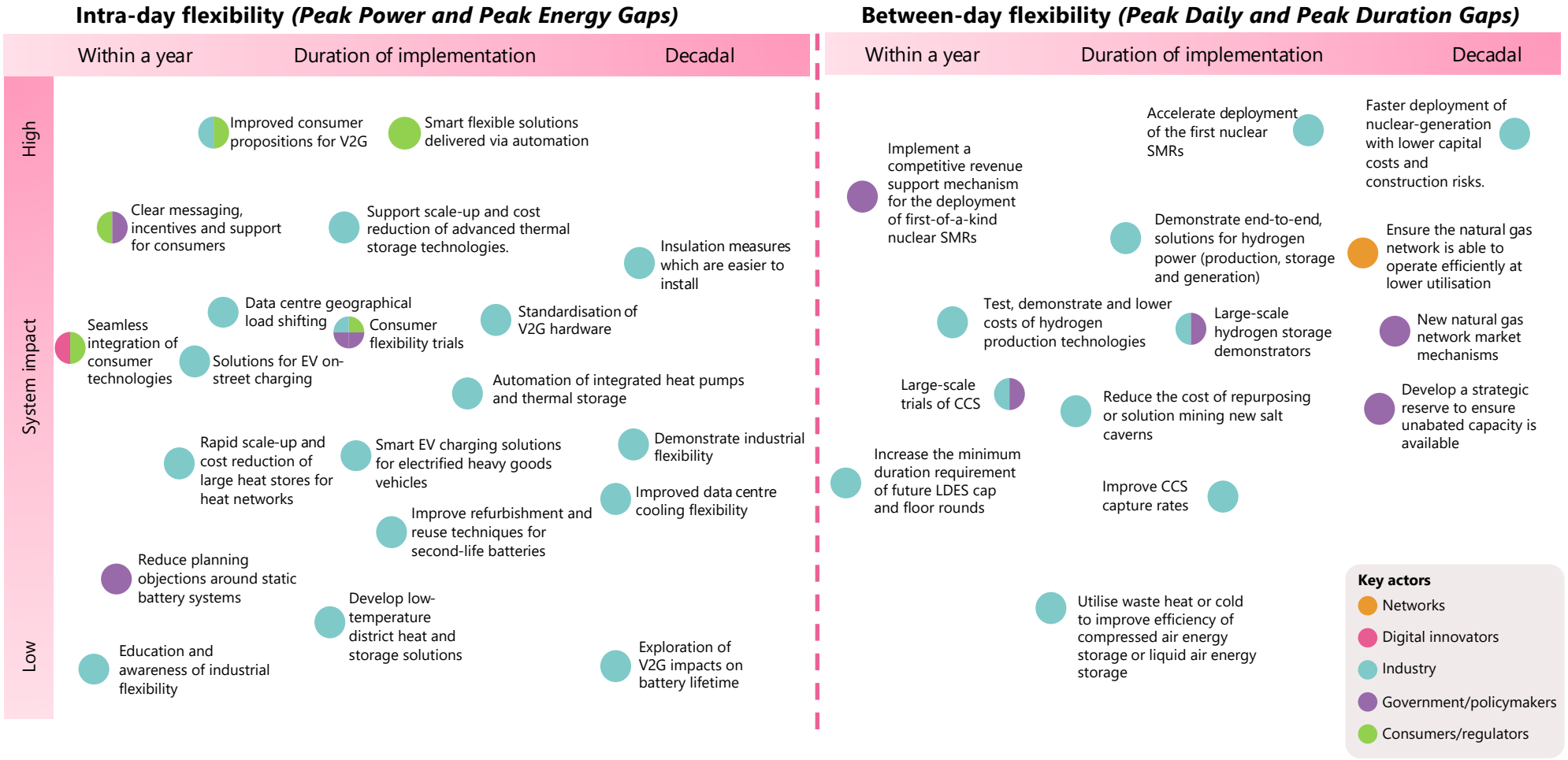
Commerical barriers to innovators

Summary

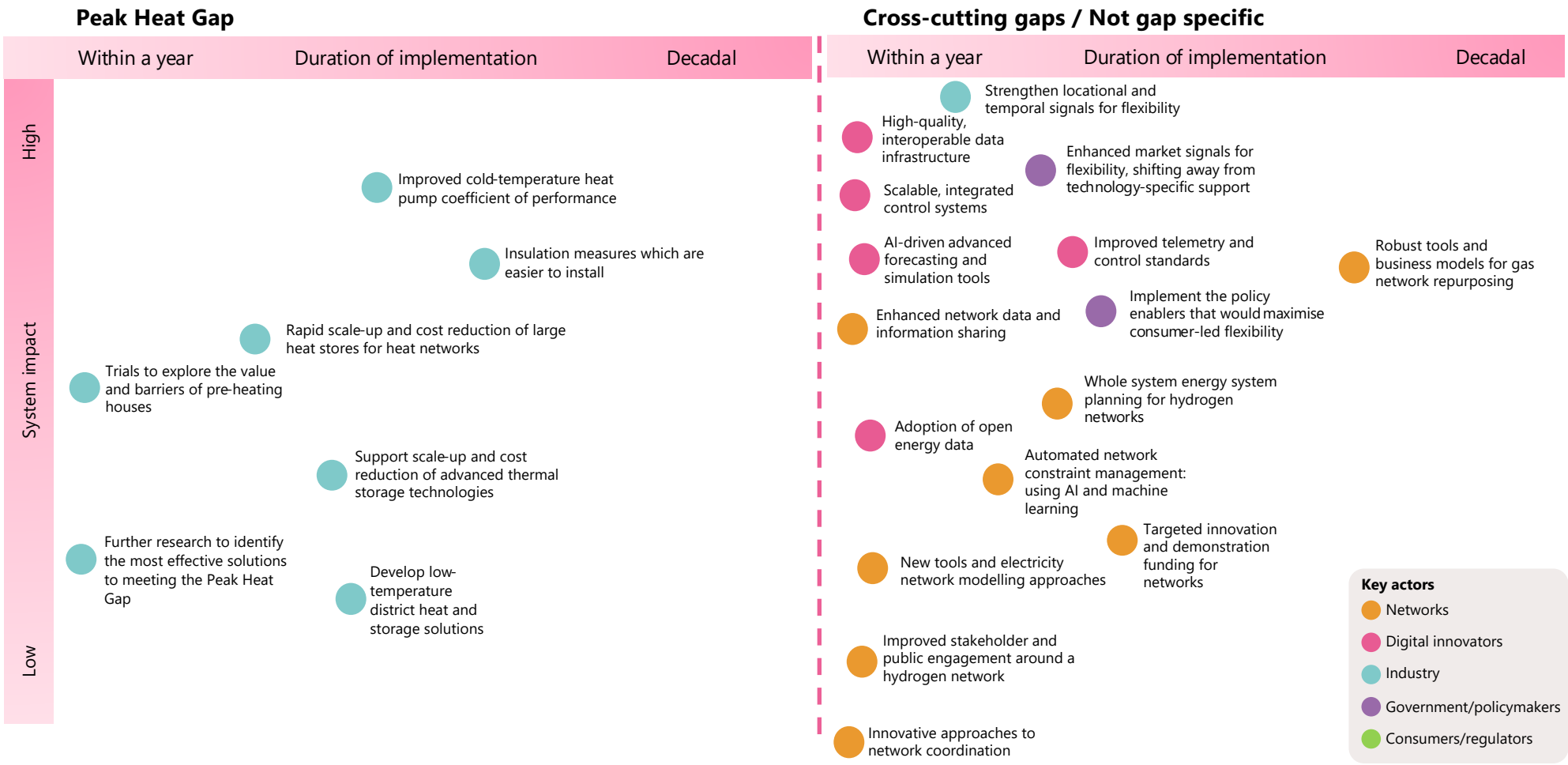
A summary of this report's key messages in terms of their impact and duration of implementation



A summary of innovation priorities in terms of their impact and duration of implementation – Peak Power, Peak Energy, Peak Daily and Peak Duration Gaps



A summary of innovation priorities in terms of their impact and duration of implementation – Peak Heat Gap and cross cutting



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[2] https://www.gov.uk/government/publications/clean-power-2030-action-plan

[3] https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/summaries/seasonal-assessment---winter25.pdf

[4] https://www.metoffice.gov.uk/blog/2025/sunny-and-cool-january-kicks-off-the-new-year

[5] The installed capacities of solar, wind, hydrogen-fired turbines, and gas CCS used in this scenario are taken from NESO's 'New Dispatch' and 'Further flex and renewables' CP2030 scenarios. These can be found here. See the Technical annex for specific assumptions.

[6] Enabling Distributed Energy Flexibility - 2024

[7] Energy flexibility solutions could unlock significant value in Europe | McKinsey

[8] https://es.catapult.org.uk/news/energy-systems-nexus-flexibility-could-cut-uk-power-grid-costs-by-billions/

[9] Analysis from the Hydrogen Innovation Initiative suggests that even under pessimistic assumptions industry demand for hydrogen will be around 35TWh by 2040.

[10] We define ultra-long duration energy storage as technologies which can discharge continuously for at least 72 hours.

[11] We define long duration energy storage as technologies which can discharge continuously at full power for at least eight hours as per the Ofgem LDES cap and floor scheme.

[12] https://www.gov.uk/government/statistics/energy-consumption-in-the-uk-2025/energy-consumption-in-the-uk-ecuk-2025

[13] Smart Meter Enabled Thermal Efficiency Rating – using measurement to determine building energy performance.

[14] https://www.energynetworks.org/work/open-networks/

[15] https://esc-production-2021.s3.eu-west-2.amazonaws.com/wp-content/uploads/2024/10/05150554/EFNZ-Report-Final-1.pdf

[16] https://www.gov.uk/government/publications/electricity-networks-strategic-framework/electricity-networks-strategic-framework-appendix-1-electricity-networks-modelling

[17] Redispatch volume is the amount of electrical generation that Transmission System Operators (TSOs) must adjust (curtailing some generation in one area and increasing others in a separate area) to manage grid congestion and manage electrical power flows to meet the demand and ensure system security.

[18] https://es.catapult.org.uk/report/key-barriers-to-the-development-of-hydrogen-in-the-uk-energy-system/

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[32] Increases in electricity demand for industry are relatively small as increased electrification of industry demand is countered by reductions in the energy intensity of industry.

[33] https://ukerc.ac.uk/publications/industrial-demand-flexibility-research-priorities/

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