NRDC

JUNE 2018
IB: 18-06-A

ISSUE BRIEF

REALITY CHECK:

BIOMASS IS UNNECESSARY FOR THE RELIABILITY OF UK ELECTRICITY SUPPLY—AND SO ARE CONTINUED SUBSIDIES TO DRAX POWER

A groundbreaking new study debunks an industry-led argument in the United Kingdom that biomass ensures the reliability of a flexible, low-carbon electricity system. According to the analysis, in 2030, and as soon as 2021, the United Kingdom can meet year-round electricity demand with a grid increasingly dominated by solar and wind—and no biomass, even under the most challenging conditions. The results show that the United Kingdom could zero out generation from Drax Power's coal-to-biomass conversions within the next three years without compromising grid reliability or carbon targets recommended by the Committee on Climate Change, and do so with low levels of nuclear power, decreasing share of natural gas generation, and no carbon capture and storage. Additional analysis suggests that delivering the new investment in generation capacity and smart resources needed to realize such a system is both technically and economically low-risk, but will require further UK government action to create a supportive policy environment. A first step in a strong enabling environment would be an immediate end to Drax's biomass subsidies, which could save British taxpayers £729 million per year between now and 2027.

COAL-TO-BIOMASS CONVERSIONS WILL NOT DELIVER ON THE UK'S ENERGY SUPPLY GOALS

The government of the United Kingdom has a three-pronged objective of grid reliability, affordability, and decarbonisation for its electricity supply. One way it endeavors to achieve this is by giving large subsidies to Drax Power and others for coal-to-biomass conversions—at a government cost to support Drax alone of nearly £2 million per day.[1] Yet, scientists neither see large-scale use of biomass for electricity as the preferred decarbonisation approach nor as the most cost-effective approach. Now, a groundbreaking new study questions if biomass is needed for reliability. And the answer is no.

Science discredits coal-to-biomass conversions as a climate change mitigation strategy

UK utility Drax Power has received billions in subsidies since 2012 to convert three of its six units to burn wood pellets, known as biomass, instead of coal. Recently, Drax received a subsidy to convert a fourth unit. The power giant receives these subsidies under programmes intended to support the deployment of renewable energy, deliver on the United Kingdom's climate commitments, and meet the country's 2025 coal phase-out target. However, as the science on biomass energy has matured, scientists and public interest advocates have discredited the assumption that replacing coal with wood is a climate solution.[2]
In addition, as the harmful environmental effects of Drax's wood pellet sourcing have come to light, the company has faced intensifying scrutiny for its supply chain harvest practices, particularly in the forests of the southeastern United States.[3]

The Natural Resources Defense Council would like to thank the following individuals for their contributions toward reviewing an early draft of this report. Their review does not constitute an endorsement of the findings: Sam Hall, Head of Research, Bright Blue.

Solar and wind are more cost-effective options than biomass to supply the UK's new electricity needs

In September 2017, the study Money to Burn II evaluated the most cost-effective path to ensure reliability of electricity supply and decarbonise the UK power system through 2025. The results revealed that solar and wind can reliably meet the United Kingdom's new electricity needs as it phases out coal—and that it can be done at lower total economic cost than new biomass, even when fully accounting for the costs of integrating solar and wind into the grid.[4]

As part of the study, Vivid Economics worked with Imperial College to develop two scenarios, which achieve reliability of supply with a mix of renewables, electricity storage, demand response, and natural gas. The study showed that by 2025, even if already installed, biomass would be costlier to operate than building completely new solar and wind capacity. In this timeframe, biomass will be too costly to meet day-to-day electricity demand and will also not be able to compete with least-cost options to meet the reliability requirements of the electricity system (i.e. to accommodate peak demand), even given the United Kingdom's legally binding carbon constraints. These results hold true even for scenarios that do not fully account for biomass carbon emissions and their associated costs.

NEW STUDY DISCREDITS CLAIM THAT BIOMASS-BURNING PLANTS ENSURE RELIABILITY OF SUPPLY

Given the climate pollution and high costs associated with coal-to-biomass conversions, Drax increasingly relies on claims that its biomass-burning plants help ensure the reliability of UK electricity supply to justify continued subsidies.[5] The company argues that because solar and wind are intermittent, meaning the sun doesn't always shine and the wind doesn't always blow, its biomass units provide necessary support services to ensure reliability in the electricity system. This is because biomass is a thermal generator—a generator which converts heat into electric power—and therefore provides a range of services which have historically contributed to system reliability.

The term "baseload" is often used to refer to this type of generation. Although the term can have several different meanings, historically it referred to a category of resources (coal, nuclear, natural gas, hydropower, and biomass) that had high upfront costs to build but provided relatively low operating-cost electricity to meet minimum round-the-clock electricity demand levels at a time when few, if any, viable alternatives existed.[6] There is a misconception that "baseload" is a system need, or a solution to meeting system needs. However, the term "baseload" has an indirect and incomplete relationship with key system needs and solutions, and is not an appropriate concept to analyse system reliability. Many system needs can be met without "baseload" generators, and some system needs are met more effectively with other types of generators. The technical appendix provides more information on misconceptions about the term "baseload" (See Box 1. Baseload is not an appropriate concept for analysing system needs and solutions).

A new study commissioned by the Natural Resources Defense Council and conducted by Vivid Economics asks whether thermal generators, such as biomass, remain relevant or necessary to meet modern electricity system reliability needs. The study examines the needs of the grid in short (sub-second) timescales, how these are affected by greater integration of solar and wind generation, and how they can be addressed with a portfolio of alternative technologies, including existing natural gas capacity, battery storage, demand side response, and interconnection with Europe.

The study concludes that in 2030, and as soon as 2021,[7] the United Kingdom can operate a highly reliable, low-carbon electricity system, which features a generation mix increasingly dominated by genuinely clean energy technologies, such as solar and wind, and with no biomass on the grid. The modelling conducted for this study demonstrates that such a system can cost-effectively:

- Meet increasingly strict carbon intensity targets for electricity generation in the United Kingdom;
- Meet UK electricity demand at all times, even in the most challenging conditions of the year;
- Provide adequate capacity in reserve[a] to account for unexpected variation in demand at all times;
- Provide sufficient thermal generation on the system to maintain inertia[b] at minimum acceptable levels at all times; and
- Ensure adequate capacity set aside to provide frequency response,[c] if needed, at all times.

These modelling results hold true even under conservative assumptions that do not make use of several proven or highly promising technologies currently being researched and adopted around the world, such as inverter-based renewables, synchronous condensers, and synchrophasers/phasor measurement units (See: New Innovations Make Deep Decarbonisation Even More Manageable).[8] This suggests that the combined challenge of decarbonising the UK electricity system while maintaining year-round system reliability beyond 2030 could be even more manageable than demonstrated here.

Further, the researchers found that the technical and economic risks of delivering the new electricity system resources are low, that they are cost effective, reliable, and could meet strong carbon targets, but that additional

a The availability of spare generating capacity to address unexpected reductions in output or increases in demand.

b Energy stored in the rotating masses of the generators and motors. Inertia is measured in gigavolt-amperes per second (GVA.s).

c The injection of active power into the electricity system to restore system frequency to normal levels following the loss of a source of supply.

The results of the analysis support the case for an immediate ramp down of biomass subsidies to Drax, which in 2017 alone totaled £729 million —or nearly £2 million per day

action is required in the United Kingdom to create the supportive policy environment needed to bring forward the necessary investment. Although there is no guarantee that such an electricity system will materialize in the United Kingdom, it is within the power of the UK government to influence the likelihood of that outcome. The results of the analysis support the case for an immediate ramp down of biomass subsidies to Drax, which in 2017 alone totaled £729 million[9]—or nearly £2 million per day. Under the status quo, Drax will continue to receive these subsidies until 2027, when they are scheduled to expire.

METHODOLOGY & RESULTS OF THE STUDY THAT SHOW UK GRID RELIABILITY DOESN'T NEED BIOMASS

To address Drax's claims that biomass units are necessary for providing "baseload" generation, Vivid Economics worked with Imperial College to develop an electricity system scenario, referred to in this Issue Brief as the *high renewables scenario*, in which low-carbon synchronous generation capacity[d] is constrained and system needs are met with a combination of renewables, smart resources, and adequate security margin.[e] Imperial College modelled the scenario using the Whole-electricity System Investment Model (WeSIM).[10] WeSIM calculates the pattern of investment in, and operation of, electricity system resources that results in the lowest overall cost, given a set of constraints (e.g. system reliability, carbon emissions limits). The technical appendix provides more technical information on the WeSIM model and the modeling conducted for this study.

The *high renewables scenario* is thus based on finding the least-cost set of investment and operational decisions to meet demand given three key constraints. First, the researchers placed a carbon constraint set at 200 gCO_2/kWh in 2020, and decreasing to 150 gCO_2/kWh in 2025, and 100 gCO_2/kWh in 2030. Second, they placed a lower bound on the level of system inertia.[11] Finally, they placed limits on the volume of low-carbon synchronous capacity, fixing nuclear generation at 4.5GW in 2030.[12] Biomass and carbon capture storage (CCS), which are both treated as alternative forms of low-carbon synchronous capacity, were excluded from the scenario.

The objectives were to (1) characterise any reliability challenges of low-carbon electricity system scenarios for each year in question, and quantify the need for thermal generators; and (2) to demonstrate how smart resources and natural gas backup can meet system needs during key stress events. Figures 1 and 2 summarize the output of these modelled scenarios. Also, for years 2020, 2025, and 2030, the *high renewables scenario* passes four key tests for system reliability: adequacy, reserve, inertia and frequency response. The results of these tests demonstrate that the system achieves reliability even under the most challenging conditions of the year.

While not included in this analysis, NRDC believes that the technology for capturing, and safely storing carbon dioxide (CCS) underground is widely demonstrated and mature, and that the practice is safe if appropriately regulated. However, CCS in conjunction with biomass (BECCS) has been proposed as a means to achieve "negative greenhouse gas emissions." There is no scientific basis for assuming that BECCS can deliver negative emissions after full emissions accounting for biomass in the power sector. Additionally, there is significant scientific basis to believe that harvesting biomass at a scale envisioned in a number of modeling scenarios would come at an untenable ecological cost.[22]

Even if power plant emissions from burning forest biomass are fully captured and injected into the subsurface, cutting down trees will almost certainly result in a lasting carbon debt for two reasons. First, it is difficult to ensure that the trees will be replanted and kept intact. Second, older trees have been shown to sequester atmospheric carbon at a higher rate, so a permanent carbon debt is created when an older and larger tree is replaced with a younger one: Not only will it take years (likely decades) for the new tree to reach the size of the felled one, but during that time period the now felled tree would have grown even larger if it had been left in place.[23] This "forgone sequestration" from additional biomass harvest in the forest creates a lasting carbon debt.[24]

BECCS demand will very likely be met primarily through crop and tree monocultures (resulting in direct and indirect land-use change) and/or from more intensive or extensive logging of forests.[25] Other more sustainable bioenergy sources are either not available on a large scale (e.g., genuine waste products or new plantations planted specifically to produce biomass) or are not commercially viable with current technology (e.g. algal biofuels).

d Synchronous generators are generators that contain mechanical components whose rotation is synchronised to the system frequency. Only synchronous generators can provide system inertia.

e This could be additional battery storage or demand response, or peaking generators that would operate only during extreme system stress events. The results of the modelling indicate the need for 37GW of security margin.

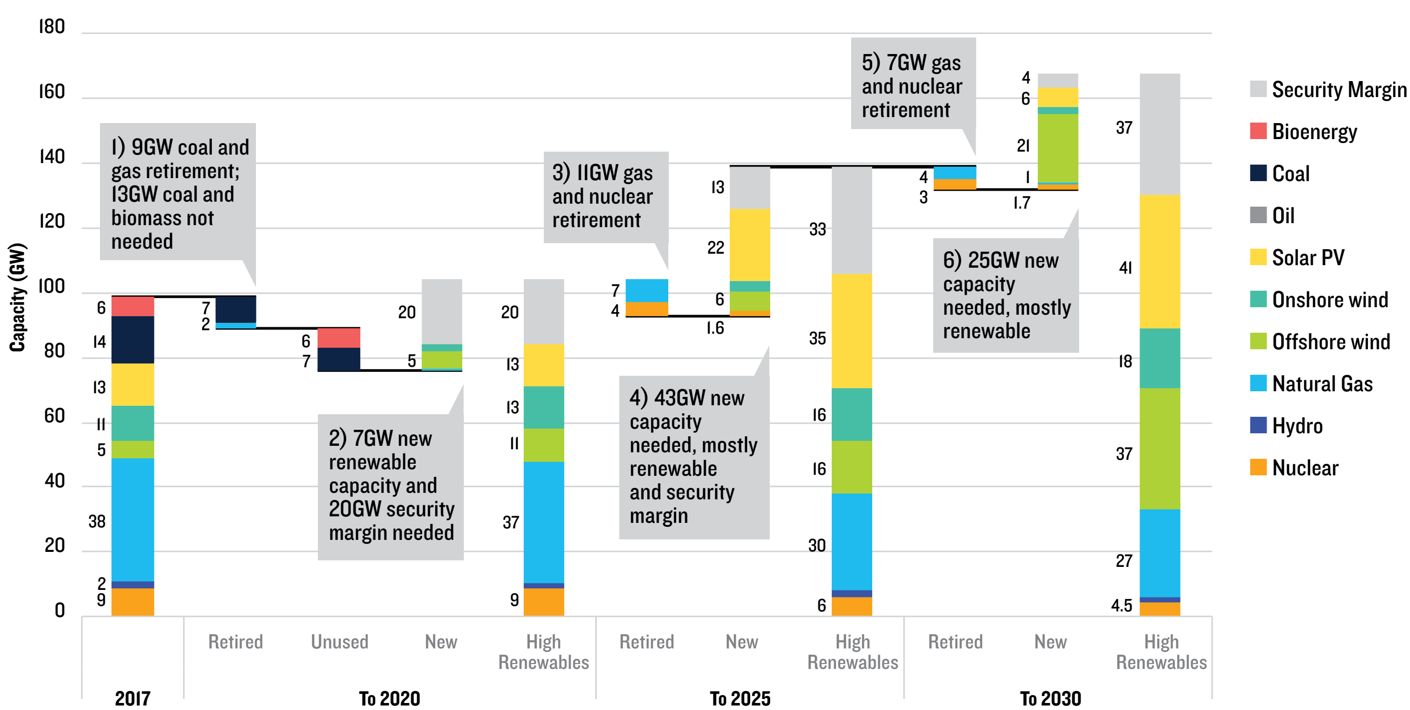
NEW INNOVATIONS MAKE DEEP DECARBONISATION EVEN MORE MANAGEABLE

There are a broad range of technologies that could be used to meet the key system needs of a low-carbon electricity system. Examples of proven or highly promising technologies are:

- **Inverter-based renewables.** This technology uses renewable generators to provide frequency response when not operating at full capacity.
- **Synchronous condensers.** This technology is a turbine that provides grid inertia without providing electricity. Synchronous condensers could substitute natural gas in providing inertia, reducing the grid CO_2 intensity without compromising reliability.
- **Synchrophasers/phasor measurement units.** This technology could measure the system frequency in real time, such that frequency response can be provided instantly, rather than following a measurement delay. Instant frequency response could reduce the requirement for natural gas or nuclear generators to provide inertia.

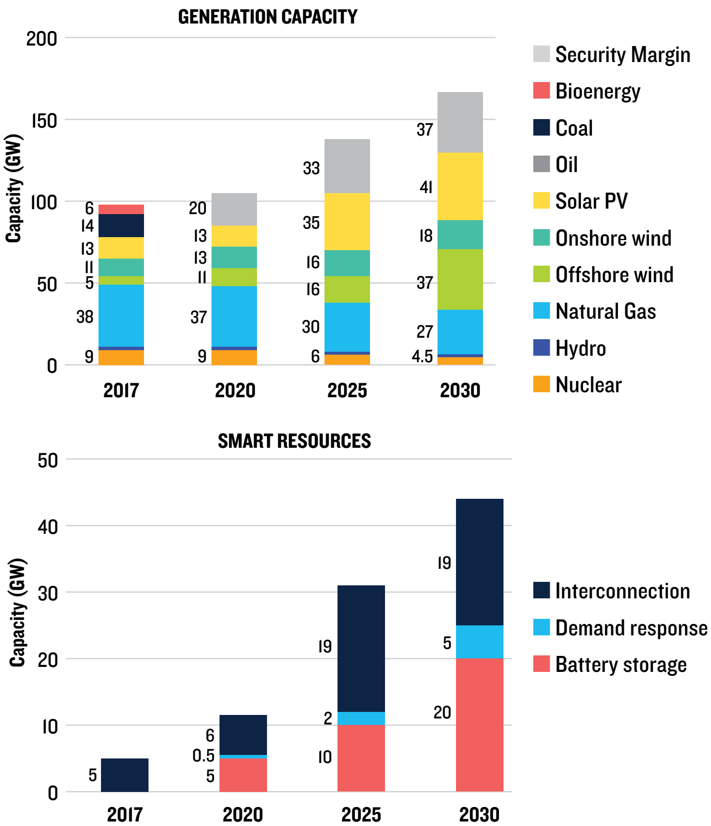
Sources: Loutan, Klauer, Chowdhury, et. Al., *Demonstration of Essential Reliability Services by a 300-MW Solar Photovoltaic Power Plant*, National Renewable Energy Laboratory, NREL/TP-5D00-67799 March 2017 available at https://www.nrel.gov/docs/fy17osti/67799.pdf; US Department of Energy, *Grid Modernization Multi-Year Program Plan* available at https://www.energy.gov/sites/prod/files/2016/01/f28/Grid%20Modernization%20Multi-Year%20Program%20Plan.pdf; EPRI Product Abstract, *The Integrated Grid: A Benefit-Cost Framework*, February 2015 available at https://www.epri.com/#/pages/product/000000003002004878/; Ofgem Electricity Network Innovation Competition Screening Submission Pro-forma available at https://www.ofgem.gov.uk/system/files/docs/2016/04/phoenix_isp.pdf ; SP Energy Networks, *PHOENIX: System Security and Hybrid Synchronous Condensers* available at https://www.spenergynetworks.co.uk/pages/phoenix.aspx

FIGURE 1: THE UNITED KINGDOM CAN SUNSET BIOMASS ELECTRICITY GENERATION BY 2020 AND SUBSEQUENTLY MEET ALL SYSTEM NEEDS WITH AN AGGRESSIVE MIX OF WIND, SOLAR, SMART RESOURCES, AND SECURITY MARGIN



The scenarios show how the United Kingdom can sunset biomass electricity generation by 2020 and subsequently meet all system needs with an aggressive mix of wind, solar, and smart resources. They also show that the United Kingdom can achieve its system reliability requirements without building any additional nuclear energy over this period beyond the committed nuclear plant at Hinkley Point. Crucially, low levels of nuclear generation and no CCS suggest minimal risk that biomass would be needed over this timeframe to substitute for alternative baseload generators if these do not materialise. The results of thermal modelling indicate the need for 37GW of security margin. This could be additional battery storage or demand response, or peaking generators[13] that would operate only during extreme system stress events. The technical appendix provides more detail on these scenarios.

FIGURE 2: UNDER AN INCREASINGLY STRICT CARBON INTENSITY CONSTRAINT THE UK CAN ACHIEVE A HIGH DEGREE OF SYSTEM RELIABILITY WITH RENEWABLES, SMART RESOURCES, MINIMAL THERMAL GENERATING CAPACITY, AND NO BIOMASS



The 2030 scenario achieves system reliability and a carbon intensity of 100g/CO_2/kWh, in line with recommendations from the UK Committee on Climate Change.[14] It does so with minimal thermal generating capacity and no biomass generation. Figure 2 shows the resulting energy mix in 2030, as well as the intervening 2020 and 2025 timeframes. The results support the recommendation that UK policymakers can ramp down biomass subsidies and generation in the immediate near-term.

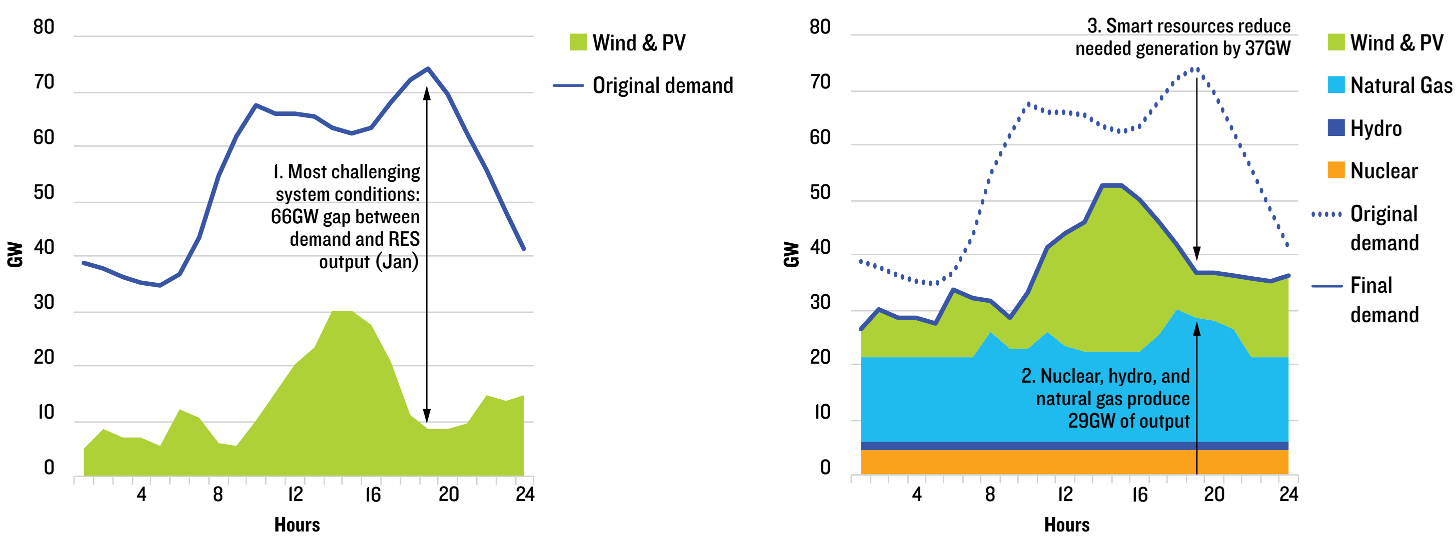
Critically, to demonstrate the feasibility of such a system in 2030, Vivid Economics and Imperial College conservatively modelled the scenario based only on a subset of those technologies that are closest to market in the United Kingdom. However, there are several other technologies that could further reduce the challenges of delivering a low-carbon electricity system, and facilitate deeper decarbonisation of the electricity system beyond 2030. (See text box: New Innovations Make Deep Decarbonisation Even More Manageable.) This bolsters the conclusions of this study. It also suggests that the challenge of integrating high levels of renewables into the UK electricity grid while ensuring year-round system reliability may become more modest as time goes on.

High renewables scenario with no biomass meets four key tests of system reliability

Tests 1-4 below detail how the 2030 *high renewables scenario* meets each of the four system reliability tests under the most challenging conditions. The technical appendix provides similar detail for 2020 and 2025, and more information on the results of all four tests.

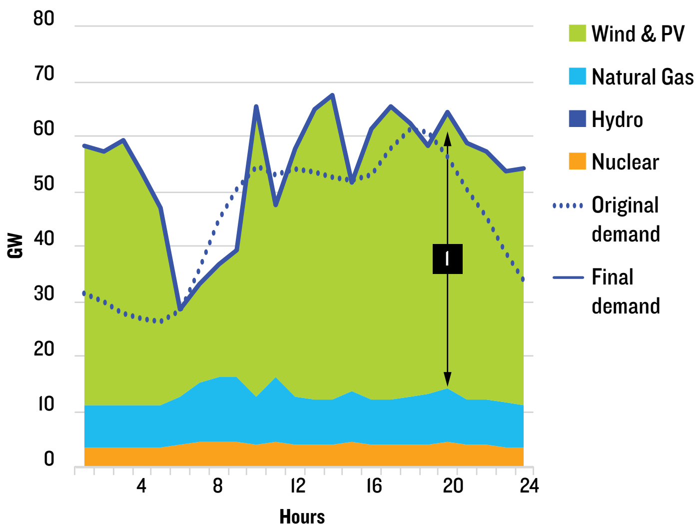
✓ TEST 1: ADEQUACY

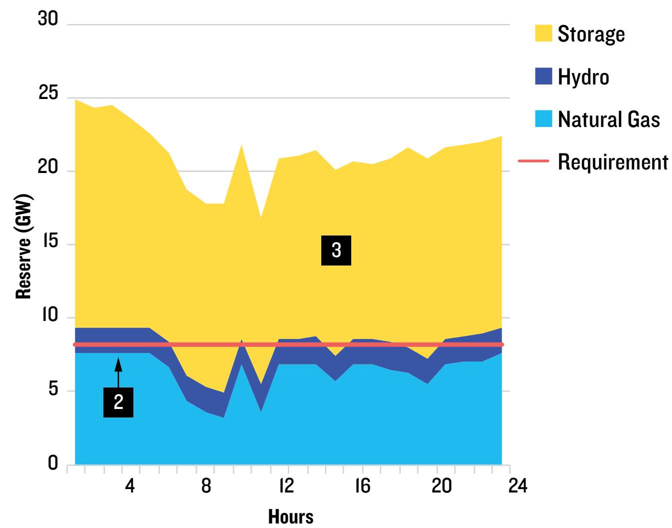
System maintains adequacy when the United Kingdom faces a huge shortfall in generation from solar and wind (occurring in January in the *high renewables scenario*). Generation meets demand during the most challenging conditions via a combination of nuclear, hydro, natural gas, storage, demand response, and interconnection.



✓ TEST 2: RESERVE

There is adequate capacity in reserve via a combination of thermal generation and smart resources to account for unexpected variation in generation and demand, even under the most challenging conditions (occurring in April in the *high renewables scenario*) when wind resources are high and potential forecasting errors are greatest.

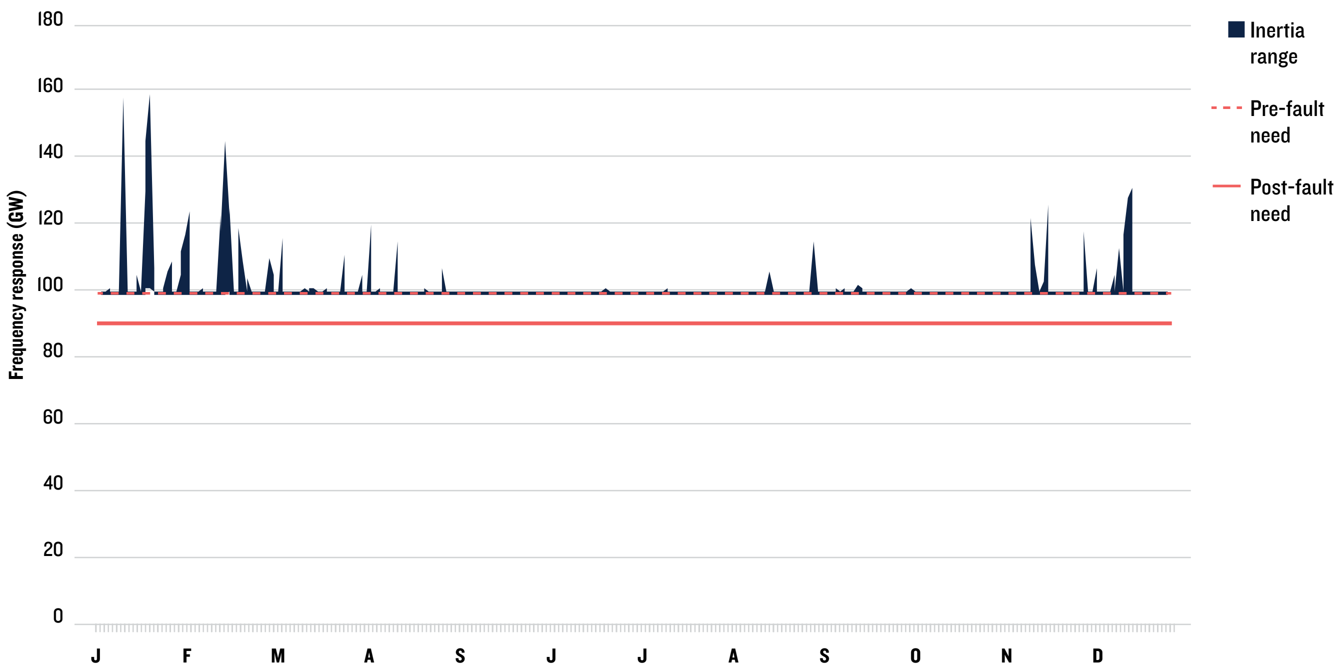




1. Most challenging system conditions: 50GW wind output (Apr).
2. During high wind conditions, 8GW of reserves are needed.
3. Spare natural gas, hydro, and storage exceeds reserve needs.

✓ TEST 3: INERTIA

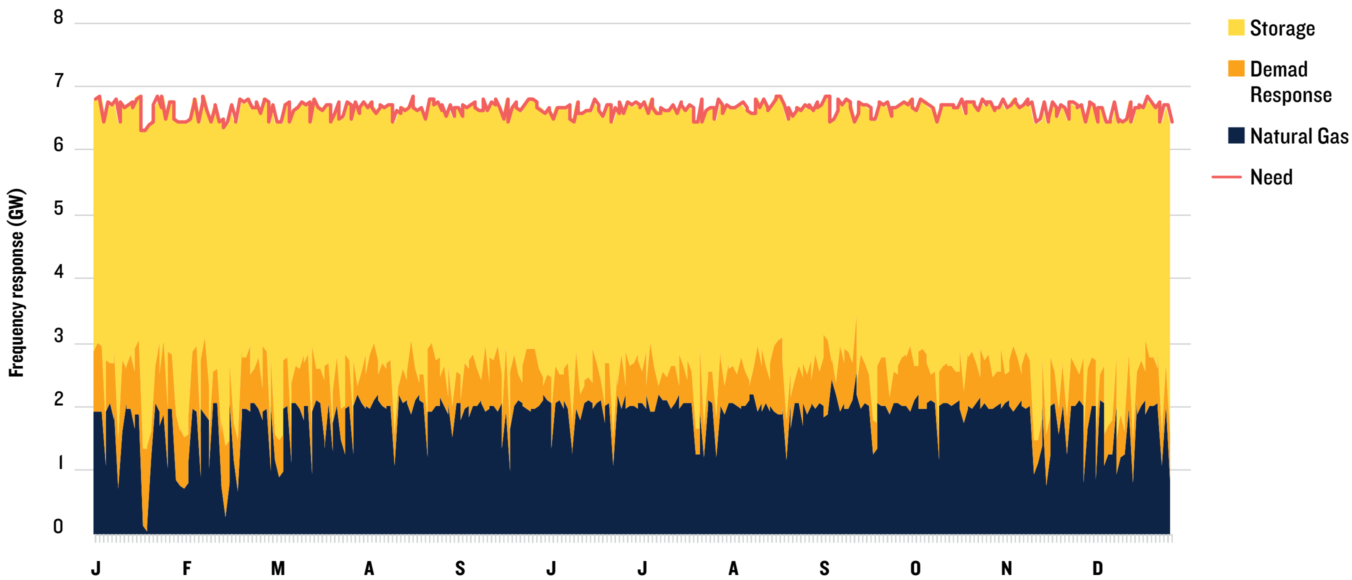
There is sufficient thermal generation on the system to maintain inertia at minimum acceptable levels all year round. Due to the tight carbon constraint, inertia is frequently at or close to these levels.



* To contain system frequency following a loss of this magnitude, inertia of 90 GVA.s would be needed. This is the "post-fault" level of inertia needed (i.e. it excludes the inertia provided by the failed generator). However, as the inertia from the failed generator will also be lost as the generator is decoupled from the electricity system, a higher "pre-fault" level of 99 GVA.s is needed.

✓ TEST 4: FREQUENCY RESPONSE

Given the consistently low inertia in the *high renewables scenario*, resources must be available to provide frequency response. Here, there is adequate capacity set aside to maintain frequency response at all times with battery storage, natural gas, and demand response.



THE UK GOVERNMENT CAN DELIVER THESE RESOURCES WITH THE RIGHT POLICY FRAMEWORK

Vivid Economics evaluated risks to system reliability under the in 2020, 2025, and 2030 to determine whether UK electricity market arrangements are likely to deliver the generators and smart resources to meet system needs. This part of the analysis concluded that technical and economic risks to delivering the needed generators and smart resources are low, and that the UK government can deliver these resources with an enabling policy framework.

Table 1 summarizes the technical and economic risks identified in this process. The technical appendix further describes the policy actions needed to deliver the levels of renewables generation and complimentary smart resources supported by the scenario modelling conducted for this study. These include:

1. a recognition by government that biomass is not needed to ensure the reliability of a flexible, low-carbon electricity system;
2. a simple set of incentive mechanisms for smart resources, such as batteries, which can store renewable output for use at times of high demand; demand response, which can shift demand to periods of high renewable output; and interconnectors, which can import electricity from neighbouring markets if they have a relative surplus, or export if they have a relative deficit; and
3. a route to market for adequate security margin.

These results underscore that the right policy environment is needed to achieve the electricity mix modelled in this study, and that technical or economic characteristics of the required energy resources are not a major impediment.

UK stakeholders should begin to use a new vocabulary to talk about electricity system needs

Earlier studies have found that solar and wind can reliably meet the United Kingdom's new electricity needs as it phases out coal—and they can do so at lower cost than new biomass conversions, even when fully accounting for the costs of integrating solar and wind into the grid. (See Money to Burn II.)[15] Nevertheless, the perception that biomass generation provides necessary "baseload" generation that makes a unique contribution to the reliability of the UK electricity supply remains, perhaps due to poor understanding of how a future electricity system will operate (See Appendix I: Grid Reliability 101.) As a result, many policymakers continue to support Drax and coal-to-biomass conversions on this basis.

UK decision makers should remove biomass subsidies for Drax and other coal-to-biomass conversions

Drax justifies the subsidies it receives by claiming that it is the only flexible, affordable, and low-carbon source of electricity in the United Kingdom, and thus critical for meeting the United Kingdom's three-pronged goal of providing reliable electricity at low cost while decarbonising its electricity system.[16]

TABLE 1: TECHNICAL AND ECONOMIC RISKS TO DELIVERING KEY ELECTRICITY SYSTEM RESOURCES				
Technology	**Maturity**	**Cost**	**Scale**	**Overall technical and economic risks**
Natural Gas*	Low risk. Mature technology, deployed in the UK since 1950s.	Low risk. Currently the cheapest fossil technology.	Low risk. Up to 5 GW built in a single year.	Low risk.
Battery storage	Low risk. Mature technology, though stationary storage applications have been limited to date, and significant further innovation is expected.	Low risk. 2030 scenario indicates that 20GW of storage is cost-competitive at battery costs of $320/kWh.	Low risk. 2030 scenario requires 20GW by 2030; this is less than expected volume of electric vehicle batteries expected over this timeframe.	Low risk.
Demand response	Moderate risk. Business model for utilisation of decentralised resources has yet to be developed.	Low risk. Demand response is highly cost-effective, reducing needed investment in new generating capacity.	Moderate risk. Government target to roll out smart meters broadly on track, but high degree of uncertainty over consumer adoption.	Moderate risk.
Interconnection	Low risk. Mature technology, deployed in the UK since 1986.	Low risk. Wide agreement that benefits strongly outweigh costs.	Low risk. 2030 scenario assumes 14GW additional interconnection by 2030; of this, 1GW is already under construction, and 6GW are in advanced development and expected to commission by 2021.	Low risk.

* Beyond the technical and economic risks of natural gas, exploration and production come with significant public health and environmental impacts that are well documented, including those from fracking. They include but are not limited to: emissions of greenhouse gas pollutants; contamination of drinking water sources; use of chemicals that are harmful to human health; generation of large amounts of waste that can be toxic or otherwise harmful; destruction of landscapes, including wildlands and vital wildlife habitat; and earthquakes caused by underground storage of oil and gas wastewater.

Yet burning wood for electricity emits more carbon than the coal it replaces per unit of electricity produced because biomass is a less efficient fuel source.[17] As part of a recent independent investigation by the Channel 4 programme *Dispatches*, Drax's pellets were tested and found to emit 8 percent more carbon emissions at the smokestack than coal.[18] Drax argues that the fact that burning wood increases smokestack emissions is irrelevant because in the future new forests regrow on the harvested land. However, years of peer-reviewed scientific research has concluded that even in a best-case scenario, it can take anywhere from 35 to more than 100 years for biomass electricity systems to begin to deliver carbon benefits.[19] In those long intervening decades, greater carbon emissions persist in the atmosphere, trapping more heat and driving more droughts, floods, wildfires, and other costly extreme weather events.

Further, 2017 economic modelling of the UK power system conducted by Vivid Economics and Imperial College demonstrates that solar and wind can reliably supply the United Kingdom's new electricity needs as it phases out coal more cost effectively than biomass conversions.[20] Now, the new modeling summarized in this report and fully described in the technical appendix shows that not only are new biomass conversions not needed to ensure the reliability of the UK electricity system, but neither are biomass conversions currently in operation.

The United Kingdom can achieve a reliable, low-carbon electricity system with high levels of renewables, and low levels of thermal generation capacity. It can do so without any new nuclear beyond Hinkley Point C, no carbon capture and storage, and no biomass. However, to get there, the UK government must focus on delivering the necessary mix of low-carbon generation capacity, smart resources, and an adequate security margin. It should not focus on delivering biomass. Biomass is not needed for adequacy or security and raises serious sustainability concerns while offering limited value in achieving deep decarbonisation of the electricity system.

APPENDIX I: GRID RELIABILITY 101

A reliable and secure electricity system requires several important components, which we refer to as system needs. These include adequacy, reserve, inertia, and frequency response. Each is described in the table below.

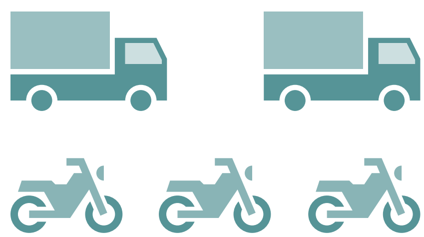
DEFINITIONS

- Electricity system reliability consists of **adequacy** and **security** components.
- **Adequacy** refers to the ability to balance supply and demand at all times during normal operation of the system.
- **Security** refers to the ability to address problems during system stress events. Elements of security that are affected by low-carbon generation include **reserve**, **inertia** and frequency **response**.
- **Reserve** is the availability of additional resources to address unforeseen events (changes in generation or demand).
- **Inertia** is provided by the mass of the turbines in spinning thermal generators. Inertia stabilises system frequency following the failure of a large plant. It is therefore a complement to frequency response.
- **Frequency response** is the provision of fast power to stabilise system frequency. It is therefore a complement to system inertia.

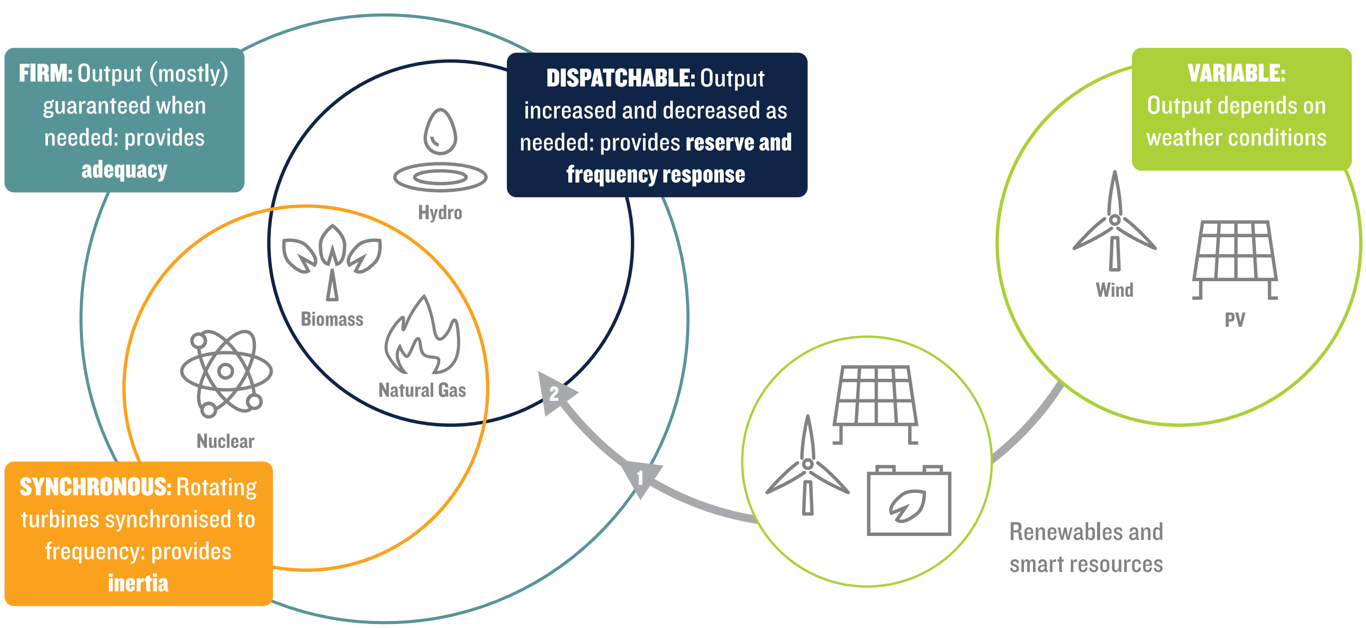
Today, UK electricity system needs are largely met with thermal generators (e.g. nuclear, coal, natural gas, biomass), often referred to as "baseload" generators. However, in a decarbonised system, variable renewables (wind and solar) paired with smart resources (battery storage, demand response, and interconnection) will increasingly meet most system needs with some firm, synchronous generators (nuclear power) needed to provide inertia. This pairing of renewables with smart resources has technical characteristics that more closely resemble firm output over short periods; in the future, if costs decline to a point where it is economic to turn the renewable and smart resources on and off as needed, they could become dispatchable over short periods, with some of the technical properties resembling those of biomass, natural gas, and hydropower. Thus, rather than focus on "baseload", stakeholders are better served by terms that describe how different technologies work: firm, dispatchable and synchronous.

VISUALISING INERTIA

- Inertia and frequency response have been compared to trucks and motorbikes
- Imagine both vehicles momentarily lose engine power
- The truck will decelerate more slowly due to its weight and greater inertia
- However, even though the motorbike decelerates more quickly, it can accelerate more quickly to catch up with the truck
- Similarly, inertia and frequency response are both used to stabilise the system frequency



TECHNICAL CHARACTERISTICS OF DIFFERENT GENERATION TECHNOLOGIES



ENDNOTES

1 Based on Drax Group plc: Full year results for the twelve months ended 31 December 2017, https://www.drax.com/wp-content/uploads/2018/02/Drax-Group-plc-Full-year-results-for-the-12-months-ended-31-December-2017.pdf . Per Drax, "We earned ROCs, reducing costs, with a total value of £481 million in 2017 (2016: £536 million) as CfD replaced ROC generation." (pg. 12). In addition, the U.K. government paid Drax a subsidy of £248m for their electricity sales under the Contracts for Difference scheme, at a price of £106/MWh.

2 Booth, M., "Not carbon neutral: Assessing the net emissions impact of residues burned for bioenergy," Environmental Research Letters, February 21, 2018, available at http://iopscience.iop.org/article/10.1088/1748-9326/aaac88; Sterman, John, et al., "Does replacing coal with wood lower CO_2 emissions? Dynamic lifecycle analysis of wood bioenergy," Environmental Research Letters, January 18, 2018, available at http://iopscience.iop.org/article/10.1088/1748-9326/aaa512/pdf; Brack, Duncan, "Woody Biomass for Power and Heat: Impacts on the Global Climate," Chatham House, February 23, 2017 available at https://www.chathamhouse.org/ sites/files/chathamhouse/publications/research/2017-02-23-woody-biomassglobal-climate-brack-final2.pdf; European Academies Science Advisory Council, "Multi-functionality and sustainability in the European Union's Forests", EASAC policy report 32, April 2017, available at http://www.easac.eu/fileadmin/PDF_s/reports_statements/Forests/ EASAC_Forests_web_complete.pdf.; Buchholz, T., and J. Gunn, "Carbon Emission Estimates for Drax Biomass Power Plants in the UK Sourcing from Enviva Pellet Mills in the U.S. Southeastern Hardwoods Using the BEAC Model," Spatial Informatics Group, LLC, prepared for the Southern Environmental Law Center, May 27, 2015, available at https://www.southernenvironment.org/uploads/audio/2015-05-27_ BEAC_calculations_SE_hardwoods.pdf; Yassa, Sami, "Think Wood Pellets Are Green? Think Again," NRDC Issue Brief, May 2015, available at https://www.nrdc.org/sites/default/files/bioenergy-modelling-IB.pdf .

3 Dogwood Alliance, Natural Resources Defense Council, Southern Environmental Law Center, "European Imports of Wood Pellets for "Green Energy" Devastating US Forests," https://www.nrdc.org/sites/default/files/european-imports-wood-pellets-greenenergy-devastating-us-forests.pdf; Channel 4 Dispatches, The True Cost of Green Energy, aired Monday April 16th, http://www.channel4.com/programmes/dispatches.

4 Stashwick, S., "Money to Burn II; Solar and Wind Can Reliably Supply the United Kingdom's New Electricity Needs More Cost-Effectively Than Biomass," NRDC Issue Brief, September 2017, https://assets.nrdc.org/sites/default/files/money-to-burn-ii-uk-biomass-ib.pdf?_ga=2.165636671.1426806616.1526490771-1380781386.1517278009.

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9 Based on Drax Group plc: Full year results for the twelve months ended 31 December 2017, https://www.drax.com/wp-content/uploads/2018/02/Drax-Group-plc-Full-year-results-for-the-12-months-ended-31-December-2017.pdf . Per Drax, "We earned ROCs, reducing costs, with a total value of £481 million in 2017 (2016: £536 million) as CfD replaced ROC generation." (pg. 12). In addition, the U.K. government paid Drax a subsidy of £248m for their electricity sales under the Contracts for Difference scheme, at a price of £106/MWh.

10 The WeSIM model has been peer reviewed and validated. The model is published by Teng, F., V. Trovato, and G. Strbac, "*Stochastic Scheduling with Inertia-Dependent Fast Frequency Response Requirements*," IEEE Transactions on Power Systems 31 (2016): 1557-1566.

11 The test for adequate inertia is whether there is enough synchronous capacity generating electricity at all times to maintain system inertia above a threshold level. The threshold level is determined by the maximum rate of change of frequency (ROCOF) set by the system operator, and the size of the largest possible loss of supply (a generator or interconnector). In the UK, it is expected that the ROCOF threshold will be set at 0.5 Hz per second from 2021. The ROCOF was therefore set to 0.5 Hz per second for the modelling conducted as part of this study. See Technical Appendix for more information.

12 This represents delivery of Hinkley Point C and continued operation of Sizewell B, the only existing nuclear plant not expected to decommission over the period to 2030.

13 It will be important to prevent excess emissions from any small peaking natural gas plants. A recent World Wildlife Fund and Sandbag report (available at: https://sandbag.org.uk/wp-content/uploads/2018/05/Coal-To-Clean-May-2018.pdf) makes the following recommendation to address this issue: "Policy is needed to address the emissions from small peaking gas as poor market design may be artificially inflating running hours. The 450gCO_2/kWh instantaneous limit proposed in the coal phase-out legislation should be extended to all new build generation with a thermal capacity of over 1MW. This will ensure small peaking gas is only used when absolutely necessary to support the grid."

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THERMAL GENERATION AND ELECTRICITY SYSTEM RELIABILITY: TECHNICAL APPENDIX

Report prepared for the Natural Resources Defense Council

CONTENTS

: vivideconomics

Imperial College London

Glossary

TYPES OF GENERATOR	
Dispatchable	Generators that are able to increase or decrease output to meet changes in demand. These include coal, gas, biomass and hydro.
Firm	Generators guaranteed to provide a given level of output when needed. These include thermal generators with their own fuel source, such as nuclear, coal, gas, biomass, as well as hydro.
Synchronous	Generators that contain mechanical components whose rotation is synchronised to the system frequency. These include nuclear, coal, gas, and biomass. Only synchronous generators can provide system inertia.
Variable	Generators whose output depends on weather conditions. These include solar and wind.
Thermal	Generators which convert heat into electric power.
SYSTEM NEEDS	
Adequacy	The ability to meet demand during normal operation of the system.
Security	The ability of the system to function, and to continue to meet demand, during unexpected stress events that occur outside normal operation of the system. Security includes reserve, inertia and frequency response.
Reserve	The availability of spare generating capacity to address unexpected reductions in output or increases in demand.
Inertia	Energy stored in the rotating masses of the generators and motors. Inertia is measured in gigavolt-amperes per second (GVA.s).
Frequency response	The injection of active power into the electricity system to restore system frequency to normal levels following the loss of a source of supply.
RELATED CONCEPTS	
Reliability	The ability to meet demand at all times, including unexpected stress events. Reliability is driven by adequacy and security.
Flexibility	In the electricity system, the ability to adjust generation or consumption to balance supply and demand for electricity. Historically, flexibility has largely been provided by adjusting generation; with smart resources, it will increasingly be provided by adjusting consumption (for example, with demand response).
System frequency	The number of cycles per second of alternating current in the electricity system.
Rate of change of frequency (ROCOF)	The rate at which the system frequency drops following a sudden loss of supply.
OTHER	
Baseload	A frequently used term to describe the operation of electricity systems. It has several meanings, referring variously to a segment of electricity demand (the minimum level of demand), a mode of operating a generator (at a high load factor), or a type of generator (generators with high capital costs and low operating costs that are well-suited to operating at a high load factor)
Smart resources	A set of technologies that provide flexibility; smart resources include battery storage, demand response and interconnection.

Executive Summary

While the UK electricity system has been able to absorb wind and solar generation relatively easily so far, higher levels of deployment must be carefully managed. At low levels, solar and wind deployment can be accommodated with little impact to the electricity system. At higher levels, however, this presents new challenges, such as the need for greater electricity system flexibility (e.g. with demand response or storage) and raises new risks to reliability that must be addressed. In the UK, the share of wind and solar generation has increased rapidly over the last decade, from less than 1% of generation in 2007 to 18% in 2017. The International Energy Agency considers the UK to be approaching levels of wind and solar deployment where risks to reliability could emerge, with new approaches needed to address them (International Energy Agency, 2017).

For an electricity system to be reliable, a number of system needs have to be met; historically these needs have been met with thermal generators. The need to maintain supply and demand in balance is well understood. However, other system needs include responding to stress events in very short timeframes (within a few seconds or less). In the past, conventional thermal generators (coal, gas and nuclear) have together met these needs by generating electricity when needed, and helping to stabilise the system frequency with the energy stored in their spinning turbines.

However, low-carbon thermal generation technologies face serious challenges. In a decarbonised electricity system, thermal generators would need to be low-carbon. Potentially low-carbon thermal generation technologies include nuclear, coal or gas generation with carbon capture and storage, and biomass, though all three technologies face serious challenges.

Given these concerns, it is critical to understand the feasibility of achieving a reliable, low-carbon electricity system with high levels of variable renewables, and low levels of thermal generation capacity. If variable renewables paired with smart resources (battery storage, demand response and interconnection) can largely substitute for thermal generators then Government should instead ensure electricity markets will deliver the mix of renewables and smart resources needed to decarbonise the electricity system.

Some commentators argue thermal generators continue to be needed to meet system needs, and as 'baseload'. For example, biomass generator Drax has stated that biomass is 'vital' as 'the only reliable and flexible renewable which can provide the grid with the full range of support services, the need for which is expected to increase as more intermittent renewables come online.' The debate is confused by a common characterisation of thermal generators as 'baseload' or as 'providing baseload', though there is no clear rationale for prioritising generation technologies that are characterised in this way.

In this context, the Natural Resources Defense Council (NRDC) has commissioned Vivid Economics to investigate the future role of thermal generation in the UK electricity system.

There are four important system needs which must be met to make an electricity system reliable. In this project we develop a High Renewables scenario and test that these needs are met:

- **Test 1: Adequacy.** The test for adequacy is whether supply is equal to demand at all times.
- **Test 2: Reserve.** The test for adequate reserve is whether there is enough spare generating capacity at all times to address unexpected reductions in output or increases in demand.
- **Test 3: Inertia.** The test for adequate inertia is whether there is enough synchronous capacity generating electricity at all times to maintain system inertia above a given threshold.
- **Test 4: Frequency response.** The test for adequate frequency response is whether there is enough spare generating capacity at all times to correct the frequency deviation that would occur in the event of a large loss of supply.

We analysed the requirements of the UK electricity system to 2030, and demonstrated that an electricity system with a high share of variable renewables and low share of thermal generation can meet these four system needs. Figure ES1 illustrates the results of these four tests.

With technological innovation, even higher levels of variable renewables could be accommodated, with lower levels of thermal generation. There are a broad range of technologies that could be used to meet the key system needs of a low-carbon electricity system. In order to demonstrate the feasibility of such a system, the High Renewables scenario is based on a subset of those technologies that are closest to market in the UK. Several other technologies are proven or highly promising, and could further reduce the challenges of delivering a low-carbon electricity system, and facilitate deeper decarbonisation of the electricity system beyond 2030.

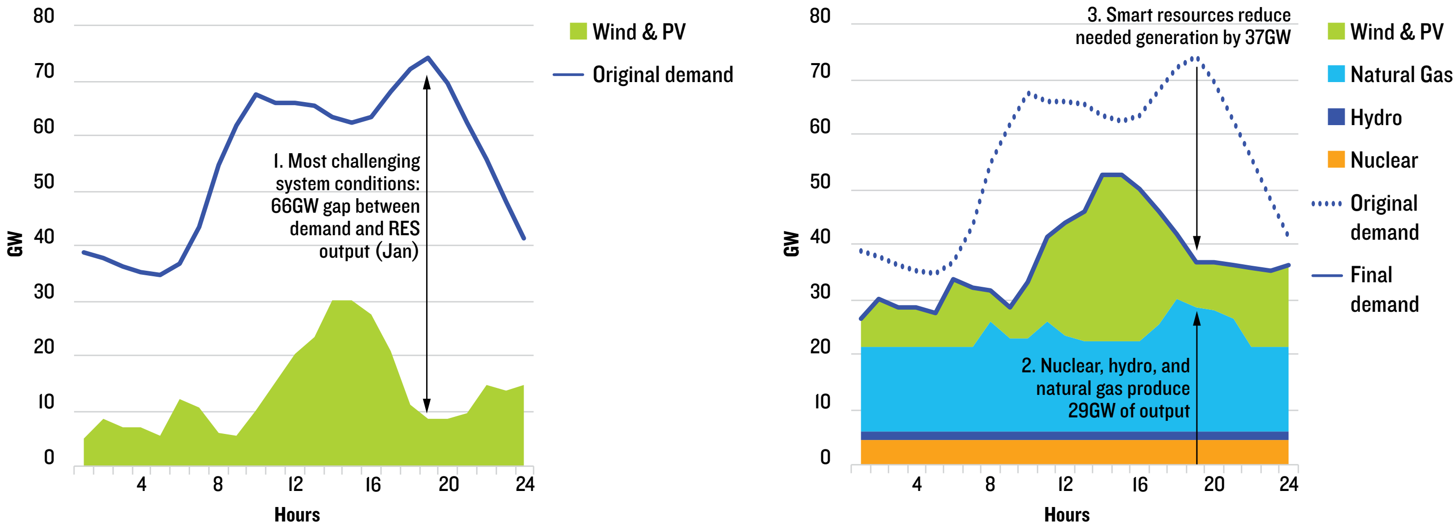
A number of key messages emerge from these findings:

- Wind and solar could provide over 60% of electricity generation by 2030.
- Thermal generation capacity, needed to provide inertia, could decrease to 20 GW - less than one third of today's level. Of this, 4.5 GW may need to be low-carbon. Provided Hinkley Point C is successfully commissioned in the 2020s, it is highly feasible to deliver this capacity.
- Biomass is not needed to ensure the reliability of a smart, low-carbon electricity system.
- To achieve a carbon constraint of 100 gCO2 per kWh, gas would need to provide less than 30% of electricity generation, down from 40% today.
- Significant investment in smart resources (battery storage, demand response and interconnection) is needed to ensure reliability, and minimise costs; over 30 GW of total smart resources could be needed by 2030.
- Significant additional investment in security margin plant is also needed. This could be additional battery storage or demand response, or peaking generators that would operate only during extreme system stress events.
- 'Baseload' is a frequently used term to describe the operation of electricity systems, but is not an appropriate concept to analyse system reliability.

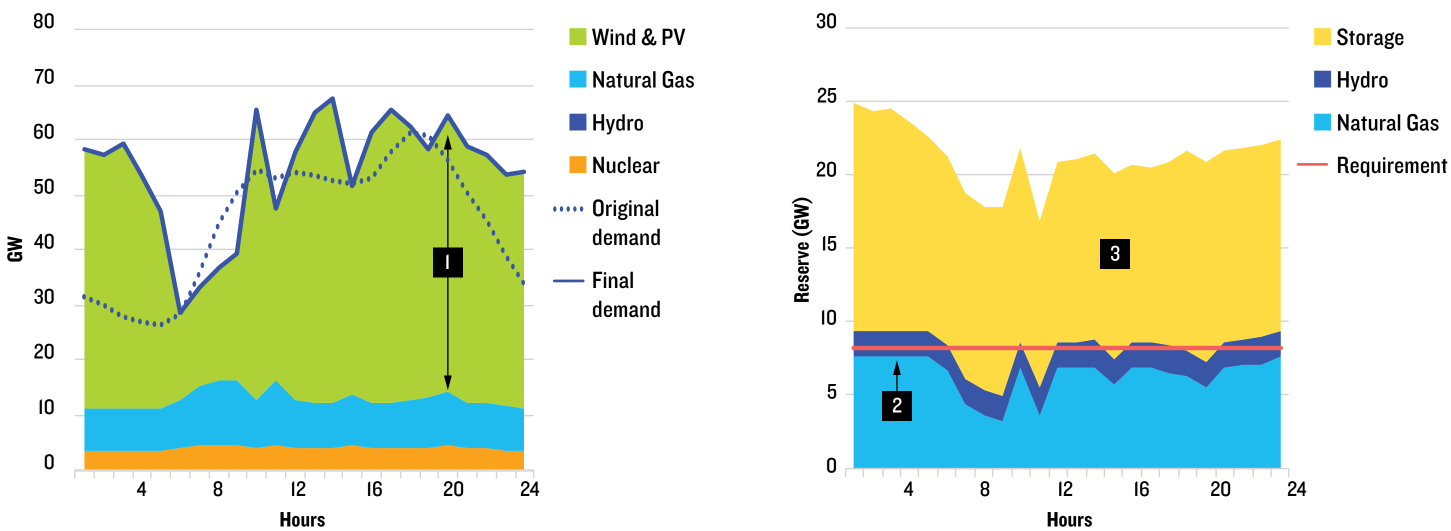
Government should therefore focus on delivering the mix of low-carbon generation capacity, smart resources and margin plant needed to achieve a reliable, low-carbon electricity system. It should not focus on delivering biomass.

FIGURE ES1. THE HIGH RENEWABLES SCENARIO MEETS THE FOUR TESTS FOR RELIABILITY IN 2030

TEST 1: ADEQUACY IS MAINTAINED WITH A MIX OF GENERATION CAPACITY AND SMART RESOURCES



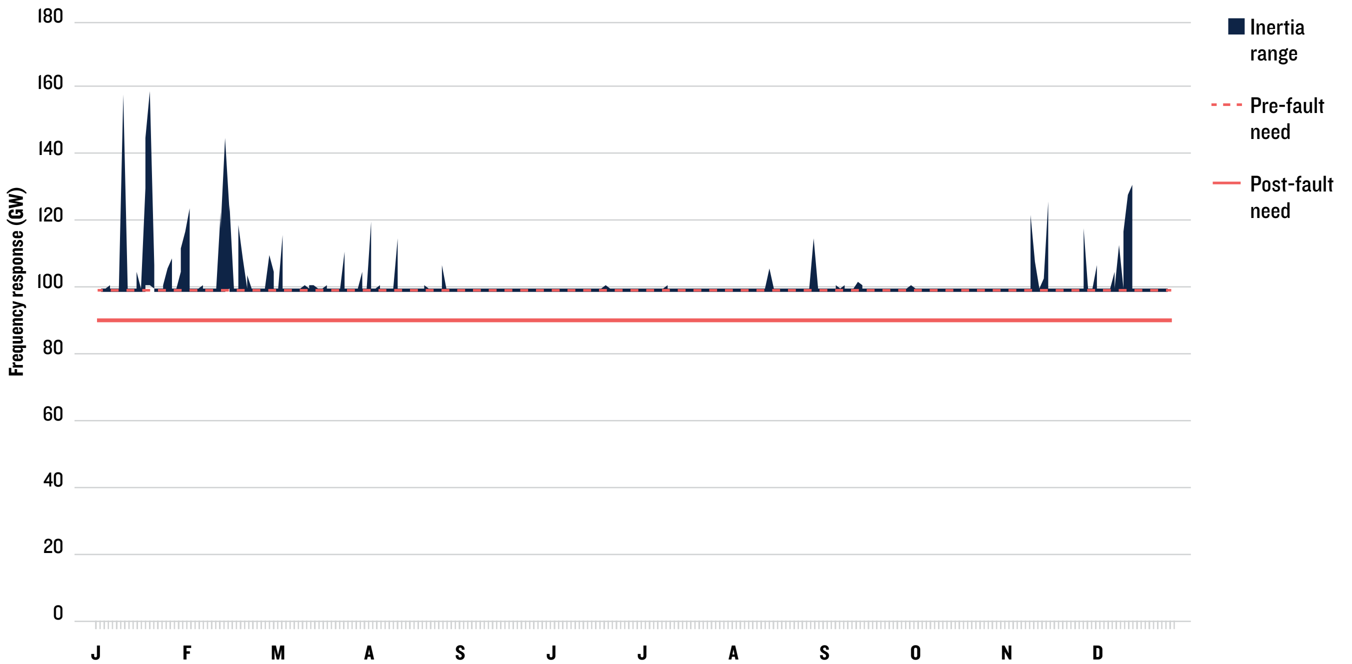
TEST 2: RESERVE IS MAINTAINED WITH A COMBINATION OF GAS, HYDRO AND BATTERY STORAGE



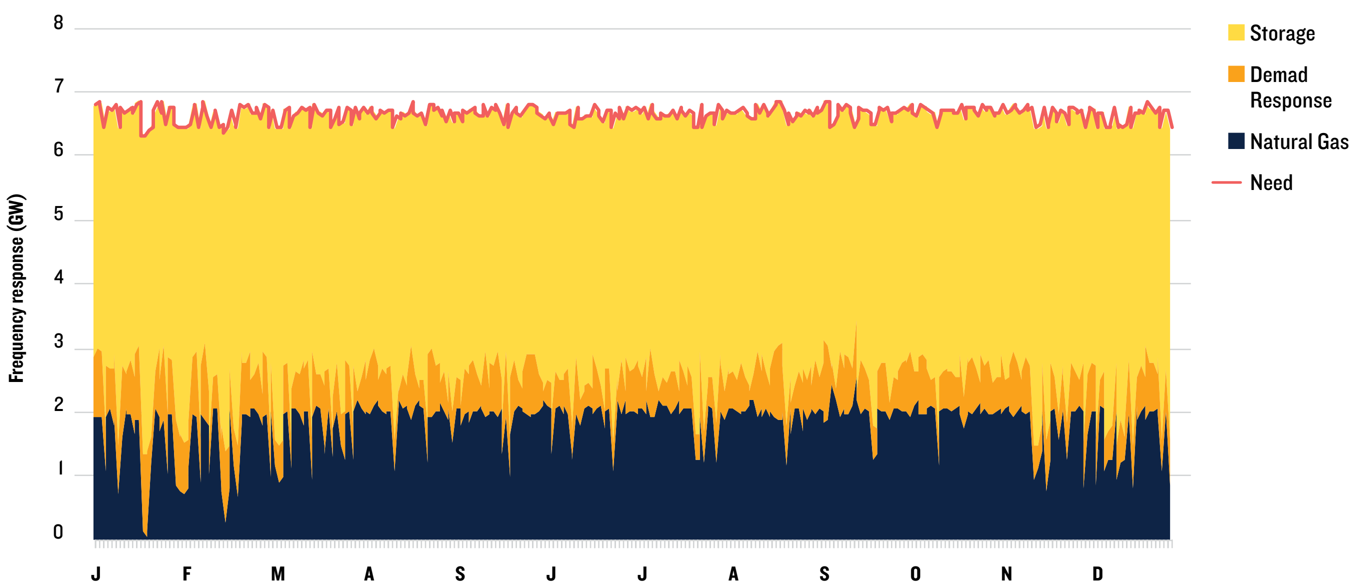
1. Most challenging system conditions: 50GW wind output (Apr).
2. During high wind conditions, 8GW of reserves are needed.
3. Spare natural gas, hydro, and storage exceeds reserve needs.

Source: Vivid Economics

TEST 3: INERTIA IS MAINTAINED AT OR ABOVE THE THRESHOLD LEVEL AT ALL TIMES



FREQUENCY RESPONSE NEEDS ARE MET WITH A COMBINATION OF GAS, DEMAND RESPONSE AND STORAGE



Source: Vivid Economics

1. Introduction

The UK electricity system needs to decarbonise substantially by 2030. The Committee on Climate Change, statutory advisors to the UK Government on setting and meeting climate targets, have advised that the emissions intensity of electricity generation should fall to below 100 gCO2/kWh by 2030 to be on the cost-effective path to meeting the UK's climate targets (Committee on Climate Change, 2017). While the Government has not fully committed to this level of decarbonisation, its 2017 Clean Growth Strategy sets out a pathway to meeting the Fifth Carbon Budget (the climate target covering the period 2028-32) where the share of clean electricity generation increases to over 80 per cent by 2032 (HM Government, 2017).

To ensure that the electricity system remains reliable as it decarbonises, the technology mix must continue to meet several system needs. These system needs ensure that demand is met at all times, during normal operation of the system as well as unexpected stress events. An important set of system needs must be met to maintain the frequency of the electricity system in the event of a large, unexpected loss of supply.

An unanswered question is how far variable renewables can substitute for thermal generators. Thermal generators are good providers of system needs. They can generate electricity at all times; many can change their output as needed; and they help to stabilise the system frequency with the energy stored within their spinning turbines. On their own, variable renewables do not share these properties. However, when paired with smart resources (battery storage, demand response and interconnection), variable renewables can meet many system needs, and some analysts believe system needs can be met with even very high levels of variable renewables.

This question is critical given concerns around the three key low-carbon thermal generation technologies: nuclear, coal or gas generation with carbon capture and storage (power CCS), and biomass. New nuclear and power CCS appear expensive and difficult to deliver relative to alternative low-carbon technologies; while biomass generation is controversial, with concerns around its cost, carbon footprint, and land use impacts. If variable renewables are a poor substitute for thermal generators even when paired with smart resources then Government will need to address these concerns. However, if variable renewables paired with smart resources can largely substitute for thermal generators then Government should instead ensure that electricity markets will deliver the mix of variable renewables and smart resources needed to decarbonise the electricity system.

The public debate on this question is polarised and confused. Some analysts argue that reliable power systems can theoretically be developed without reliance on thermal generators. For example, the US National Renewable Energy Laboratory (NREL) describe a theoretical 100% variable renewable electricity for the United States (National Renewable Energy Laboratory, 2017). However, others argue that the electricity system cannot be decarbonised securely without a mix of low-carbon thermal technologies. For example, biomass generator Drax has stated that biomass is 'vital' as 'the only reliable and flexible renewable which can provide the grid with the full range of support services, the need for which is expected to increase as more intermittent renewables come online' (Bioenergy Insight, 2018). Further, thermal generators are commonly characterised as 'baseload' or as 'providing baseload'. For example, former Secretary of State for Energy and Climate Change Amber Rudd stated in 2015 that 'we have to secure baseload' as justification for the Government's decision to contract nuclear power station Hinkley Point C (*The Guardian*, 2015). However, there is no clear rationale for prioritising generation technologies characterised as 'baseload'.

In this context, the Natural Resources Defense Council (NRDC) have commissioned Vivid Economics to investigate the future role of thermal generation in the UK electricity system. Specific objectives of this commission are to answer two related questions:

- Are there risks to reliability as the electricity system decarbonises to 2030, and is there a need for low-carbon thermal generation to manage these risks during this period of transition?
- Is the concept of 'baseload' generation useful in developing a low-carbon electricity system, and if so, how does baseload generation contribute to electricity system reliability?

This report sets out the findings of this analysis:

- Section 2 is an overview of key electricity system concepts and presents the 'reliability tests' framework.
- Section 3 presents our High Renewables scenario, and describes the detailed electricity system modelling that demonstrates that these tests are met, and that it is technically feasible to achieve a reliable, low-carbon electricity system with high levels of variable renewables, and low levels of thermal generation capacity.
- Section 4 assesses risks and policy implications.
- Section 5 concludes.

2. System needs and solutions

Key messages

- Electricity system reliability is achieved by meeting key system needs. These are adequacy and security; security comprises **reserve**, **inertia** and **frequency response**.
- Generators with particular technical characteristics can meet these needs. **Firm**, **synchronous** and **dispatchable** generators are good providers of system needs.
- **'Baseload'** is a frequently used term to describe the operation of electricity systems, but is not an appropriate concept for analysing system reliability.

This section describes the system needs that must be met to achieve a reliable electricity system, and the solutions to these needs. First, this section introduces the concept of electricity system reliability, and identifies and describes key system needs that must be met to ensure reliability. It also describes four tests that demonstrate the reliability of an electricity system by verifying that the key system needs are met. Second, it describes the technical characteristics of different types of generator that provide solutions to these needs. Third, it introduces the concept of 'baseload', and explains why it is not an appropriate concept for analysing system reliability.

2.1 Electricity system reliability and system needs

Security of supply is a key UK Government objective for the electricity system. The three Government objectives are security of electricity supply, decarbonisation and affordability.

To achieve the security of supply objective the Government sets a reliability standard of a Loss of Load Expectation (LOLE) of three hours per year. This means that expected supply should not be lower than expected demand for more than three hours in a given year. In the event that supply is lower than demand, the system operator must take mitigating actions to ensure that customers are not disconnected.

The reliability standard imposes two categories of system need: adequacy and security. Adequacy is the ability to meet demand at all times, during normal operation of the system. **Security** is the ability of the system to function, and to continue to meet demand, during unexpected stress events that occur outside normal operation.

Security itself comprises several system needs: reserve, and system frequency services: inertia and frequency response. Reserve is the availability of spare generating capacity to address unexpected reductions in output or increases in demand. **Inertia** and **frequency response** are two key tools to manage system frequency.

We have identified four diagnostic tests to confirm the reliability of an electricity system. These tests examine the behaviour of the electricity system under different conditions and verify that its resources are meeting the system needs at all times, including during the most challenging conditions for each need.

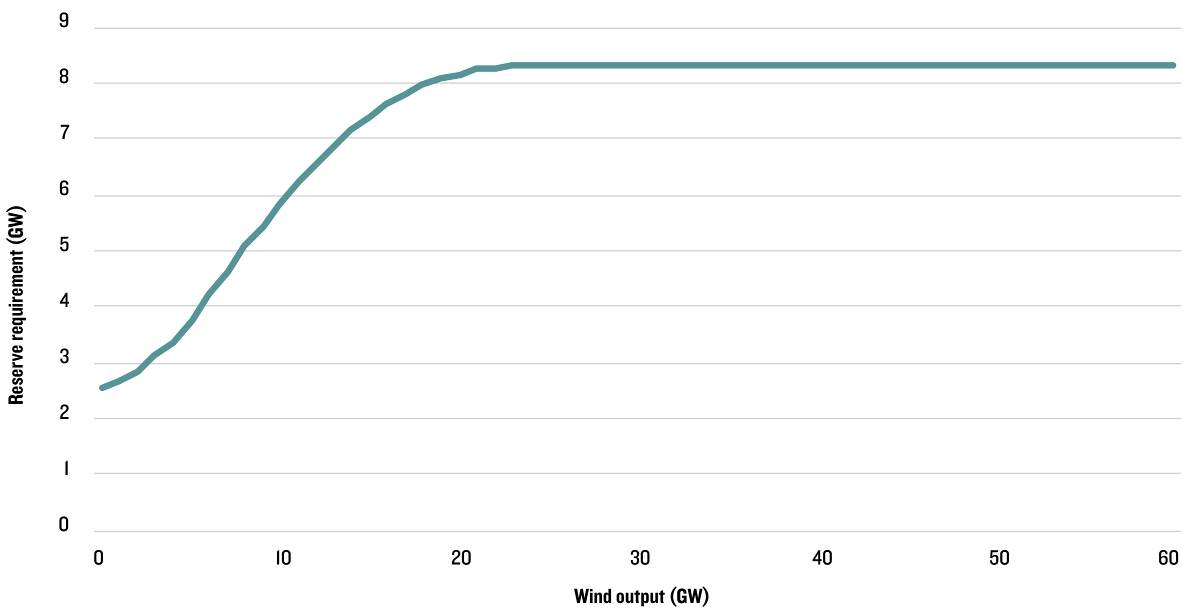
We describe the system needs in turn, and explain the test for each.

Adequacy is the ability to meet demand at all times, during normal operation of the system. In a conventional electricity system, where generators change their output to balance supply and demand, adequacy is provided by ensuring that there is enough generating capacity to meet demand over the whole year. However, as the system evolves, adequacy will increasingly be provided with a combination of generating capacity and smart resources to adjust demand to available output. Smart resources are batteries, which can store renewable output for use at times of high demand; demand response, which can shift demand to periods of high renewable output through intelligent operation of industrial and commercial equipment, and smart appliances in homes; and interconnectors, which can import electricity from neighbouring markets if they have a relative surplus, or export it if they have a relative deficit.

Test 1: Adequacy. This test considers whether supply is sufficient to meet demand at all times. It is passed if sufficient firm capacity and smart resources are available to ensure that supply equals demand during the period with the greatest excess of demand over renewables output (the most challenging conditions for adequacy).

Reserve is the availability of spare generating capacity to address unexpected reductions in output or increases in demand. Unexpected reductions in output include the failure of a generator or interconnector; the unexpected unavailability of an interconnector due to an increase in demand in connected markets; or forecasting errors in wind and solar generation. Unexpected increases in demand may occur due to normal forecasting error, or to underestimating the magnitude of specific demand events such as heating or cooling demand, or sudden spikes in appliance demand (such as the use of kettles during a televised sports event). A key driver of reserve needs is the magnitude of likely errors in forecasting wind output. If the volume of wind output is lower than forecast, there will be a shortfall in supply that must be met by alternative sources of output. Wind output is characterised by a degree of uncertainty, which increases with the level of output. However, the uncertainty range reaches a maximum at a certain level of output; beyond this, output is highly likely to remain within the uncertainty range of the forecast. Figure 1 illustrates the level of reserve that must be kept available, for different levels of wind output.

FIGURE 1: RESERVE NEEDS FOR DIFFERENT LEVELS OF WIND OUTPUT



Source: Vivid Economics analysis of Imperial College Consultants modelling

Test 2: Reserve. This test considers whether there is enough spare generating capacity at all times to address unexpected reductions in output or increases in demand. It is passed if the level of spare generating capacity meets the level of reserves needed during the period with the highest wind output (the most challenging conditions for reserve).

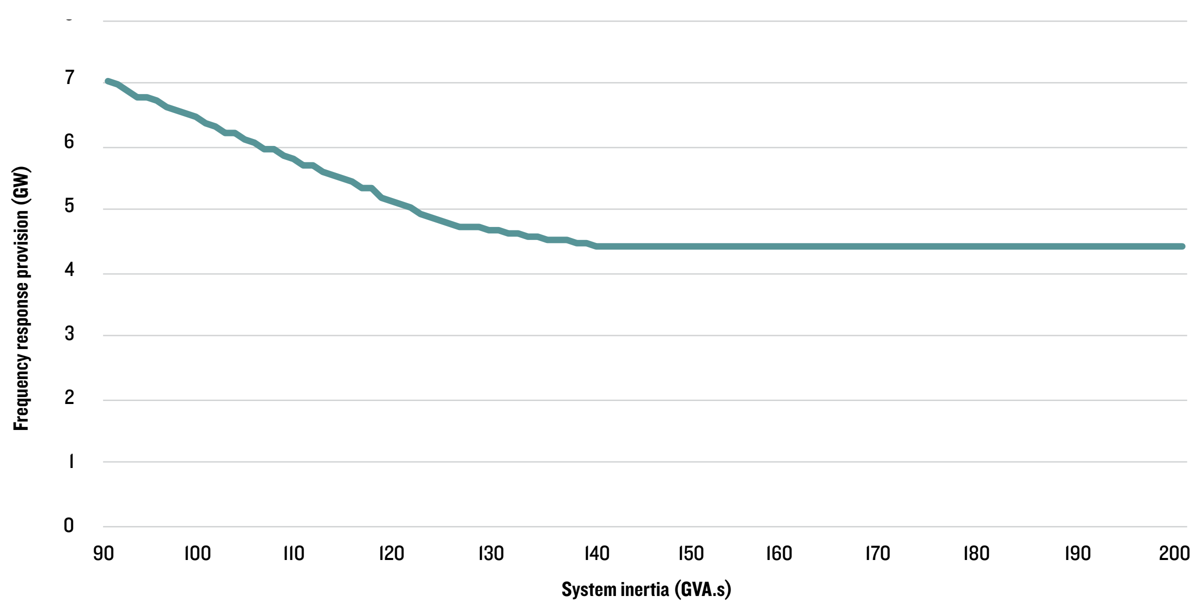
The system frequency is the number of cycles per second of alternating current in the electricity system. Frequency is produced by the rotation of the turbines and rotors of the generators and electric motors that are coupled to the electricity system. The frequency of the UK electricity system is 50 Hz, and the turbines and rotors are designed to rotate at 3,000 rotations per minute to achieve this frequency. National Grid is required to maintain system frequency within a small range of 50 Hz plus or minus 1% (49.5-50.5 Hz). When there is a shortage of electricity (for example, in the event of a generator outage or increase in demand), the shortage is met by the energy stored in the rotating masses of the generators and motors, known as **inertia**. This use of energy reduces the speed of the rotating masses, causing the system frequency to drop. The rate at which the frequency drops is called the **rate of change of frequency (ROCOF)**.

Inertia automatically moderates the change in system frequency in the event of a loss of supply. Inertia is important as large deviations require a high speed and magnitude of frequency response to stabilise and correct the system frequency. Inertia is measured in gigavolt-amperes per second (GVA.s).

Test 3: Inertia. This test considers whether there is enough synchronous capacity generating electricity at all times to maintain inertia above a given threshold. This threshold level is determined by the ROCOF set by the system operator, and the size of the largest possible loss of supply (a generator or interconnector). In the UK, it is expected that the ROCOF threshold will be set at 0.5 Hz per second from 2021.[1]

Frequency response acts together with system inertia to control system frequency. Frequency response is the injection of active power into the electricity system to restore system frequency to normal levels following the loss of a source of supply. Frequency response is typically provided at time frames ranging from 0-2 seconds to two minutes; this allows reserve plant to prepare for operation to maintain system frequency for longer periods. Because inertia reduces the rate of change of frequency, the less inertia on the system, the more frequency response is needed following a loss of supply. Figure 2 shows the level of spare capacity that must be kept available to stabilise system frequency following the loss of a source of supply, for different levels of system inertia.

FIGURE 2: FREQUENCY RESPONSE NEEDS FOR DIFFERENT LEVELS OF SYSTEM INERTIA



Source: Vivid Economics analysis of Imperial College Consultants modelling

Test 4: Frequency response. This considers whether there is enough spare generating capacity at all times to correct the frequency deviation that would occur in the event of the largest possible loss of supply (a generator or interconnector). This test is passed if the amount of spare capacity meets the level of response needed during the period with the lowest level of system inertia (the most challenging conditions for frequency response).

Frequency response can substitute for inertia to a degree, but not entirely. Even with resources that can provide fast frequency response, such as battery storage, system inertia is still needed for three reasons. First, the lower the inertia, the greater the ROCOF and the more frequency response is needed to stabilise frequency. The behaviour of the electricity system under very low levels of inertia, and the volume of frequency response needed to stabilise frequency at these levels are not well understood. Second, while battery storage and demand response are in theory able to provide active power in very short (sub-second) timescales, it takes time to take the accurate measurement of the reduction in

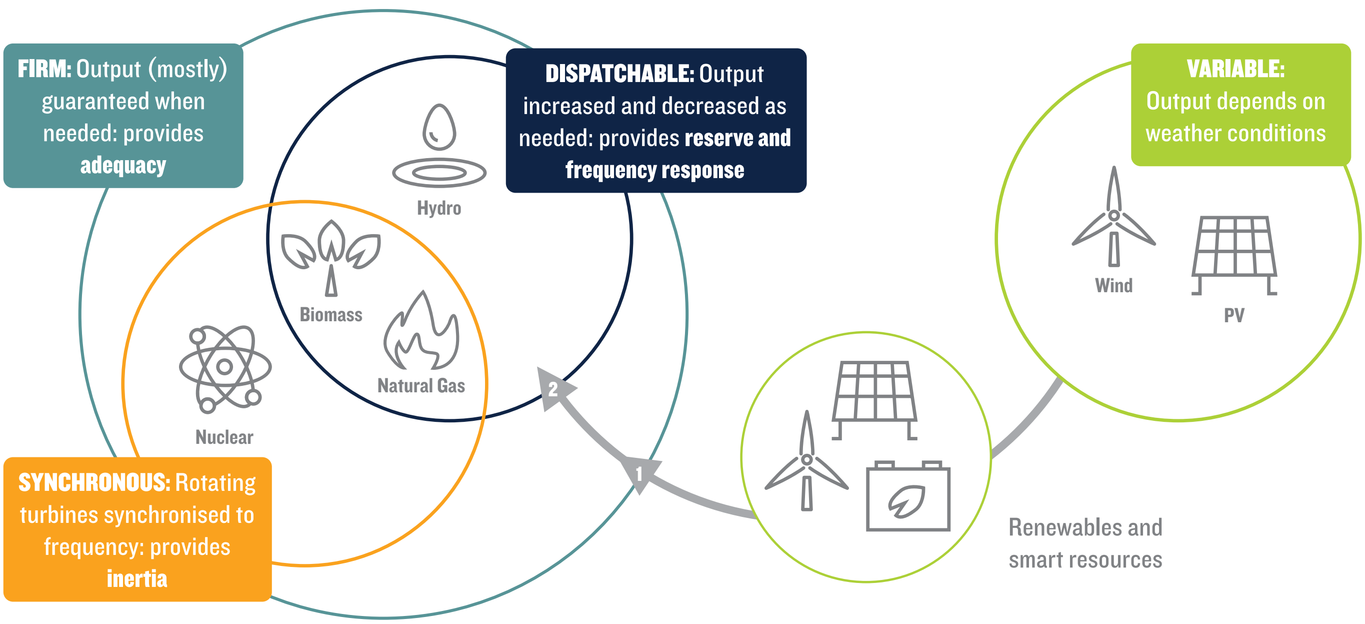
1 National Grid (2017), personal communication.

frequency needed to determine the amount of active power to be provided. Third, many resources on the electricity system are designed to shut down in the event of a frequency deviation that crosses a certain threshold. Historically, this threshold has been a ROCOF of 0.125 Hz per second. National Grid is currently carrying out a series of system upgrades, due to be completed in 2021, to raise the threshold across all system resources to 0.5 Hz per second.[2] A minimum level of inertia is needed to maintain ROCOF at this level in the event of a large loss of supply. The larger the loss of supply, the greater the inertia needed to maintain ROCOF at a given level. In the UK, the largest possible loss of supply would occur in the event of a fault at Hinkley Point C, the new nuclear station contracted by Government to deliver in 2025. In such an event, an inertia of 90 GVA.s would be needed to maintain ROCOF at 0.5 Hz per second.

2.2 Solutions to system needs

Generation technologies have different technical characteristics, and are therefore suited to meeting different system needs. Adequacy is best provided by firm generators; reserve and frequency response are best provided by dispatchable generators; and inertia can be provided only by synchronous generators. Figure 3 explains the technical characteristics of different generation technologies, and the system needs they are suited to meeting.

FIGURE 3: TECHNICAL CHARACTERISTICS OF DIFFERENT GENERATION TECHNOLOGIES



Source: Vivid Economics

Firm generators are guaranteed to provide a given level of output when needed. While no capacity is fully firm, several types of generation capacity are able to generate output at their nameplate (full) capacity with a high degree of certainty (over 80% certainty). These include thermal generators with their own fuel source (e.g. nuclear, coal, gas, biomass) and hydro. Firm generators are good providers of **adequacy**.

In contrast, variable generators may not always generate when needed. Variable ('non-firm') generators include variable renewables (e.g. solar and wind) whose output depends on weather conditions, and interconnectors, whose output depends on demand for electricity in neighbouring markets. Due to their variability, on their own, these technologies are poor providers of adequacy, reserve and frequency response, and provide no inertia. However, their utility in providing these system services is increased when used in combination with other variable technologies with different generation profiles (e.g. a mix of wind, solar and nuclear), and with smart resources (battery storage, demand response and interconnection).

2 National Grid (2017), personal communication.

Dispatchable generators are able to increase or decrease output to meet changes in demand. A generator that is dispatchable is able to operate efficiently and securely at all levels of output, and while changing the level of output. These include coal, gas, biomass and hydro; current nuclear generators are not dispatchable. Dispatchable generators are good providers of reserve and frequency response.

Synchronous generators contain mechanical components whose rotation is synchronised to the system frequency. Currently available synchronous generators are thermal generators (coal, gas, nuclear and biomass): they operate by generating heat to produce steam, which drives a turbine. The turbine is designed to rotate at 3,000 rotations per minute, or 50 Hz, and is therefore synchronised to the system frequency. In the event of a deviation in system frequency (for example, due to the loss of a generator), the inertia in the rotating mass of the turbines automatically and instantaneously limits the deviation. This is important as large deviations require a high speed and magnitude of frequency response to stabilise and correct the system frequency. Only synchronous generators can provide system inertia. System inertia is different from synthetic inertia, which refers to the injection of active power from wind generators that are not operating at full capacity, and is in fact a form of frequency response.

2.3 The relationship between 'baseload', system needs and solutions

'Baseload' is not an appropriate concept for analysing system reliability. Sections 2.1 and 2.2 identified the key system needs (adequacy, reserve, inertia and frequency response) and technical characteristics of generators that provide solutions to these needs (firm, dispatchable and synchronous). In addition to these concepts, thermal generators are commonly characterised as 'baseload' or as 'providing baseload'.

Box 1 presents the various uses of the term 'baseload', and explains why this term is not an appropriate concept for analysing system reliability.

BOX 1: 'BASELOAD' IS NOT AN APPROPRIATE CONCEPT FOR ANALYSING ELECTRICITY SYSTEM RELIABILITY

'Baseload' is a frequently used term to describe the operation of electricity systems. It has several meanings, referring variously to a segment of electricity demand, a mode of operating a generator, or a type of generator. There is a misconception that baseload is a system need, or a solution to meeting system needs. However, the term 'baseload' has an indirect and incomplete relationship with key system needs and solutions, and is not an appropriate concept for analysing system reliability.

Uses of the term 'baseload'

There is no single, accepted definition of the term 'Baseload'. The term is typically used in one of three ways: to describe a segment of electricity demand; a mode of operating a generator, or a type of generator:

- **Baseload as a segment of electricity demand.** Traditionally, total electricity demand is thought to comprise three segments: baseload, mid-merit and peak. **Baseload demand** is the minimum level of demand and must be met at all times, and typically accounts for a large share of electricity demand. In contrast, **peak demand** is the maximum level of demand, and must be met in a small number of periods, while **intermediate demand** is the level of demand between baseload and peak, and must be met, to varying degrees, in most hours in the year.
- **Baseload as a mode of operating a generator.** A firm generator (that is guaranteed to provide a given level of output when needed) that runs at a high load factor (a high share of its maximum output) is considered to be **operating at baseload**. A generator operating at baseload is one way of meeting baseload demand; however, baseload demand can also be met by layering multiple sources of variable generation, and shifting output and demand with smart resources.
- **Baseload as a type of generator.** Generators with high capital costs and low operating costs are able to recover their costs only if they generate at high load factors (in other words, at close to full capacity for a large proportion of the time). As this makes them well-suited to operating at baseload, these generators are considered **baseload generators**. Other categories include peaking generators (those suited to meeting peak demand) and mid-merit generators (those suited to meeting intermediate demand). However, the distinction between these categories is blurring. For example, historically, coal and nuclear were considered baseload generators, while gas generators were previously cost-effective only at moderate load factors and considered mid-merit. However, gas generators are now cheaper than coal and nuclear at high load factors and are equally suited to operating at baseload.

Baseload, system needs and solutions

As explained in Sections 2.1 and 2.2, key system needs are adequacy, reserve, inertia and frequency response, while solutions to these needs are firm, dispatchable and synchronous generation.

There is a misconception that 'baseload' is a system need, or a solution to system needs. This may be because baseload generators are firm and synchronous, and therefore have certain advantages:

- As baseload generators are firm, they contribute to adequacy, and unlike wind do not require large amounts of reserve to account for forecasting errors.
- As baseload generators are synchronous, they contribute to inertia, reducing the amount of frequency response needed to stabilise system frequency in the event of a loss of supply.

However, many system needs can be met without baseload generators, and some system needs are met more effectively with other types of generator:

- Baseload generators are not needed to provide adequacy. Adequacy can also be provided with a combination of variable renewable generators and smart resources to adjust demand to available output, with gas providing backup during times of high demand and low renewables output. In principle, power CCS can also provide adequacy.
- Reserve can be provided cost-effectively with technologies such as gas, hydro and battery storage.
- Baseload generators are not needed to provide inertia. Gas generators also produce inertia, and in principle new technologies such as power CCS or non-generator options such as synchronous condensers (see Section 3) can provide inertia with few or no CO_2 emissions.
- As baseload generators are not dispatchable, they do not provide frequency response. Gas, storage and demand response can all provide frequency response, and to some extent compensate for the impact of reduced inertia on system frequency.

Due to the ambiguity of the term 'baseload', and its indirect and incomplete relationship with key system needs and solutions, it is not an appropriate concept to analyse system reliability.

3. Feasibility of a high renewables electricity system

Key message

- The UK can achieve a reliable, low-carbon electricity system with high levels of variable renewables, and low levels of thermal generation capacity. It can do so without no new nuclear beyond Hinkley Point C, no CCS and no biomass.
- Wind and solar could provide over 60% of electricity generation by 2030.
- 20 GW of thermal generation capacity is needed to provide inertia. Of this, 4.5 GW may need to be low-carbon (and would be achieved with delivery of Hinkley)

Section 2 discussed key electricity system concepts and described how firm, synchronous and dispatchable generators meet key system needs. This section describes an electricity system scenario that demonstrates that in a decarbonised system, variable renewables (solar and wind) and smart resources (battery storage, demand response and interconnection) can meet most system needs, with some firm, synchronous generators needed to provide inertia.

We have carried out detailed modelling to confirm feasibility of achieving a reliable, low-carbon electricity system with high levels of variable renewables, and low levels of thermal generation capacity. In partnership with Imperial College Consultants, we have developed an electricity system scenario designed to meet reliability criteria and a carbon constraint with low levels of synchronous generation capacity. This involved using Imperial College's Whole-electricity System Investment Model (WeSIM) to estimate the pattern of investment in and operation of electricity system resources (generation, network, storage, demand response and interconnection resources) which minimises the overall electricity system cost, given constraints to ensure reliability (continuous balancing of generation and demand, reserve and adequacy constraints) and respect the characteristics of the electricity system (power flow limits, dynamic characteristics of generation plants, and operational constraints of storage and demand response), while meeting a carbon target.

Specifically, we have developed a scenario, the High Renewables scenario, with constraints on the volume of low-carbon synchronous generation capacity. The High Renewables scenario is based on finding the least-cost set of investment and operational decisions to meet demand given three key constraints. First, a carbon constraint is imposed; this is set at 200 gCO_2/kWh in 2020, and decreasing to 150 gCO_2/kWh in 2025, and 100 gCO_2/kWh in 2030. Second, the maximum ROCOF is set to 0.5 Hz per second in line with National Grid's current system upgrades (see Section 2), which sets a minimum level of system inertia. Third, limits are placed on the volume of low-carbon synchronous capacity. Nuclear is fixed at 4.5 GW in 2030, representing delivery of Hinkley Point C and continued operation of Sizewell B, the only existing nuclear plant not expected to decommission over the period to 2030. Biomass and power CCS, alternative forms of low-carbon synchronous capacity, are excluded from the scenario.

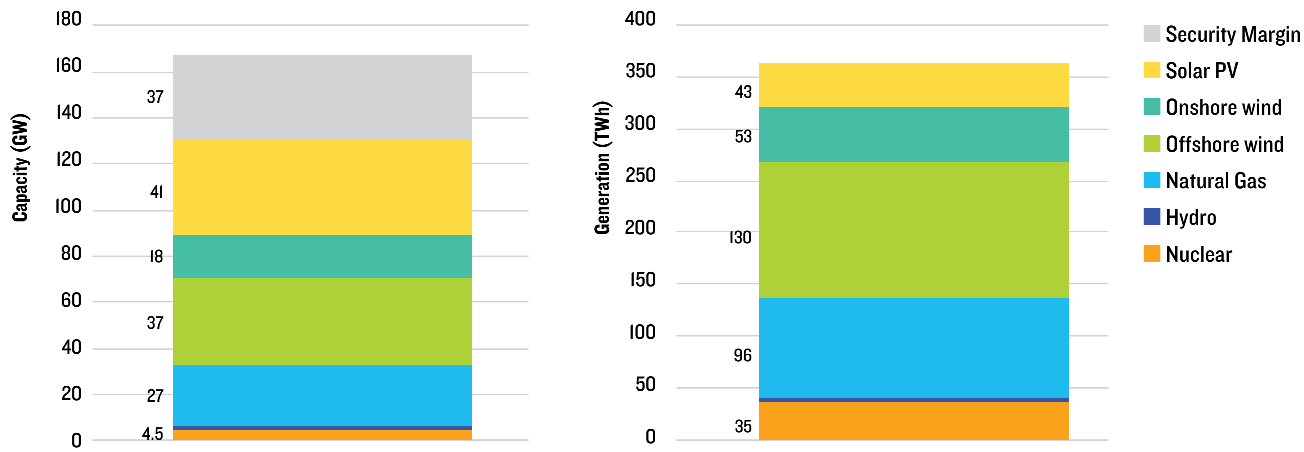
The High Renewables scenario is conservative, and based only technologies that are in operation or close to market in the UK. There are a broad range of technologies that could be used to meet the key system needs of a low-carbon electricity system. In order to demonstrate the feasibility of such a system, we have modelled a scenario based on a subset of those technologies that are closest to market in the UK. There are several other, proven or highly promising, technologies that could further reduce the challenges of delivering a low-carbon electricity system, and facilitate deeper decarbonisation beyond 2030. Examples of these are:

- **Inverter-based renewables.** This technology uses renewable generators to provide frequency response when not operating at full capacity.
- **Synchronous condensers.** This technology is a turbine that provides grid inertia without providing electricity. Synchronous condensers could substitute for gas in providing inertia, reducing grid CO_2 intensity without compromising reliability. In the UK a synchronous condenser demonstrator, Project Phoenix, is underway and set to conclude by 2021. Project Phoenix is led by distribution company SP Energy Networks, and funded through Ofgem's Network Innovation Competition (Ofgem, 2017).
- **Synchrophasers/phasor measurement units.** This technology could measure the system frequency in real time, such that frequency response can be provided instantly, rather than following a measurement delay. Instant frequency response could reduce the requirement for gas or nuclear generators to provide inertia.

The High Renewables scenario demonstrates that it is technically feasible to achieve a reliable, low-carbon electricity system with high levels of variable renewables, and low levels of thermal generation capacity. WeSIM is an optimisation model; in other words, it attempts to calculate the least-cost solution to a problem given a set of constraints. If the constraints are sufficiently restrictive, it is possible that the problem has no solution, and the scenario cannot be characterised. In the case of the High Renewables scenario, WeSIM successfully identified the pattern of investment in, and operation of, electricity system resources which minimises the overall electricity system cost, given the constraints to ensure reliability and carbon emissions. This means that it is technically feasible to achieve a reliable, low-carbon electricity system with high levels of variable renewables, and low levels of thermal generation capacity.

To meet the carbon constraint, wind and solar provide over 60% of electricity generation by 2030; with gas generation providing around 25%. Figure 4 describes the capacity and generation mixes in 2030 in the High Renewables scenario. The capacity mix includes 56 GW of wind, 41 GW of solar, 27 GW of gas, 4.5 GW of nuclear and 2 GW of hydro. The capacity mix also includes 37 GW of security margin plant, which are not expected to run during normal operation of the electricity system, but are needed to address extreme stress events, in which multiple challenging conditions occur simultaneously. These conditions might include a combination of zero renewables output, depleted storage and demand response, no availability of interconnectors, and multiple generator outages. Security margin plant could be additional battery storage or demand response, or peaking generators. The generation mix is dominated by wind and solar, which together provide 62% of generation; the remainder of generation is provided by natural gas (26%), and nuclear and hydro (11%). The high share of wind and solar generation is possible due to the very low level of curtailment: only 0.2% of wind generation and 0.4% of solar generation are curtailed in this scenario.

FIGURE 4: GENERATION AND CAPACITY MIX IN THE HIGH RENEWABLES SCENARIO (2030)

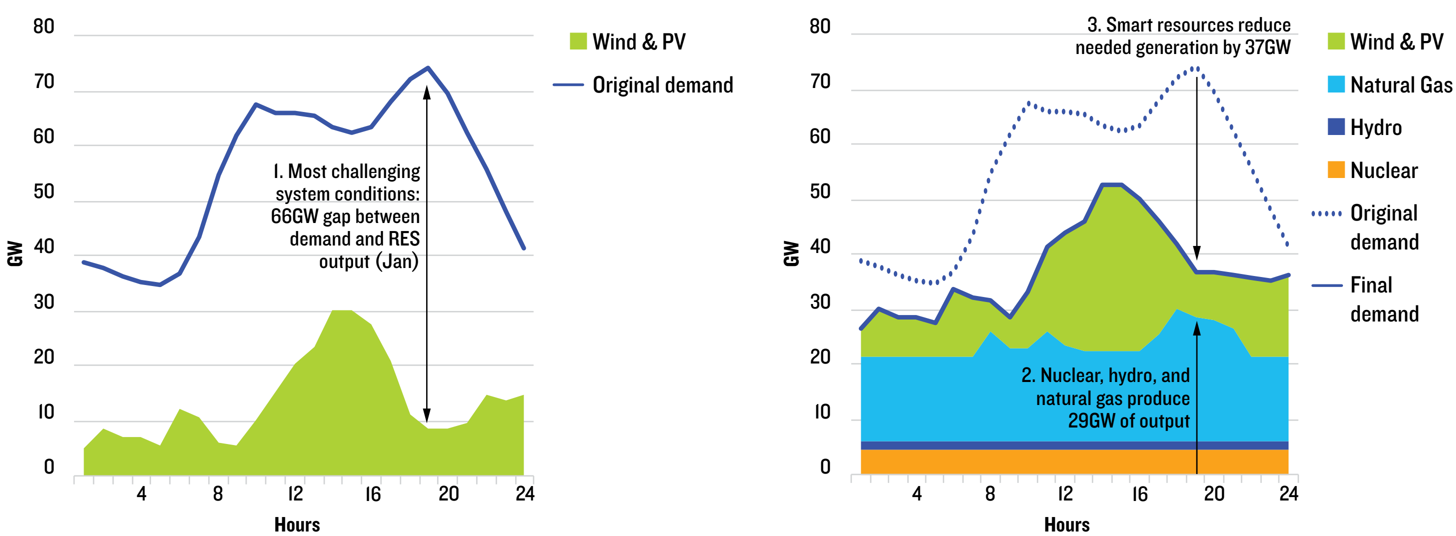


Source: Vivid Economics analysis of Imperial College Consultants modelling

The reliability of the High Renewables scenario can be demonstrated with the four tests. These tests, outlined in Section 2, demonstrate that four key system needs are met at all times. First, adequacy is maintained with a mix of generation capacity and smart power resources. Second, reserve is maintained with a combination of gas, hydro and battery storage. Third, inertia is maintained with moderate volumes of nuclear and gas, and surplus generation is absorbed with smart power resources. Fourth, frequency response is maintained with gas, demand response and storage. This section describes the test results for the High Renewables scenario in 2030; the Annex describes the test results that demonstrate system needs are met in 2020 and 2025.

First, adequacy is maintained with a mix of generation capacity and smart power resources. The most challenging conditions for adequacy are high demand and low renewables output. Figure 5 shows how adequacy is maintained during the most challenging modelled system conditions in 2030. Under these conditions, demand is 74 GW, while output from renewables has decreased rapidly from 29 GW to 8 GW, creating a potential imbalance of 66 GW. The system is balanced in two ways. First, nuclear, hydro and gas generation contribute 29 GW of output, so that total output reaches 37 GW. Second, storage, demand response and interconnection reduce needed output by 37 GW. The system is therefore balanced.

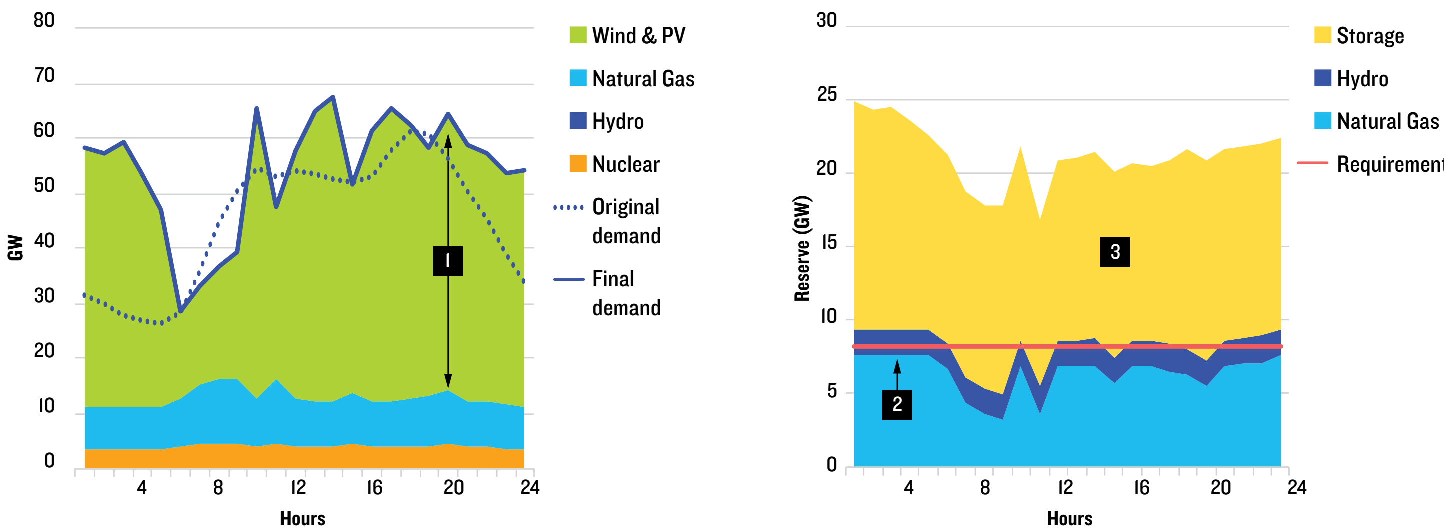
FIGURE 5: TEST 1. ADEQUACY IS MAINTAINED WITH A MIX OF GENERATION CAPACITY AND SMART POWER RESOURCES



Source: Vivid Economics analysis of Imperial College Consultants modelling

Second, reserve is maintained with a combination of gas, hydro and battery storage. The most challenging conditions for reserve are high wind output. Figure 6 shows how adequacy is maintained during the most challenging modelled system conditions in 2030. Under these conditions, wind produces 50 GW of the total 56 GW variable renewable output (the remainder being provided by solar). Due to the high volume of wind output, the potential for forecasting errors is also high. The quantity of reserves that must be held to address the risks of unexpected imbalances between supply and demand therefore increases from under 3 GW when there is no wind output to over 8 GW to account for potential forecasting errors. In this period, the volume of capacity that is online and able to provide reserve is roughly double the reserve requirement, at around 16 GW. This consists of gas running at moderate load factors, hydro, and a large volume of storage that is not needed to supply electricity given the high volume of wind output.

FIGURE 6: TEST 2. RESERVE IS MAINTAINED WITH A COMBINATION OF GAS, HYDRO AND BATTERY STORAGE

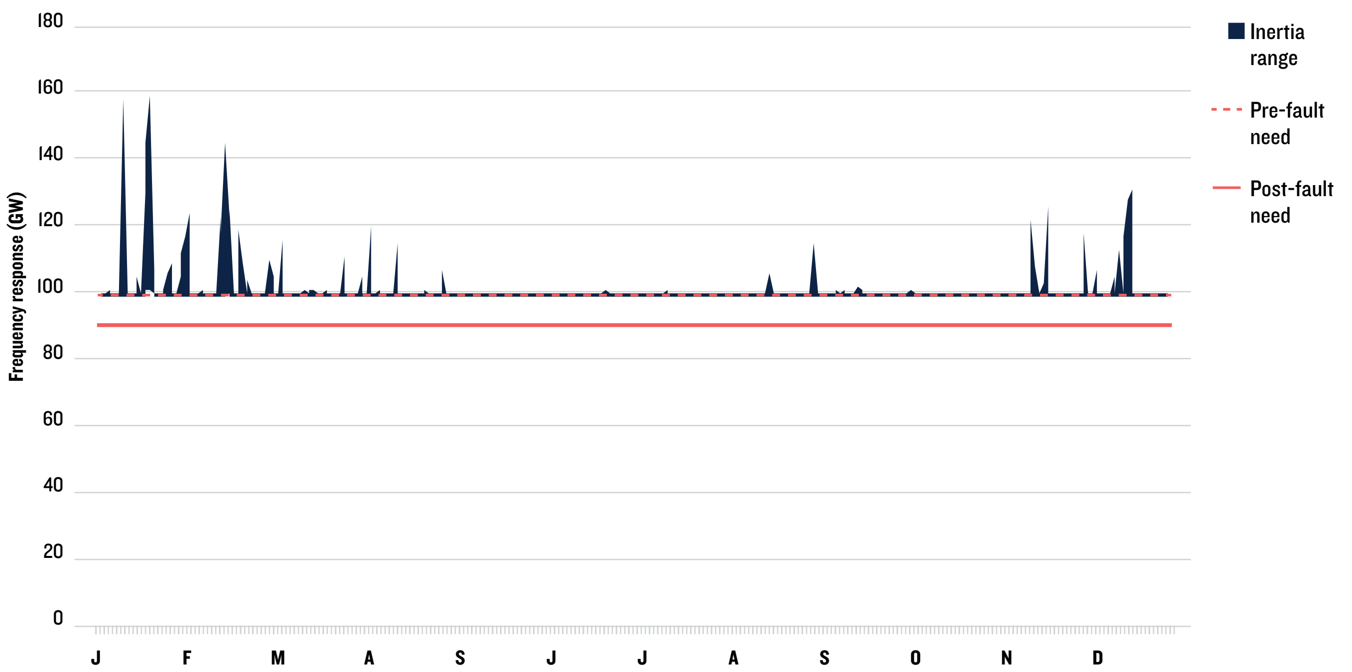


1. Most challenging system conditions: 50GW wind output (Apr).
2. During high wind conditions, 8GW of reserves are needed.
3. Spare natural gas, hydro, and storage exceeds reserve needs.

Source: Vivid Economics analysis of Imperial College Consultants modelling

Third, inertia is maintained with moderate volumes of nuclear and gas. In the High Renewables scenario, the largest potential loss is 1.8 GW, representing one of the Hinkley Point C generating units. In order to contain system frequency following a loss of this magnitude, inertia of 90 GVA.s would be needed. This is 'post-fault' level of inertia needed (in other words, it excludes the inertia provided by the failed generator). However, as the inertia from the failed generator will also be lost as the generator is decoupled from the electricity system, a higher 'pre-fault' level of 99 GVA.s is needed. This is equivalent to the inertia provided by 20 GW of synchronous generators, though these can operate at lower load factors to limit operating costs and CO2 emissions. The need to maintain inertia means that some synchronous generation operates when it would not otherwise be needed to, for example under conditions of low demand and high wind and solar output. Figure 7 shows how 99 GVA.s of inertia is maintained year-round in the High Renewables scenario. Due to the carbon constraint, inertia is close to this minimum threshold on most days.

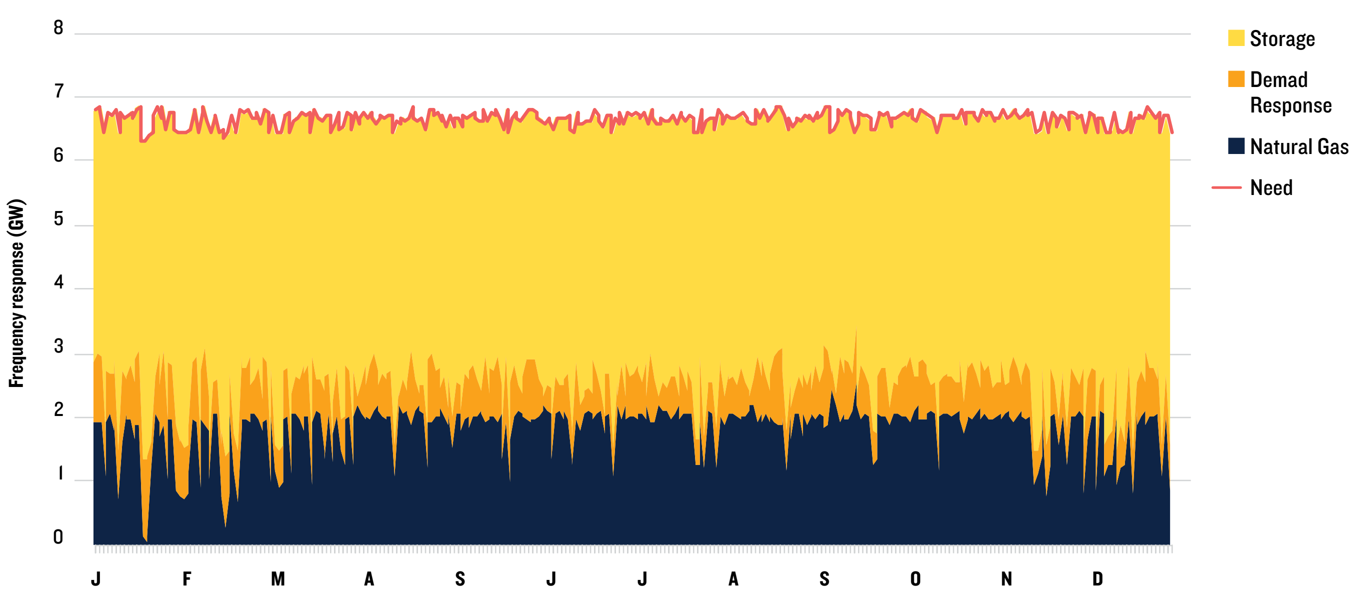
FIGURE 7: TEST 3. INERTIA IS MAINTAINED AT OR ABOVE THE THRESHOLD LEVEL AT ALL TIMES



Source: Vivid Economics analysis of Imperial College Consultants modelling

Fourth, frequency response is maintained with gas, demand response and storage. In the High Renewables scenario, inertia is close to its minimum threshold on most days. As a result, ROCOF is close to its highest allowed level of 0.5 Hz per second on most days. The quantity of resources that must be available to provide frequency response in the event of a large generator or interconnector outage therefore increases from under 4 GW when inertia levels are over 150 GVA.s to 7 GW when inertia is 99 GVA.s. Figure 8 shows how sufficient spare resources are available to provide frequency response year-round in the High Renewables scenario. This consists of gas running at moderate load factors, around 1 GW of potential demand response, and 4 GW of storage.

FIGURE 8: TEST 4. FREQUENCY RESPONSE NEEDS ARE MET WITH A COMBINATION OF GAS, DEMAND RESPONSE AND STORAGE



Source: Vivid Economics analysis of Imperial College Consultants modelling

4. Risks and policy implications

Key messages

- Of the 127 GW of generating capacity needed in 2030, 69 GW of new investment is needed, while the remaining 58 GW can be provided by existing capacity.
- In addition, significant volumes of smart resources will be needed to maintain adequacy and security; over 30 GW of total smart resources could be needed by 2030.
- Technical and economic risks to delivering this investment are generally low, with greater risks around demand response.
- Significant investment in security margin plant is also needed. This could be additional battery storage or demand response, or peaking generators that would operate only during extreme system stress events.
- Biomass is not needed to ensure the reliability of a smart, low-carbon electricity system.

Section 3 demonstrated that it is technically feasible to achieve a reliable, low-carbon electricity system with high levels of variable renewables, and low levels of thermal generation capacity, with flexibility provided by a combination of battery storage, demand response and interconnection. This section assesses the risks to delivery of the High Renewables scenario, and the policy implications of these findings. First, it examines the profile of capacity retirement to 2030 to identify the volumes of new capacity needed for each resource. Second, it considers the technical and economic risks to delivery of these resources, and makes an overall assessment of deliverability risk. Third, it identifies the policy implications of the findings.

4.1 Investment needs to 2030

Some existing resources are expected to remain online over the period to 2030, while others are expected to retire over this period. This section examines the profile of capacity retirement to 2030, to identify the volumes of new capacity needed for each resource in the High Renewables scenario.

Of the 127 GW of generating capacity needed in 2030 in the High Renewables scenario, 69 GW is new investment, while the remaining 58 GW can be provided by existing capacity. Figure 9 sets out the profile of capacity retirements and new capacity investments needed to deliver the High Renewables scenario in 2020, 2025 and 2030:

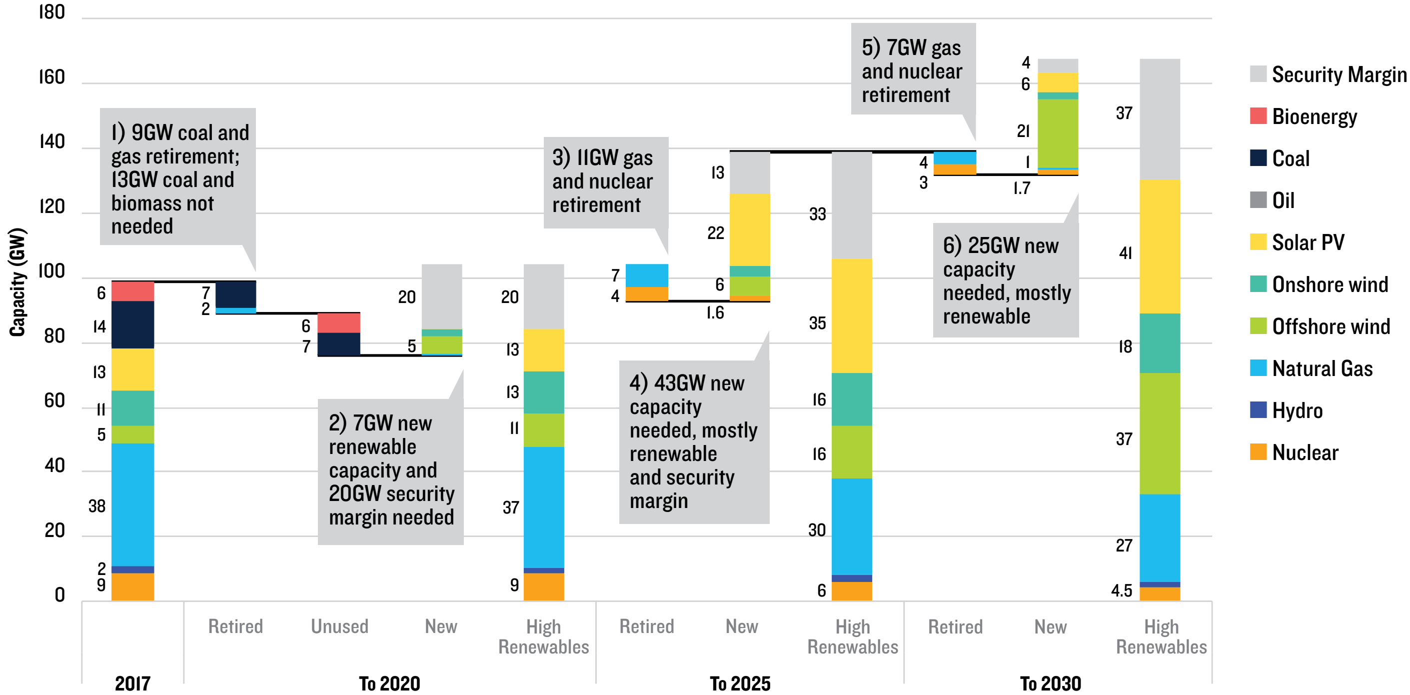
- **There is currently close to 100 GW of generating capacity on the electricity system.** This includes 14 GW of coal, 38 GW of gas, 9 GW of nuclear, 31 GW of renewables (onshore and offshore wind, solar and hydro) and 6 GW of bioenergy.[3]
- **Of this, 28 GW is expected to retire over the period to 2030; a further 13 GW is not needed to deliver the High Renewables scenario.** Planned retirements are made up of 7 GW of coal, 12 GW of gas, and 8 GW of nuclear.[4] In addition to these retirements, a further 7 GW of coal, and 6 GW of biomass will not be needed to deliver the High Renewables scenario in 2020.
- **The remaining 58 GW of existing capacity is expected to stay on the system in 2030.** This includes 1.2 GW of Nuclear (Sizewell B), 2 GW of hydro, 26 GW of natural gas and 29 GW of wind and solar.
- **Significant investment in new generating capacity will be needed to replace retired capacity with a low-carbon capacity mix.** This consists of 39 GW of wind, 25 GW of solar, and 3.5 GW of new nuclear (representing Hinkley Point C).

Investment in new security margin plant is also needed. This consists of 37 GW of security margin plant, which are not expected to run during normal operation of the electricity system, but are needed to address extreme system stress events, in which multiple challenging conditions occur simultaneously. Security margin plant could be additional battery storage or demand response, or peaking generators.

3 This includes the 2 GW of biomass units at Drax, and around 4 GW of other bioenergy plant, with feedstocks comprising wood products and a range of waste products.

4 Numbers may not sum due to rounding

FIGURE 9: CAPACITY RETIREMENTS AND NEW INVESTMENTS IN THE HIGH RENEWABLES SCENARIO

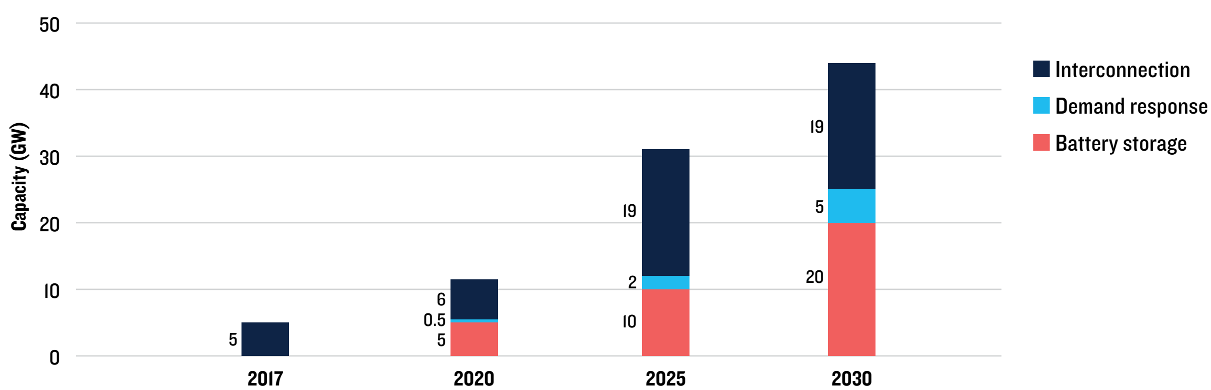


Note: Bioenergy includes the 2 GW of biomass units at Drax, and around 3.7 GW of other bioenergy plant, with feedstocks comprising wood products and a range of waste products.

Source: Vivid Economics analysis of BEIS (2017): Updated Energy and Emissions Projections 2017

In addition, significant volumes of smart resources will be needed to maintain adequacy and security. Figure 10 sets out the profile of new investments in smart resources needed to deliver the High Renewables scenario in 2020, 2025 and 2030.

FIGURE 10: NEW INVESTMENTS IN SMART RESOURCES IN THE HIGH RENEWABLES SCENARIO



Source: Vivid Economics

4.2 Technical and economic risks

This section considers the technical and economic risks to delivery of the new electricity system resources needed to 2030, and makes an overall assessment of deliverability risk.

Technical and economic risks to delivering the necessary investment are generally low, with greater risks around new nuclear and demand response. There are potential technical and economic risks in terms of technical performance, cost and the ability to deploy at scale. Table 1 considers the maturity, cost and deployability at scale of the key technologies needed to complement wind and solar in the High Renewable scenario, and provides a qualitative assessment of these risks. Overall technical and economic risks to delivering gas, battery storage and interconnection are low. While technical and economic risks to delivering demand response are moderate due to uncertainty over consumer adoption, additional battery storage could compensate for any shortfall.

TABLE 1: TECHNICAL AND ECONOMIC RISKS TO DELIVERING KEY ELECTRICITY SYSTEM RESOURCES

Technology	Maturity	Cost	Scale	Overall technical and economic risks
Gas	**Low risk.** Mature technology, deployed in the UK since 1950s	**Low risk.** Currently the cheapest fossil technology.	**Low risk.** Up to 5 GW built in a single year.	**Low risk**
Battery storage	**Low risk.** Mature technology, though stationary storage applications have been limited to date, and significant further innovation is expected.	**Low risk.** 2030 scenario indicates that 20 GW of storage is cost-competitive at battery costs of $320/kWh.	**Low risk.** 2030 scenario requires 20 GW by 2030; this is less than expected volume of electric vehicle batteries expected over this timeframe.	**Low risk**
Demand response	**Moderate risk.** Business model for utilisation of decentralised resources has yet to be developed.	**Low risk.** Demand response is highly cost-effective, reducing needed investment in new generating capacity.	**Moderate risk.** Government target to roll out smart meters broadly on track, but high degree of uncertainty over consumer adoption	**Moderate risk**
Interconnection	**Low risk.** Mature technology, deployed in the UK since 1986.	**Low risk.** Wide agreement that benefits strongly outweigh costs	**Low risk.** 2030 scenario assumes 14 GW additional interconnection by 2030; of this, 1 GW is already under construction, and 6 GW are in advanced development and expected to be delivered by 2021.	**Low risk**

Source: Vivid Economics

4.3 Policy implications

This section identifies the policy implications and actions to deliver the new electricity system resources needed to 2030.

Biomass is not needed to ensure the reliability of a smart, low-carbon electricity system. Some commentators argue that biomass generation is needed to ensure the reliability of a low-carbon electricity system as both a substitute for fossil feedstock and a form of firm, synchronous generation. However, biomass generation is controversial, with concerns around its cost, carbon footprint, and land use impacts. The High Renewables scenario demonstrates that it is technically feasible to achieve a reliable, low-carbon electricity system with high levels of variable renewables, and low levels of thermal generation capacity. Biomass is therefore not needed to ensure the reliability of a smart, low-carbon electricity system.

A simple set of incentive mechanisms is needed for battery storage and demand response. As set out in section 2, battery storage and demand response provide adequacy, reserve and frequency response, the system needs that ensure reliability. To deliver these resources, developers must be rewarded for meeting these needs. However, there is widespread recognition that the current set of markets for solutions to system creates barriers that will inhibit investment. Some of these barriers are described in Box 2. These barriers have been recognised by the Department for Business, Energy and Industrial Strategy (BEIS), Ofgem and National Grid. National Grid has committed to address these with a set of actions, including standardising existing products to deliver greater transparency, and reviewing their provisions to lower barriers to entry.

BOX 2: KEY BARRIERS TO EFFICIENT PROVISION OF SOLUTIONS TO SYSTEM NEEDS

In 2016 National Grid carried out a consultation on the current balancing services markets. The consultation indicated that the current set of markets for system services created barriers to efficient provision of services:

- **There are too many products.** National Grid defines more than 20 'products' (specific processes for providing key system services) that providers can choose to offer, each with different technical requirements and routes to market. For example, there are 14 different products for reserve provision, and six different products for frequency response provision. A related problem is that the products are differentiated with narrow definitions, which may exclude many important new technologies and business models.
- **Requirements and interactions are unclear.** Products are typically not defined in a way which makes clearly communicates to participants the specific set of system needs (and potential interaction between system needs) that the product is intended to address.
- **The assessment criteria are unclear.** Product specifications differ from one procurement period to the next, such that market participants are frequently unable to evaluate the opportunities to participate across different products.

Source: National Grid (2017)

Significant investment in security margin plant is also needed. The Capacity Market currently exists for the purpose of bringing forward new security margin plant, and adequate capacity will need to be auctioned to deliver the necessary investment.

5. Conclusions

The UK can achieve a reliable, low-carbon electricity system by 2030 with high levels of variable renewables, and low levels of thermal generation capacity. It can do so no new nuclear beyond Hinkley Point C, no CCS and no biomass. We have identified four diagnostic tests to confirm the reliability of an electricity system. These tests examine the behaviour of the system under different conditions and verify that the resources are meeting the system needs at all times. In partnership with Imperial College Consultants, we have developed an electricity system scenario designed to meet reliability criteria and a carbon constraint, with high levels of variable renewables and low levels of thermal generation capacity, and carried out detailed modelling to demonstrate that this scenario meets these four tests.

Wind and solar could provide over 60% of electricity generation by 2030. In the High Renewables scenario, wind capacity is 56 GW in 2030, of which 37 GW is offshore wind, and 18 GW onshore; and solar capacity is 41 GW.[5] Together these sources provide over 60% of electricity generation in 2030.

20 GW of thermal generation capacity is needed to provide inertia. Of this capacity, 4.5 GW may need to be low-carbon. National Grid's system upgrades to raise the threshold rate of change of frequency, due to be completed in 2021, will allow the electricity system to tolerate relatively low levels of inertia, and will reduce the need for synchronous generators. In the High Renewables scenario, 20 GW of synchronous generators operates at all times to provide the inertia needed to ensure system reliability. This consists of 4.5 GW of nuclear generators, and 15.5 GW of gas generators. The carbon constraint is met by running the gas capacity part-loaded.

Adequate investment in smart resources is needed to ensure reliability. Smart resources provide flexibility in the electricity system. Smart resources include batteries, which can store renewable output for use at times of high demand; demand response, which can shift demand to periods of high renewable output; and interconnectors, which can import electricity from neighbouring markets if they have a relative surplus, or export it if they have a relative deficit. In the High Renewables scenario, electricity system flexibility is provided by 20 GW of battery storage, 5 GW of demand response and 18.5 GW of interconnectors.

5 Numbers may not sum due to rounding.

Significant investment in security margin plant is also needed. The security margin is needed to ensure that there is sufficient capacity available to address unexpected stress events, such as multiple generator outages coinciding with zero output from variable renewables. The greater the volume of variable renewables, the higher the need for security margin plant. In the High Renewables scenario, 37 GW of security margin plant is needed. This could be additional battery storage or demand response, or peaking generators that would operate only during extreme system stress events.

Biomass is not needed to ensure the reliability of a smart, low-carbon electricity system. Biomass generation is controversial, with concerns around its cost, carbon footprint, and land use impacts. Further, previous work by Vivid Economics for NRDC has indicated that at current technology costs, biomass is not part of a least-cost capacity mix (NRDC, 2017). As it is technically feasible to achieve a reliable, low-carbon electricity system with low levels of thermal generation capacity, biomass generation is not needed to achieve such a system.

Provided Hinkley Point C is successfully commissioned in the 2020s, delivery of sufficient synchronous generators it is highly feasible. In addition to the 3.3 GW of capacity provided by Hinkley Point C, under 17 GW of synchronous generation is needed to provide inertia. This can be provided by the existing nuclear and gas capacity expected to remain on the system in 2030.

Beyond 2030, there are additional options to facilitate deeper decarbonisation of the electricity system. Gas capacity could be run at lower load factors; and inverter-based renewables, synchronous condensers and synchrophasers/phasor measurement units could further reduce the need for thermal generation and allow integration of larger volumes of variable renewables.

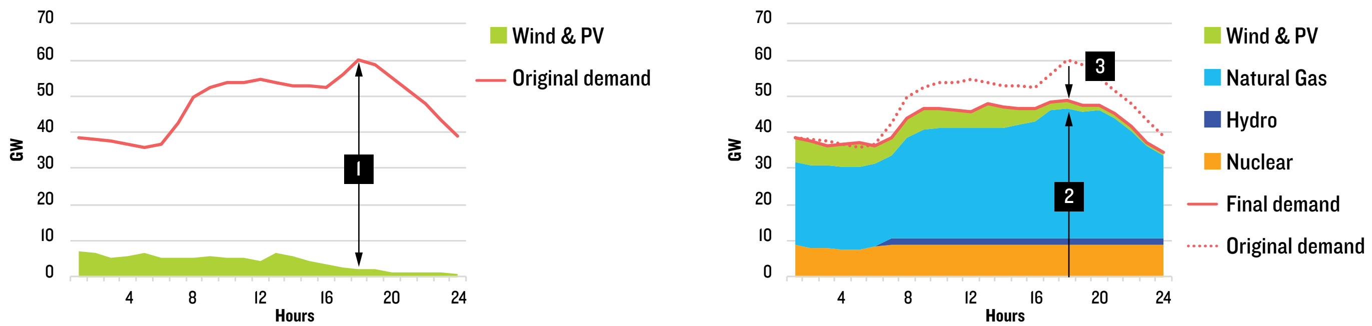
Government should therefore focus on delivering the mix of low-carbon generation capacity, smart resources and margin plant needed to achieve a reliable, low-carbon electricity system. It should not focus on delivering biomass. Biomass is not needed for adequacy or security, and it raises serious sustainability concerns while offering limited value in achieving deep decarbonisation of the electricity system.

Annex: reliability tests for 2020 and 2025

This Annex describes how the High Renewables scenario meets the reliability tests in 2020 and 2025. These tests are described in Section 2, while the results for the High Renewables scenario in 2030 are described in Section 3.

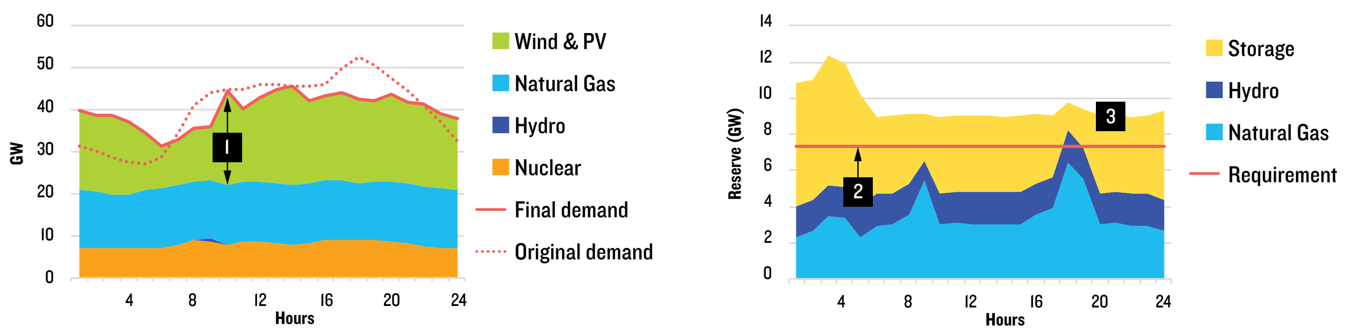
FIGURE A1. THE HIGH RENEWABLES SCENARIO MEETS THE FOUR TESTS FOR RELIABILITY IN 2020

Test 1: Adequacy is maintained with a mix of generation capacity and smart resources



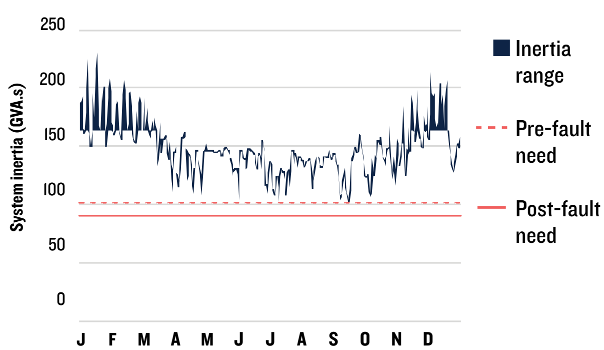
[1] Most challenging system conditions: 58 GW gap between demand and wind and solar output (Jan). [2] Nuclear, hydro and gas produce 47 GW of output. [3] Smart resources reduce generation needed by 11 GW.

Test 2: Reserve is maintained with a combination of gas, hydro and battery storage

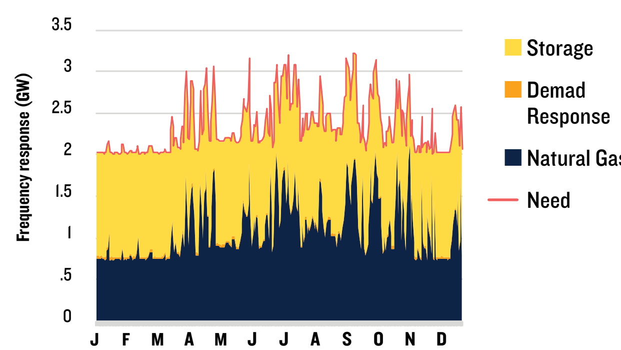


[1] Most challenging system conditions: 21 GW wind output (Apr). [2] During high wind conditions, over 7 GW of reserves are needed. [3] Spare gas, hydro and storage exceed reserve needs.

Test 3: Inertia is maintained at or above the threshold level at all times



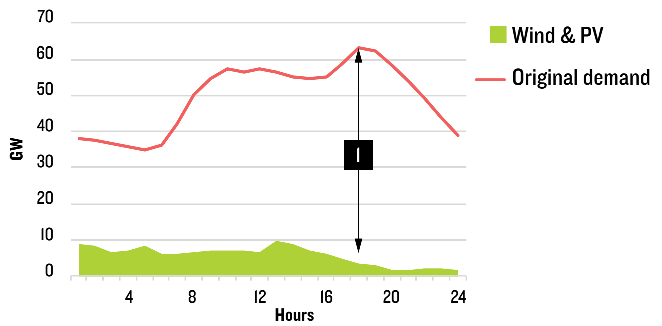
Test 4: Frequency response needs are met with a combination of gas, demand response and storage

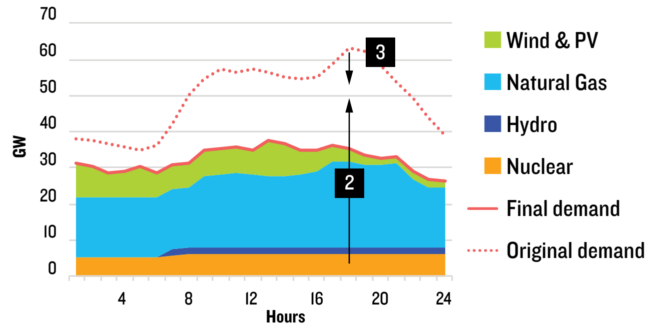


Source: Vivid Economics

FIGURE A2. THE HIGH RENEWABLES SCENARIO MEETS THE FOUR TESTS FOR RELIABILITY IN 2025

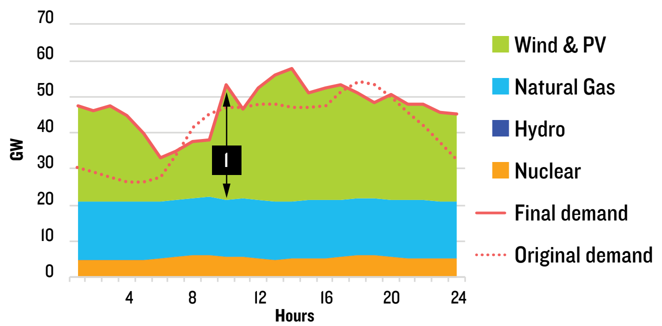
Test 1: Adequacy is maintained with a mix of generation capacity and smart resources

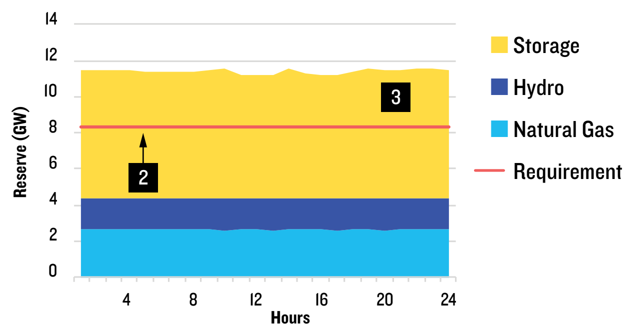




[1] Most challenging system conditions: 60 GW gap between demand and wind and solar output (Jan). [2] Nuclear, hydro and gas produce 32 GW of output. [3] Smart resources reduce generation needed by 28 GW.

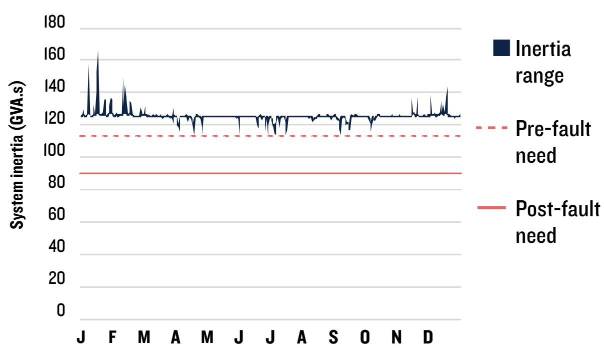
Test 2: Reserve is maintained with a combination of gas, hydro and battery storage



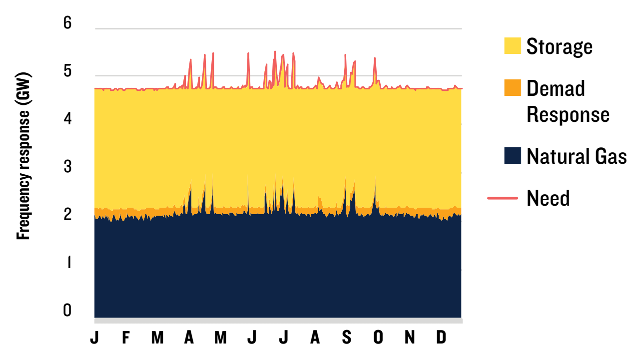


[1] Most challenging system conditions: 30 GW wind output (Apr). [2] During high wind conditions, 8 GW of reserves are needed. [3] Spare gas, hydro and storage exceed reserve needs.

Test 3: Inertia is maintained at or above the threshold level at all times



Test 4: Frequency response needs are met with a combination of gas, demand response and storage



Source: Vivid Economics

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Company Profile

Vivid Economics is a leading strategic economics consultancy with global reach. We strive to create lasting value for our clients, both in government and the private sector, and for society at large.

We are a premier consultant in the policy-commerce interface and resource- and environment-intensive sectors, where we advise on the most critical and complex policy and commercial questions facing clients around the world. The success we bring to our clients reflects a strong partnership culture, solid foundation of skills and analytical assets, and close cooperation with a large network of contacts across key organisations.