NRDC

OCTOBER 2016
IB: 16-10-A

ISSUE BRIEF

MONEY TO BURN?

THE U.K. NEEDS TO DUMP BIOMASS AND REPLACE ITS COAL PLANTS WITH TRULY CLEAN ENERGY

A new study commissioned by the Natural Resources Defence Council and conducted by Vivid Economics concludes that in the period 2020–2025, wind and solar are likely to be the least-cost way to ensure U.K. reliability of supply while also achieving power sector decarbonisation goals, not biomass.

The United Kingdom's electricity system is undergoing a major transformation. Under the Climate Change Act of 2008, the United Kingdom set ambitious climate targets, committing to reduce greenhouse gas (GHG) emissions by at least 80 percent from 1990 levels by 2050, and put significant policy support behind them. The United Kingdom also has an aging power sector and a program of scheduled retirements of all coal plants by 2025, and so needs new investment to ensure reliability of supply[i] in the period 2020–2025 and beyond.

To build new electricity capacity and meet its climate targets, the United Kingdom has relied heavily on biomass—basically any plant matter used for energy—beginning in 2013, when Drax Power completed conversion of its first boiler. To date, biomass has been a low-cost form of generation, largely because renewable energy subsidies treat the fuel as "carbon neutral." Utilities are not required to fully account for the carbon emissions associated with burning biomass for electricity, as the carbon emitted at the power plant is assumed to be reabsorbed by future plant growth. Today, biomass supplies the lion's share of U.K. "renewable" electricity generation. However, recent science shows that many forms of biomass produce more carbon emissions than fossil fuels like coal and natural gas—especially biomass from forests—increasing carbon pollution precisely when the United Kingdom aims to rapidly decarbonise its electricity sector. At the same time, the costs of building low-carbon alternatives to biomass, in particular wind and solar energy, have fallen rapidly and are expected to continue to do so.

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[i] Represents the number of hours per annum in which, over the long term, it is statistically expected that supply will not meet demand. Our modelling assumed this is three hours per year, in line with the current standard for the U.K. power system.

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: Doug Parr, Chief Scientist and Policy Director, Greenpeace UK, Mike Hemsley, Power Sector Analyst, Committee on Climate Change, and Indra Thillainathan, Senior Analyst, Committee on Climate Change.

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A new study commissioned by NRDC and executed by Vivid Economics, a London-based consultancy with expertise in U.K. energy systems, examines the economics of biomass compared with these alternatives to achieve reliability of supply and decarbonisation objectives in the U.K. over the next decade. The analysis accounts for three key costs, which together make up the total economic costs of different scenarios for power generation. These are:

1. The latest technology costs across biomass, solar, onshore wind, and offshore wind technologies[ii];
2. The cost of ensuring a reliable electricity supply; and
3. The cost of GHG emissions given the United Kingdom's legislative commitment to keeping global warming below 2 degrees Celsius—the basis for international commitments on climate change enshrined in the 2015 Paris Climate Agreement.[iii]

The study then models the total economic costs of power generation under varying assumptions about technological deployment and carbon intensity of biomass electricity, and compares those costs with the total costs of wind and solar energy.

The study concludes that in 2020, when fully accounting for the total economic cost of different energy technologies, biomass is more costly than wind and solar alternatives. Even for scenarios that do not include a full accounting of biomass carbon emissions and thus exclude their associated carbon costs, the total economic cost of biomass is comparable to or higher than that of onshore wind and solar.

In 2025, the results of the modelling indicate that wind and solar are likely to be the least-cost way to ensure U.K. reliability of supply, not biomass. A further review of cost data shows that the costs of building low-carbon alternatives to biomass, in particular wind and solar energy, have fallen rapidly and are expected to continue declining.[1,2] By contrast, biomass conversion is already a mature technology, so comparatively little capital cost reduction is expected over time; fuel costs, which make up the bulk of biomass costs, are highly uncertain; and it is now widely understood that biomass emits more carbon than coal within timeframes relevant for solving climate change.[3,4]

The United Kingdom's recent vote to exit the European Union has raised questions about the nation's commitment to its climate and renewable energy targets. However, the historic 2015 Paris Climate Agreement requires all countries—developed and developing—to make significant commitments to addressing climate change and to strengthen their emissions reduction targets over time. The world is now poised to implement an unprecedented, long-term decarbonisation agenda. An August 2016 report by the independent Energy and Climate Change Select Committee stated, "If the U.K. misses, or reneges on its commitment to [the 2020 renewables targets], this will undermine confidence in its commitment to future targets, including the 2050 decarbonisation objectives of the Climate Change Act [of] 2008."[5]

Building enough wind and solar capacity to supply the United Kingdom over the next decade will undoubtedly come with challenges, in particular zoning restrictions. However, public surveys indicate overwhelming support for renewables, such as onshore wind and solar.[6] Careful and timely planning that involves stakeholders from various perspectives and avoids obvious environmental, cultural, and community conflicts with the siting of wind and solar generation and transmission projects is both possible and necessary to success.

A MAJOR HOLE IN THE EU'S CLIMATE AND ENERGY PACKAGE

The European Commission's 2020 climate and energy package is the primary driver of investments in biomass-fueled electricity in Europe.[7] It aims to reduce GHG emissions and increase the contribution of renewable energy to the European Union's (EU) total energy consumption. The package sets three key targets for 2020: (1) a 20 percent reduction in GHG emissions from 1990 levels; (2) a requirement that 20 percent of EU energy be generated from renewable sources; and (3) a 20 percent improvement in energy efficiency. In 2009, the EU passed binding legislation to ensure it meets these targets.

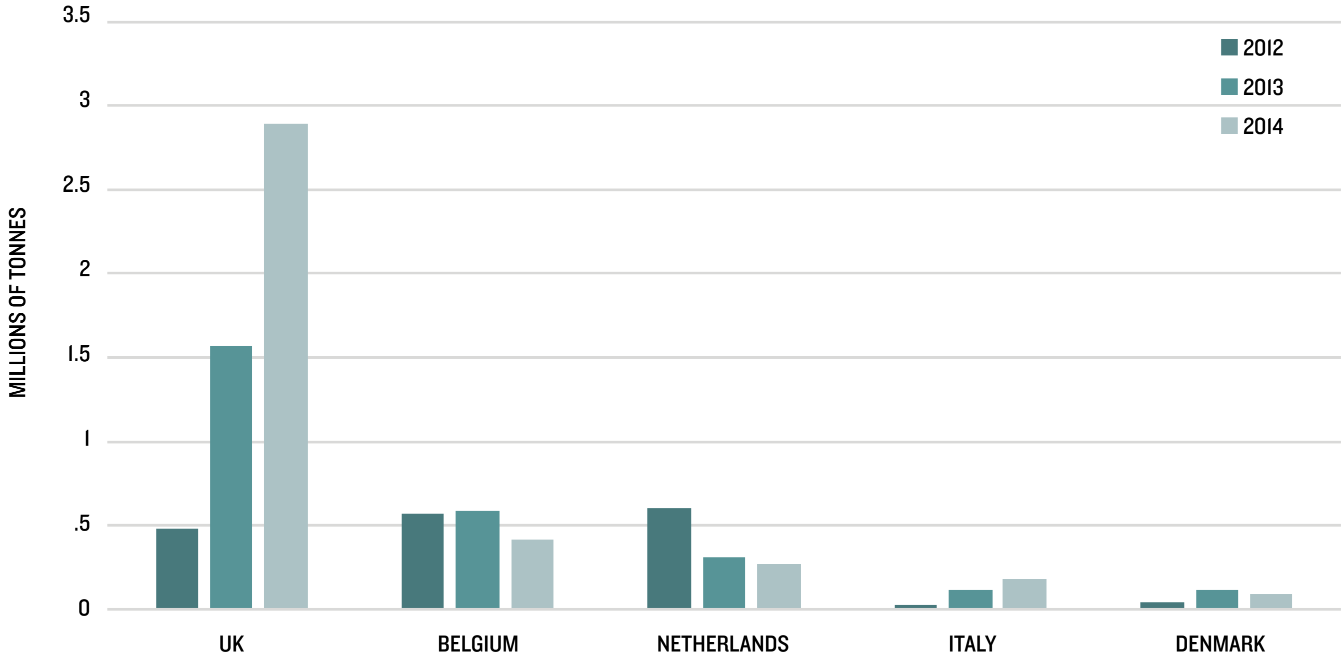
While laudable, these policies came with a gaping loophole around bioenergy: all biomass, whether switchgrass, wood chips and sawdust from a sawmill, or whole trees from old growth forests, was considered categorically "carbon neutral." As a result, when utilities in Europe burn biomass, they are not required to account for power plant emissions.

Under EU policy, member states are assigned national renewable energy targets. To meet its targets, the United Kingdom has invested heavily in biomass-fueled electricity. Biomass has played an increasing role in the United Kingdom's generation mix, more than tripling from 6.6 TWh in 2009 to around 22.4 TWh in 2015, or 9 percent of total generation.[8] These increases are predominantly due to biomass conversions of existing coal plants. One utility, Drax Power, is now responsible for 38 percent of total generation from biomass in the United Kingdom and has converted three of its coal plants to burn biomass since 2013. Drax's conversions have been financed with generous public subsidies; press analyses estimate that subsidies account for anywhere from three-quarters of the company's 2014 gross profits to potentially several times the company's 2012 gross profit after 2016.[9]

[ii] Here and throughout, the term "technology costs" includes both capital and operating costs.

[iii] See Technical Appendix for more information on how the U.K. translates its climate commitments into economic decision-making.

FIGURE 1: TOP FIVE EU 28 EXPORT MARKETS FOR U.S. WOOD PELLETS



Source: Vivid Economics based on Eurostat (2015a). International Trade cited in EC (2015) Environmental implications of increased reliance of the EU on biomass from the southeast U.S.

To feed this growing demand for biomass-fueled electricity, the United Kingdom has become the largest importer of wood pellets in the world. In 2014, almost three-quarters of all U.S. wood pellet exports went to the United Kingdom, mainly to generate electricity.[10] Figure 1 shows the top five EU export destinations for U.S. wood pellets, with the United Kingdom representing an ever-growing market.

A detailed study commissioned by the European Commission to help guide EU reforms to its climate and energy policy package post-2020 found that U.S. wood pellet imports are being sourced primarily from whole trees in southeastern forests. The report concludes that the rapidly expanding wood pellet industry poses a serious risk to biodiversity found only in the region and could undermine the EU's ability to achieve its climate targets. The study also underscores the importance of accounting for full emissions from biomass, including power plant emissions.[11]

Recent evidence—including a report from the United Kingdom's own previous Department of Energy and Climate Change (DECC)—shows that burning biomass derived from whole trees and other large-diameter wood increases carbon emissions relative to coal and natural gas for decades.[12,13] To a limited degree, the risk of biomass emissions has been reflected in some government safeguards, such as overall emissions limits on biomass. To date, however, all biomass is still considered "carbon neutral" by the government's calculations. U.K. policy only requires biomass-burning utilities to account for GHG emissions associated with the cultivation, processing, and transport of wood pellets—not the emissions produced when biomass is combusted at power plants or the forgone carbon sequestration in the forest from the additional harvest of biomass for energy production.[14]

MODELLING APPROACH, SCENARIOS, AND KEY OUTPUTS

This study seeks to evaluate the least-cost option to ensure reliability of supply and decarbonise the U.K. power system through 2025 when all economic costs are taken into account. The study models scenarios that estimate the economics of biomass and other renewable technologies (onshore wind, offshore wind, and large-scale solar photovoltaic) and compares their costs. It varies assumptions about technology costs, including fuel costs for biomass, and GHG emissions intensity in each scenario.

To conduct the modelling, Vivid Economics used the Whole Electricity System Investment Model (*WeSIM*) to compare the total economic cost of wind, solar, and biomass technologies in 2020 and 2025, including technology costs, carbon pollution costs, and the cost of ensuring reliability of supply.[15] The latter includes system integration costs (SICs), which are the costs associated with backup generation required to "firm up" wind and solar, and the costs associated with increasing the flexibility of the system to adapt to fluctuations in demand. The Technical Appendix provides a detailed description of all cost assumptions and the *WeSIM* model.

TABLE 1: BIOMASS EMISSIONS SCENARIOS

SCENARIO	DESCRIPTION	EMISSIONS ACCOUNTING	KGCO$_2$/KWH	MODELLED
1	Estimate of Drax biomass[a]	Partial accounting, including cultivation, processing, transport	122	Yes
2	U.K. emissions limits for 2020–2025[b]	Partial accounting, including cultivation, processing, transport	200	Yes
3	SELC low estimate using BEAC calculator[c]	Full emissions accounting	1,277	Yes
4	SELC customized mix using BEAC calculator[d]	Full emissions accounting	2,717	No

Sources: a. Drax (2015) Biomass Supply. b. Represents the upper limit of allowed emissions from cultivation, processing, transportation. c. Represents the low end of estimates of full emissions accounting from SELC (2015) Carbon Emissions Estimates for Drax biomass power plants in the U.K. sourcing from Enviva Pellet Mills in the southeastern U.S. hardwoods, using the BEAC model. SELC used a scenario including 17% mill residue (scenario 3), 48% fine forest residues (scenario 7), and 35% from additional hardwood harvests (scenario 13). d. SELC (2015) scenario assuming a dominant share (80%) of the feedstock is derived from additional biomass harvests in the southeastern U.S. hardwoods, with the remainder coming from sawmill or forest residues.

The study generated three biomass emissions scenarios for inclusion in the modeling analysis, based on three assumed levels of biomass carbon intensity and derived from different accounting methods, summarized in Table 1. It should be noted that the high-end emissions scenario that was modelled (scenario 3) is based on the U.K. government's Biomass Emissions and Counterfactual (BEAC) calculator and represents a conservative estimate, assuming biomass pellets are made of 65 percent forest residues. A fourth scenario, which was not modelled, also derived from the BEAC calculator, is included in Table 1 (scenario 4) to indicate the significantly higher full emissions impacts associated with biomass harvest from natural hardwood forests of the southern United States. The analysis includes a low-end, partial emissions estimate of biomass emissions based on Drax's self-reporting on the emissions profile of its wood pellets. It should be noted, however, that this estimate has been discredited.[16] The study also includes wind and solar lifecycle emissions. The Technical Appendix provides a detailed description of all emissions assumptions.

The key outputs from the analysis are:

- *Generation mix in 2025.* By comparing the generation mix in 2025 with the generation mix in 2020, the study assesses which technologies meet the requirements of the electricity system in 2025—both reliability of supply and decarbonisation[IV]—at lowest cost. Because different scenarios impact the uptake of new biomass generation, this approach shows the switching points between technologies.
- *System costs in 2020 and 2025.* Since reliability of supply challenges are greater in 2025 than 2020, the system costs are expected to be greater in 2025 than 2020.

BURNING WOOD FOR ELECTRICITY

For biomass-fueled electricity to be a lasting solution to climate change, carbon benefits must be realized within short timeframes relevant to climate policy and action. Limited categories of biomass feedstocks meet these criteria. True wood waste, such as sawdust and chips from sawmills that would otherwise quickly decompose and release carbon anyway, could be a low-carbon source for producing pellets.

However, whole trees and other large-diameter wood is a high-carbon fuel for two key reasons. First, just like coal, when trees are burned in power plants, the carbon they have accumulated over long periods of time is released into the atmosphere. However, freshly cut wood is nearly half water by weight, and that water must be boiled off before energy can be generated, requiring significant energy. This makes biomass facilities far less efficient than fossil fuel plants per ton of carbon emitted. Lower efficiency means more wood must be burned to generate the same amount of electricity, increasing carbon pollution at the power plant. Burning wood for electricity emits roughly 40 percent more carbon pollution than burning coal to produce an equivalent amount of energy.[17]

Second, if left alone, trees will continue to absorb carbon, unlike coal. Harvesting and burning trees as biomass thus not only emits a lot of carbon dioxide, but also disrupts vital carbon sinks and impedes ongoing forest carbon sequestration. Even if replanted immediately, trees take decades to reach maturity. Young trees may grow at a faster rate relative to their small existing stock of carbon than older trees, but older trees have been found to sequester more carbon from the atmosphere.[18] The emissions from biomass-fueled power plants and the lost sequestration create a large "carbon debt" that can take new trees anywhere from 35 to 100 years or more to repay—far beyond the timeframe of existing U.K. and international climate policy commitments.[19]

[iv] All technologies except wind, solar, and biomass are fixed at 2025 levels for National Grid's "Gone Green" scenario. This scenario includes coal phase-out and no new nuclear plants by 2025. See: http://fes.nationalgrid.com.

RESULTS

The modelling in this study indicates that in 2020, when power plant emissions from burning biomass and their associated carbon costs are accurately accounted for, biomass is uneconomical relative to wind and solar alternatives (see Figure 2). Even in scenarios that do not fully account for biomass carbon emissions, the total economic cost of biomass is comparable to or higher than that of onshore wind and solar. In 2025, the analysis finds that as their costs continue to fall, wind and solar are likely to be the least-cost way to ensure U.K. reliability of supply, not biomass. This holds true across all emissions scenarios examined (see Figure 3).

FIGURE 2: TOTAL ECONOMIC COSTS IN 2020

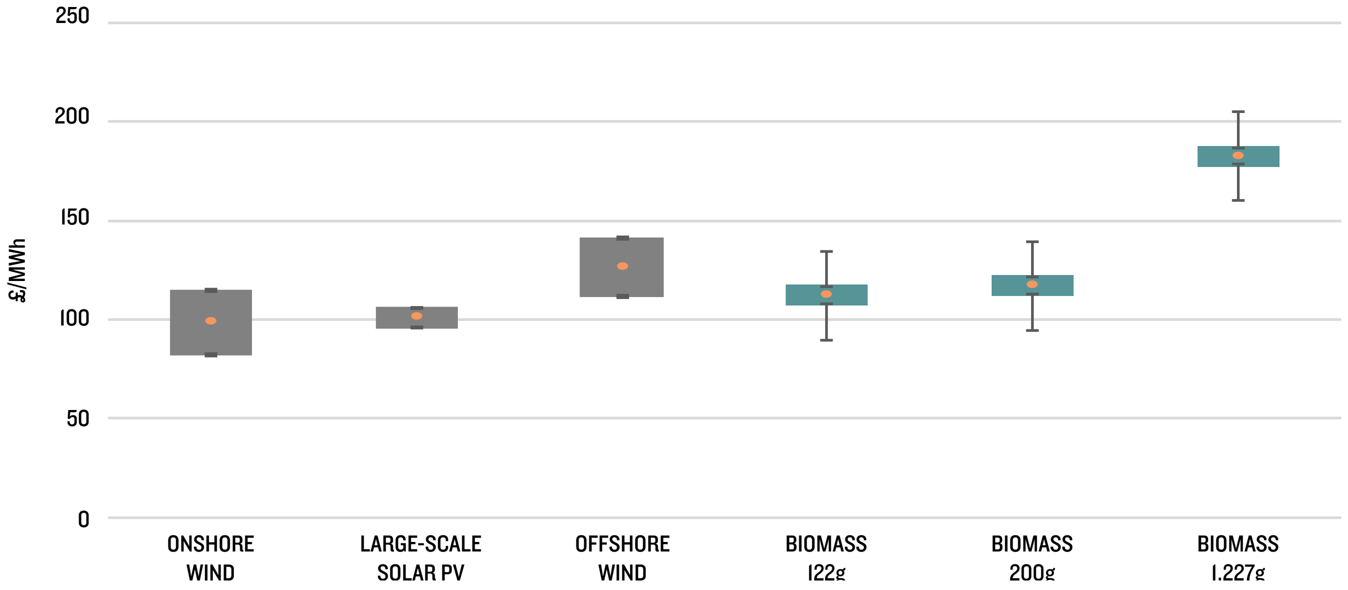
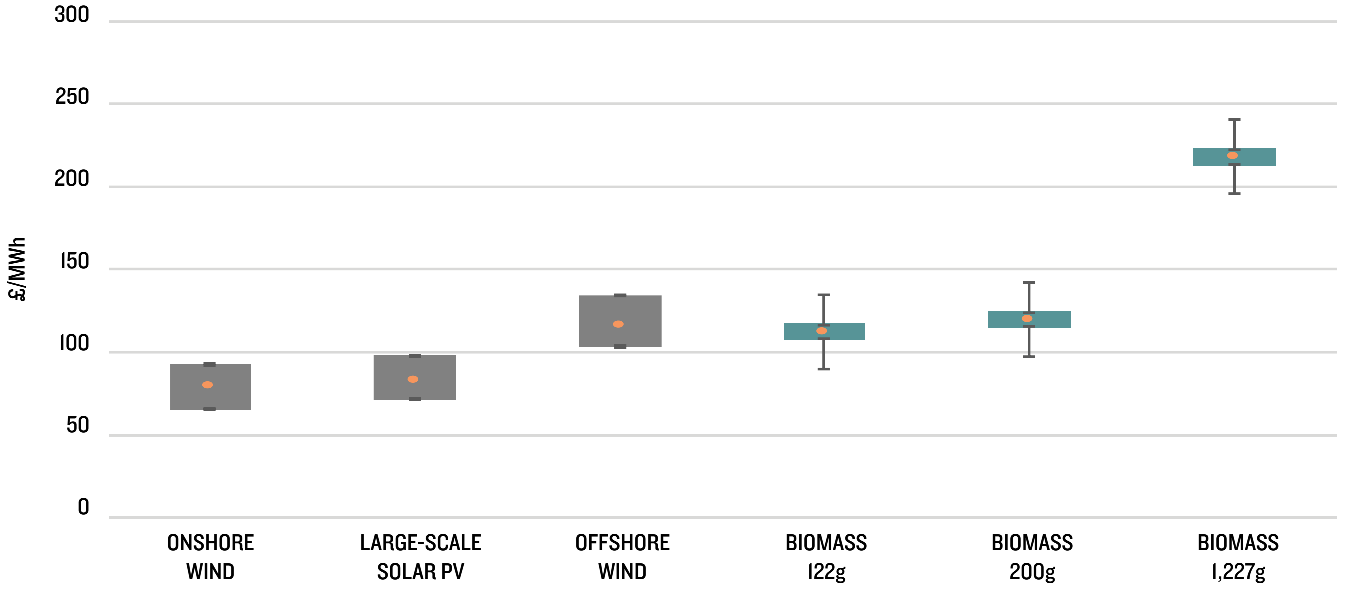


FIGURE 3: TOTAL ECONOMIC COSTS IN 2025



BIOENERGY WITH CARBON CAPTURE AND STORAGE

Carbon capture and storage in conjunction with biomass (BECCS) has been proposed as a means to achieve "negative GHG emissions." While not explicitly included in this analysis, NRDC believes that the technology for capturing, compressing, and safely storing carbon dioxide (CO_2) underground is widely demonstrated and mature, and that the practice is safe if appropriately regulated. However, we also believe that BECCS in the power sector remains an unproved climate mitigation proposition in that it suffers from the major shortcomings associated with stand-alone biomass generation—in particular when biomass is sourced from forests.

There is no scientific basis for assuming that BECCS can deliver negative emissions after full emissions accounting for biomass in the power sector. 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.[20] This "forgone sequestration" from additional biomass harvest in the forest creates a lasting carbon debt.[21]

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.[22] 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).

CONCLUSION AND DISCUSSION

U.K. policymakers and utilities are seeking to address reliability of supply and decarbonisation objectives for the power sector in 2025 at the lowest cost. To date, biomass has been wrongly assumed to be a low-cost source of electricity, largely because the U.K. bioenergy strategy has omitted critical components of full biomass emissions accounting—most notably, power plant emissions.

This study assessed the total economic costs of different scenarios for power generation, including technology costs, system integration costs, and carbon costs. It then modeled the total economic costs of power generation under varying assumptions about technological deployment and carbon emissions impacts of biomass electricity and compared them with the total costs of wind and solar energy.

Based on the results of this modelling, the study concludes that wind and solar are likely to be the lowest-cost technologies to ensure the reliability of U.K. electricity supply in the period 2020 to 2025. In 2020, when biomass power plant emissions are accurately taken into account, biomass is more costly than wind and solar alternatives. Even for scenarios that do not include a full accounting of biomass emissions, costs of biomass are comparable to or higher than those of onshore wind and solar. In 2025, wind and solar are likely to be the least-cost technology mix to ensure U.K. reliability of supply across all emissions scenarios examined, not biomass.

For biomass to be a lower-cost investment than wind and solar in 2020 and 2025, wind and solar would have to be at the upper bounds of their costs, and biomass costs would have to be low and remain so. In addition, biomass would have to produce very low GHG emissions. While not a direct output of the modelling conducted for this study, an examination of the latest and most robust cost data indicates all three conditions are unlikely to be met for the following reasons.

The most recent data suggests that onshore wind and solar projects are already contracted at the lower end of the range of 2020 cost assumptions in this study, giving confidence that these costs could materialize for future projects. Recently, the United Kingdom's National Audit Office published its 2016 cost projections for wind and solar, suggesting that costs could fall even further than the projections cited above and assumed in this analysis.[23]

At the same time, the potential for biomass technology costs to fall is limited. Biomass conversion is a mature technology, so comparatively little capital cost reduction is expected over time. Further, the bulk of biomass costs are fuel costs. By contrast, wind and solar consume no fuel and have minimal operations and maintenance costs. The majority of costs associated with building wind and solar projects are capital costs of construction. As a result, even significant reductions in capital costs would have a smaller impact on the overall cost of biomass than capital cost reductions in wind and solar.

Biomass fuel prices are also uncertain given the immaturity of the market and because international competition is likely to increase in the coming decades. There is no established spot or futures market for biomass, and trade is done via bilateral contracts. To reduce risk, generators have entered into joint ventures with pellet suppliers. In the future, investment in new capacity for biomass import terminals and associated infrastructure, as well as maturing supply chains, may lead to lower prices. However, increased demand for biomass fuel over time will tend to increase prices.

Finally, if wood pellets are made from whole trees—even in relatively small proportions—their carbon emissions will rival or exceed fossil fuel emissions for more than five decades. The emissions risks associated with biomass are therefore too big to be ignored. There is now ample evidence that the wood pellets currently burned in U.K. power plants far exceed government emissions thresholds.[24] Biomass emissions higher than the government limits would make it very costly to meet carbon budgets, as it would require investment in other more expensive emissions abatement measures to proceed.

RECOMMENDATIONS

Wind and solar energy are the cheapest, cleanest, and fastest-deploying technologies to replace coal. U.K. policymakers seeking to achieve the dual objectives of reliability of supply and power sector decarbonisation should invest in lower-cost wind and solar energy and not plan to replace retired coal plants with expensive and dirty biomass conversions. Policymakers should also reduce existing subsidies for biomass, strengthen sustainability requirements for biomass sourcing, reform the carbon accounting system for biomass to require accounting for power plant emissions and forgone carbon sequestration in the forest, and place an overall cap on biomass for energy to reflect the limited supplies of truly sustainable low-carbon sources.

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TECHNICAL APPENDIX

Prepared for the Natural Resources Defense Council
by Vivid Economics

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1 Introduction

This technical appendix supports the Natural Resource Defense Council's issue brief on the economics of coal phase-out in the UK without biomass. This document contains:

- a briefing on the modelling assumptions, authored by Vivid Economics; and,
- a detailed description of the *WeSIM* model employed by this study, authored by Imperial College.

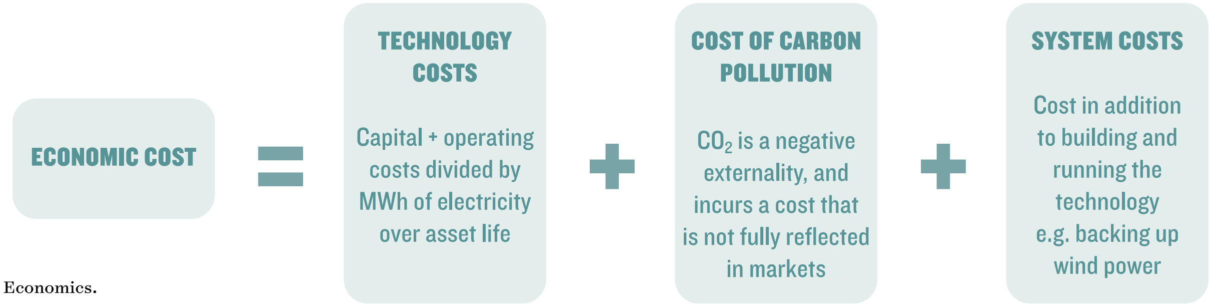
2 Modelling assumptions

2.1 Technology cost assumptions

Levelised cost assumptions

The most common way of comparing the costs of electricity generation technologies is using the levelised cost metric. Levelised costs are calculated over the lifetime of the plant, and are annualised capital and operating costs divided by MWh of electricity that it is expected to generate over its lifetime. However, from the perspective of government interested in making decisions in the best interests of society, it is important to take account of externalities which are omitted from the levelised cost metric. Two key externalities are important: carbon costs and the system integration costs. From the government's perspective, it is therefore total economic cost which is important, including levelised costs, carbon costs and system integration costs (SICs) as set out in Figure 1.

FIGURE 1: THE FULL ECONOMIC COST INCLUDES LEVELISED COST, CARBON COST AND SYSTEM LEVEL COSTS



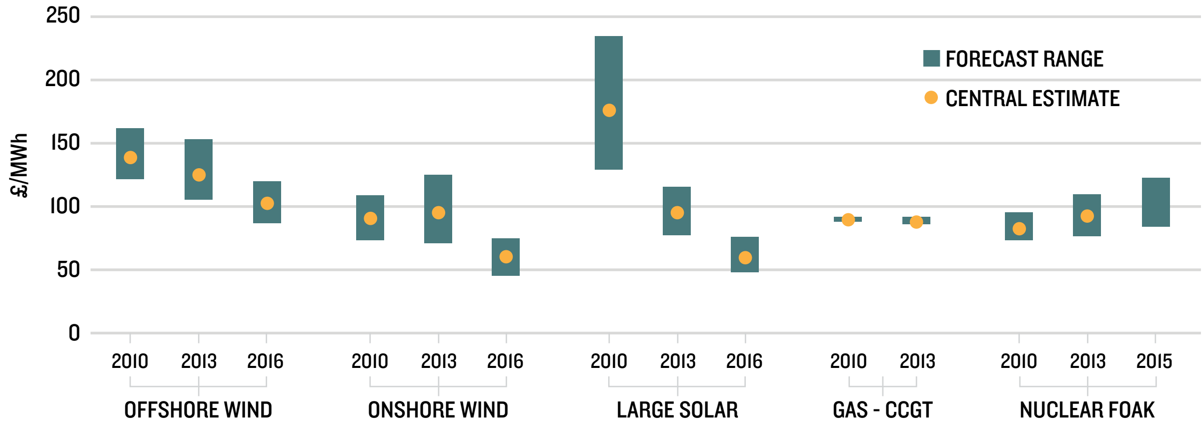
Source: Vivid Economics.

Levelised costs of variable renewables—onshore wind, offshore wind and solar—have fallen substantially in recent years, with scope for further reductions in future:

- *Solar:* The costs of solar panels have fallen sharply over the last decade, and it is now one of the most cost effective low-carbon generation technologies. Solar module costs have fallen around 65 per cent over the last two years alone, and appear to be falling at around 20 per cent for every doubling of capacity (IRENA, 2016a).
- *Onshore wind* is already one of the most cost-competitive low carbon technologies, and costs are falling globally from cheaper turbine prices and higher output (IRENA, 2016b). In the UK, deployment of onshore wind is ultimately limited by site availability.
- *Offshore wind:* In the UK, costs have been falling in recent years as a result of larger turbines and other improvements (Catapult, 2015). Opportunities exist for further cost reduction in line with achieving £100/MWh or below in the 2020s.

A recent report by the National Audit Office (NAO, 2016) shows that the Government's cost projections have been falling rapidly since 2010. Figure 2 below shows the UK Government's estimates for costs in 2025 in 2010, 2013 and 2016 on a falling trajectory. In comparison the costs of gas and nuclear have stayed flat or even increased.

FIGURE 2: THE UK GOVERNMENTS' ESTIMATE OF 2025 LEVELISED COSTS HAS BEEN FALLING



NOTES
1. Figures in 2014 real prices.
2. Levelised costs exclude the wider system and external costs typically associated with intermittent generation.
3. FOAK: First of a kind.

Source: National Audit Office analysis on data from: Department of Energy & Climate Change, *Review of the generation costs and deployment potential of renewable electricity technologies in the UK*, October 2011; *Electricity Generation Costs*, October 2012; *Electricity Generation Costs 2013*, July 2013; *Review of Renewable Electricity Generation Costs and Technical Assumptions*, March 2016.

Note: Figures are in 2014 real prices. FOAK = First of a kind.

Source: National Audit Office (2016) Nuclear Power in the UK.

Biomass conversion, by contrast, is a mature technology and comparatively little cost reduction is expected. The potential for costs to fall in the future is limited, as biomass in the power sector relies on existing combustion techniques that are already achieving high efficiencies. Notwithstanding this, there is some potential for cost reduction through the improvement in the level of competition—moving from the Renewables Obligation (RO) to the Contracts for Difference (CfD) auction mechanism. The cost structure of biomass conversion is also different to that of wind and solar, comprised of around 60-70 per cent fuel costs. Renewables consume no fuel and as a consequence, have minimal operations and maintenance costs. The majority of the costs associated with building renewable energy projects are capital costs of construction. As a result, even significant reductions in capital cost would have a smaller impact on overall cost of biomass than capital cost reductions in wind and solar. Summarising the literature on biomass generation costs:

- Estimates from DECC (2013) are in the range of £108-114/MWh, based on a capacity factor of 65 per cent. Costs are denominated in real 2012 prices, for ease of comparison to the DECC (2013) reference. A discount rate of 10 per cent is assumed.
- CCC (2016) estimates biomass costs at £87/MWh, based on the likely costs of plant proceeding under the RO.

These costs include both capital and operating costs, and fuel costs. In this study we adopt a range for technology costs that spans those in the literature, using sensitivities that account for uncertainty in both technology costs and fuel costs.

- *Central estimate:* we take the DECC (2013) value but increase the capacity factor to 90 per cent, so that the capacity factor assumptions are more in line with recent generation profiles (Table 1).
- *Technology cost sensitivity:* technology costs vary by +/-30 per cent, broadly consistent with comparable studies (for example, CCC, 2010 assumed +/- 25 per cent on capital costs), but accounting for some additional uncertainty as these technology costs have not yet been subjected to a competitive procurement mechanism such as the CfDs.
- *Fuel cost sensitivity:* A central value from the literature is around £8.5/GJ, with a range of around +/-17 per cent, and kept flat over time. In this study we adopt the central value of £8.5 kept flat over time, with a sensitivity of +/-20 per cent to encompass the range in the literature (Table 2).

As described above, while the majority of biomass costs are fuel costs, wind and solar costs are largely comprised of upfront capital costs.

TABLE 1: BIOMASS CAPACITY FACTORS

YEAR	CAPACITY FACTOR (PER CENT)
2015 1st quarter	89
2015 2nd quarter	88
2015 3rd quarter	75
2015 4th quarter	88
2016 1st quarter	96

Source: DECC (2016).

TABLE 2: BIOMASS FUEL COSTS

YEAR	AUTHOR	SCENARIO	CURRENT (£/GJ)	FUTURE (£/GJ)	NOTES
2010	E4tech	Central	7.40	7.40-8.50	"Values for new contracts and the spot market in 2020 are most likely to be found in the Central to High region of the [current] price ranges"
		Low	6.40	-	
		High	8.50	-	
2011	CCC and DECC	Central	-	7.80	"We expect biomass prices to rise significantly beyond 2030 as emissions constraints tighten"
		Low	-	6.80	
		High	-	9.10	
2011	AEA	Central	8.30	-	"In the base case wood pellet and wood chip prices rise by just under 10 per cent in real terms between 2010 and 2020, and then remain roughly unchanged"
		Low	9.40	-	
		High	11.0	-	
2013	DECC (cited in NERA, 2016)	Central	8.5	-	Back calculated from £86/MWh, assuming 65 per cent load factor from DECC 2013

Source: AEA (2011); CCC (2011); E4Tech (2010).

TABLE 3: LEVELISED COSTS ASSUMED IN THIS STUDY

TECHNOLOGY	LOW 2020	MEDIUM 2020	HIGH 2020	LOW 2025	MEDIUM 2025	HIGH 2025
Large scale solar	80	85	90	45	60	75
Onshore wind	65	80	100	50	60	75
Offshore wind	100	115	130	85	100	120

Note: Figures rounded to nearest £5/MWh. Unless otherwise noted, costs are in £2012, consistent with latest published Government estimates for all technologies.

Source: NAO (2016); CCC (2016); CCC (2015).

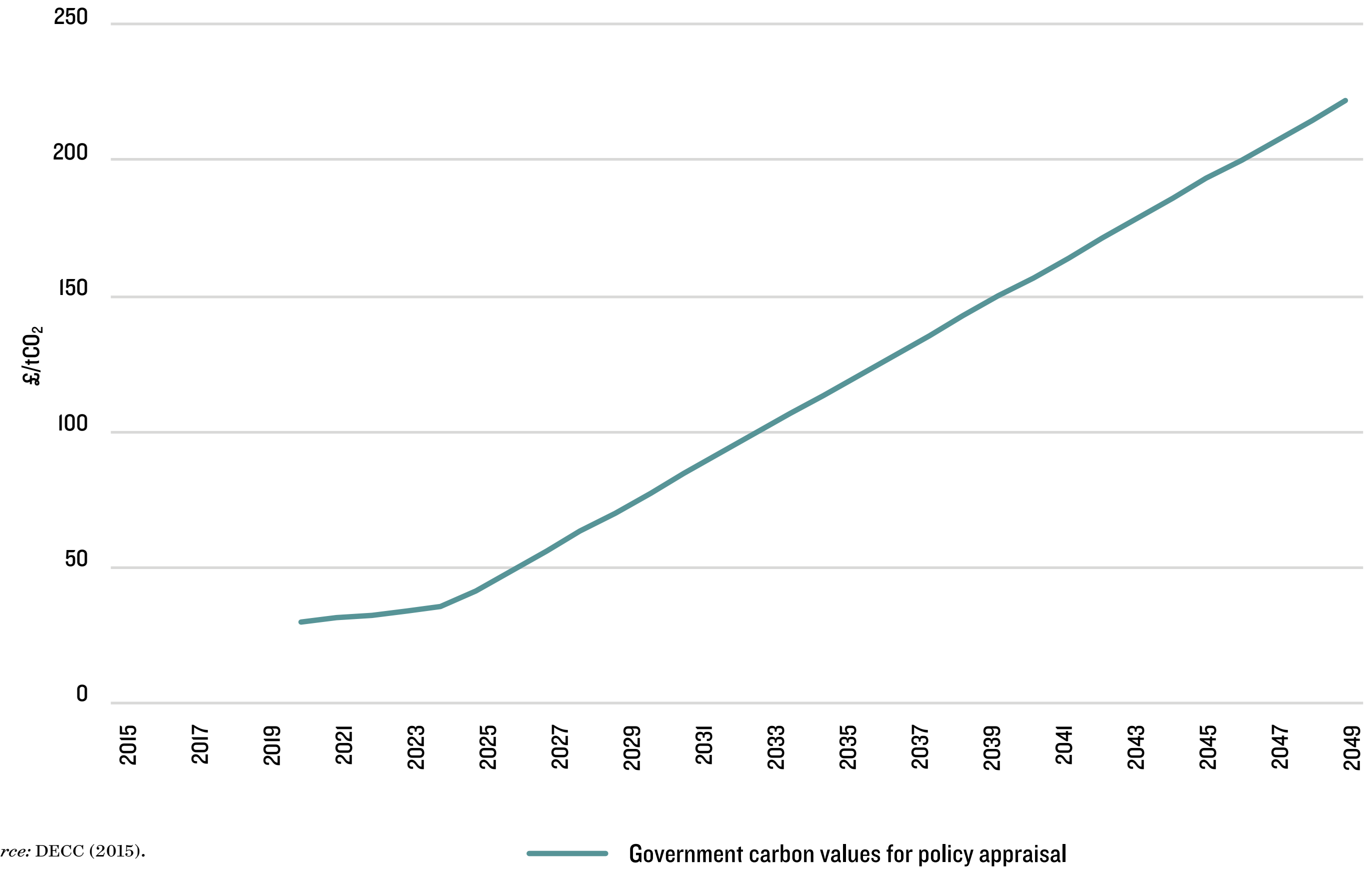
Carbon emissions costing

The UK is statutorily committed to action to reduce emissions, and this has implications for the costing of options for the power sector. The Climate Change Act commits the UK to reduce emissions by at least 80 per cent in 2050 from 1990 levels. The Act requires the Government to set legally binding Carbon Budgets. A Carbon Budget is a cap on the amount of greenhouse gases emitted in the UK over a five-year period. The first five Carbon Budgets have been put into legislation and run up to 2032.

The UK's *target consistent* carbon values serve as a way to translate the UK's commitments into economic decision-making. In order to do so, government has produced a carbon price trajectory for policy appraisal, which reflects a set of *target consistent* carbon values that reflect the cost of meeting the UK Government's domestic and international targets in the short- and long-term. These values are based on literature and modelled scenarios, and are peer reviewed by an expert panel. This study adopts this trajectory in estimating carbon values. In a central case the carbon values reach £78/tCO_2 in 2030, growing steadily to £220/tCO_2 in 2050 (Figure 3).

This study assesses three potential biomass emissions scenarios, spanning the results of different accounting methods. Our first two scenarios represent only partial emissions accounting, but are consistent with UK policy. In the UK an emissions limit on new biomass of 285 kg CO_2e/MWh, falling to 200 kg CO_2e/MWh in 2020 and 185 kg CO_2e/MWh in 2025, is based on the EU Renewable Energy Directive methodology that covers only cultivation, harvesting, processing and transport as well as direct land use change since 2008 (EC, 2009). The third emissions scenario modeled represents a low-end estimate of full emissions accounting, using the Biomass Emissions And Counterfactual (BEAC) calculator to estimate emissions from cultivation, processing, transport, as well as emissions from changes in forest carbon stocks and estimates of indirect land use change. A higher-end estimate, also based on the BEAC calculator, is presented in Table 4 for the purpose of comparison, but was not modeled. Figure 4 and its underlying text provides a diagram of the components of full biomass emissions accounting and an explanation of what is and is not included in the EU Renewable Energy Directive methodology.

FIGURE 3: CARBON VALUES USED IN THIS STUDY



Source: DECC (2015).

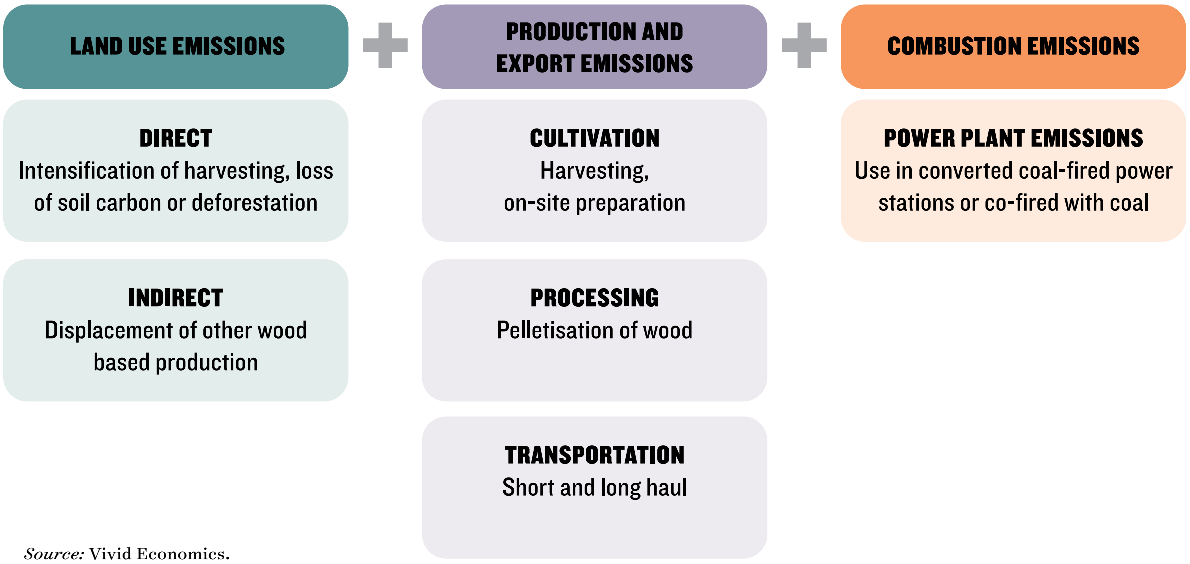
TABLE 4: EMISSIONS LEVELS ASSUMED IN THIS STUDY

EMISSIONS SCENARIO	GCO_2/KWH
Estimate of Drax biomass (partial accounting)	122
UK emissions limits for 2020-20252 (partial accounting)	200
SELC low estimate – using BEAC calculator (full emissions accounting, low-end estimate)	1277
SELC customised mix – using BEAC calculator (full emissions accounting, high-end estimate, not used in cost modelling)	2677

Source: Drax (2015); SELC (2015).

Notes: UK emissions limits represent the upper limit of allowed emissions from cultivation, processing, transportation. SELC low estimate represents the low end of estimates of full emissions account from SELC (2015). SELC used a scenario including 17 per cent Mill residue, 48% per cent Fine forest residues and 35 per cent from Additional hardwood harvests. SELC customised mix scenario assuming a dominant share (80 per cent) of the feedstock is derived from additional biomass harvests in the Southeastern U.S. hardwoods with the remainder coming from sawmill or forest residues.

FIGURE 4: COMPONENTS OF FULL BIOMASS EMISSIONS ACCOUNTING



Source: Vivid Economics.

The Renewable Energy Directive lifecycle accounting (LCA) methodology requires only partial emissions accounting for biomass. This includes the emissions from the cultivation, harvesting, processing and transport of the biomass feedstocks. It also includes direct land use change where the land use has changed category since 2008, e.g. from forest to annual crop land, grassland to annual crop land. However, this accounting methodology does not account for changes in the carbon stock of a forest, foregone carbon sequestration of land, or indirect impacts on carbon stocks in other areas of land, which are necessary for full biomass emissions accounting. According to the Department of Energy & Climate Change's 2014 report, *Life Cycle impacts of Biomass Electricity in 2020*, these CO_2 fluxes can be significant. The report finds, "Recent reports have shown that the above factors omitted in the Renewable Energy Directive LCA methodology can have significant impacts on the total GHG intensities of some types of bioenergy feedstocks, and therefore need to be considered if we wish to understand the true GHG intensities of different bioenergy feedstocks and technologies".

System integration costs

The replacement of firm capacity with intermittent technologies creates a negative externality at the system level – *System Integration Costs* (*SICs*). SICs are the costs of backup generation to supplement wind and solar generation during periods of lower generation, as well as the costs associated with increasing the flexibility of the system to adapt to fluctuations in supply and demand. Previous studies of SICs in the UK context have shown that these can add around 10 per cent to the cost of variable renewables such as wind and solar (NERA, 2015). In this study we incorporate the full costs of meeting reliability of supply through the inclusion of SICs. We adopt the values in the NERA (2016) for 2020 and 2025, which also use the *WeSIM* modelling framework used in this study.

Table 5 shows the system integration costs from providing backup and flexibility to variable renewables, with the final column showing how high system costs could be in a world where the emissions constraint on the power sector was binding and other zero carbon plant had to be built to compensate for the higher emissions of biomass. We however choose conservatively not to include these higher levels of system costs in our analysis. These figures are all outputs of the *WeSIM* model developed by Imperial College to estimate these costs; a summary of their modelling approach can be found later in the Appendix.

TABLE 5: SYSTEM INTEGRATION COSTS

TECHNOLOGY	£/MWH IN 2020	£/MWH IN 2025	2025 IF POWER SECTOR EMISSIONS ARE CONSTRAINED
Large scale solar	9	14	25-37
Onshore wind	16	18	17-22
Offshore wind	8	15	17-22
Biomass	1	-3	46-98

Note: System costs. Blue columns are the values adopted in this study. The right hand column shows the risk of higher system costs if the power sector emissions path is constrained.

Source: NERA (2016) and Imperial College modelling for this study.

The system integration costs estimated in the NERA (2016) report and used in this study arise from:

- *Backup capacity costs:* with any generation technology there is a risk that a plant will be unable to produce electricity some of the time. For this reason, electricity systems need ‘back-up’ capacity to reduce the risk of a shortage. Intermittent technologies like wind and solar have a much greater risk than conventional technologies of not being available when needed. As a consequence, they require more back-up capacity to meet demand.
- *Increased balancing costs:* these arise due to a need for operating reserve driven by the intermittency of renewable generation technologies, or the result of the generation pattern associated with a given technology.
- *Transmission costs:* these are costs associated with reinforcement of transmission and distribution networks. Generators are likely to face higher transmission charges in more remote locations. Distribution and Transmission Network Use of System Charges (DUoS and TNUoS) seek to charge generators in different places and of different technologies a price for network access reflecting the marginal cost these assets impose on the networks.
- *Cost of achieving a level of carbon emissions:* these are the costs associated with additional low-carbon capacity in order to compensate for increased emissions associated with higher system balancing requirements.

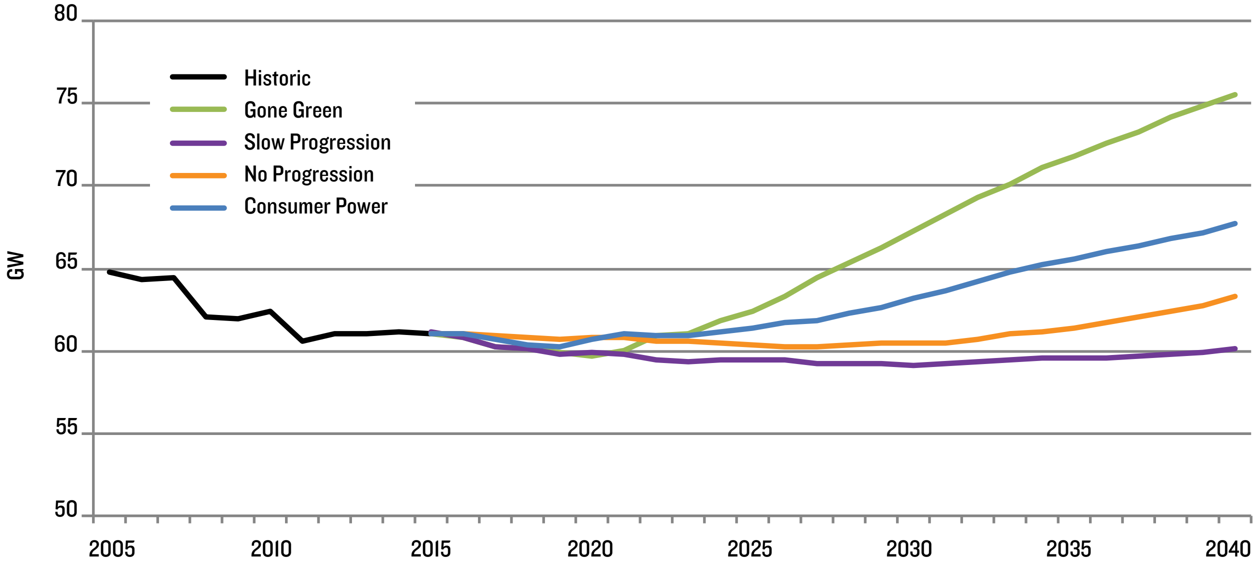
System costs are estimated relative to a benchmark technology, assumed here to be nuclear power. Nuclear is used as a benchmark as it has relatively low system integration costs but also has low carbon emissions. Any technology can in principle be used as a benchmark.

Previous studies of the system integration costs have not included estimates for the full emissions of biomass. When these emissions are included, a new category of system costs arises. This is because the emissions associated with biomass, similar to the addition of other high-emissions generation sources, force the whole electricity grid to compensate with additional emissions reduction technologies (and associated) costs to ensure total emission coverage towards 100 g/kWh in 2030. We use the trajectory to 2025 suggested by the CCC as consistent with meeting the legislated carbon commitments at the whole-of-economy level. Although these power sector specific reductions are not legislated, if they were to be mandated, and to include lifecycle emissions similar to those in Table 4, then biomass emissions would force the construction of significant additional zero carbon plant by 2025 in order to compensate for the higher emissions from biomass.

2.2 Demand assumptions

For both demand and capacity assumptions we assume development along the lines of the Gone Green scenario as developed by National Grid in their analysis of possible futures for the UK electricity system. The Gone Green scenario represents a future in which the renewable energy target for 2020 and CO_2 reduction targets for 2020, 2030 and 2050 are all met. We have conservatively chosen this scenario as it is the most favourable to biomass due to the higher peak demand and therefore requirement for firm generation. To fully test whether the system can cope without further biomass, the Gone Green scenario will test the potential to fill the capacity gap with wind and solar.

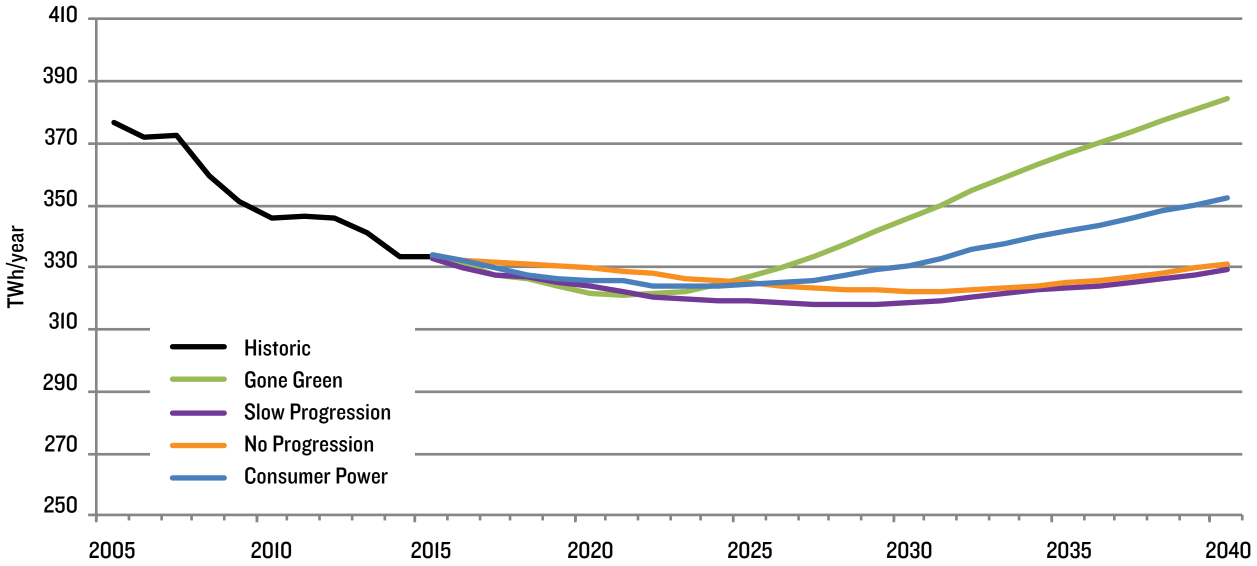
FIGURE 5: PEAK DEMAND ASSUMED IN NATIONAL GRID'S GONE GREEN SCENARIO VERSUS ALTERNATIVES



Source: National Grid (2016).

Demand in the Gone Green scenario is 322 TWh in 2020, rising to 327 TWh in 2025. Peak demand is 59.7 GW in 2020 rising to 62.4 GW in 2025. This level of demand is relatively similar to other scenarios in 2025, as shown below in Figure 6. The demand trajectory for Gone Green rises substantially following 2025 due to increasing penetration of electric vehicles and heat pumps.

FIGURE 6: ELECTRICITY DEMAND PROJECTIONS ASSUMED BY NATIONAL GRID



Source: National Grid (2016).

2.3 Capacity assumptions

In order to assess whether biomass is required to meet reliability of supply in the period 2020 to 2025, we conducted model runs which begin with a specified capacity mix in 2020 and then solve for the cheapest mix of technologies to meet demand in the period to 2025. Given the requirement to meet a declining emissions trajectory (from above 250 g/kWh in 2020, to 146 g/kWh in 2025, on a path to less than 100 g/kWh in 2030) we constrain the ability for high carbon power sources to be constructed to meet the capacity gap (that is, gas, oil, coal). We also fix other low carbon technologies such as tidal and hydro at the levels expected under National Grid's Gone Green scenario for 2025 (Table 6). The model is then allowed to make up any remaining gap in capacity with the cheapest of biomass, wind or solar in the period to 2025.

Due to retirements of coal and nuclear power in the UK, there is a need for a large amount of new capacity to be built in the UK in the 2020s. We used the *WeSIM* model to optimise the UK power system and fill this capacity gap with the least cost mix of low-carbon power capacity. When left to optimise for the uptake of biomass, solar and wind, the *WeSIM* model estimated around 17 GW of solar build and 17 GW of new wind (Table 7). This level of uptake in the period 2020-2025 is within the range of what is assumed in other studies, albeit at the upper end of deployment rates that are expected to be possible:

- *Onshore wind:* Site availability, rather than build rate, is the relevant constraint here, although numerous studies suggest available onshore sites of between 20-30 GW (CCC, 2015; National Grid, 2016). Given that 12.3 GW is expected in 2020, this allows room for the remaining 7 GW required in our uptake scenario. It is also consistent with the historical installation rates of onshore wind, for example, 1.6 GW was installed (CCC, 2016).
- *Offshore wind:* The constraining factors on wind build include the rate of annual offshore build that can be achieved without the market overheating so that prices remain on a falling cost trajectory. Previous studies by the CCC suggest this rate is around 2 GW per annum or 10 GW over the period 2020-2025 (BVG, 2015). Overall, the uptake of 17 GW of wind is consistent with the upper levels in the national grid Gone Green scenario.
- *Solar:* The UK installed 3.5 GW of solar in 2015 (CCC, 2016), so the rate of solar build in the period 2020 to 2025 is of a similar level.

If these rates of renewables were not to come forward, there are other options which could be increased to rebalance. For example, studies suggest there is potential for Tidal to contribute at least 3.6 GW by 2023, and possibly higher. It is unclear the extent to which these projects would be higher cost, as there are not projects in operation that can be used for cost comparison. Pöyry (2014) suggests that a programme of 3.6 GW of tidal power could be delivered in the UK at an average cost of around £111/MWh, and that tidal would be able to produce power with low system integration costs. This is similar to the central estimate for biomass in the lowest cost of our scenarios. If biomass costs are higher than this, it is possible that the tidal programme would also be lower cost.

TABLE 6: RENEWABLE CAPACITY ADDITIONS

TECHNOLOGY	WIND	SOLAR	BIOMASS
Capacity additions 2020-2025 (GW)	16.76	17.11	0

Source: Output of modelling conducted for this study.

TABLE 7: ASSUMED CAPACITIES IN 2020 AND 2025 FROM THE GONE GREEN SCENARIO

TECHNOLOGY	2020	2025
Storage	4.2	5.5
Biomass	**3.2**	**N/A**
CCS	0	0
CHP	6.1	6.2
Gas	25.4	27.8
Coal	1.9	0
Hydro	1.7	1.8
Interconnectors	7.6	19.4
Marine	0.09	0.9
Nuclear	9	4.7
Offshore wind	**9.9**	**N/A**
Onshore wind	**12.3**	**N/A**
Solar	**16.2**	**N/A**
Other thermal	2.1	2.2
Other renewable	2.6	3

Note: Bolded technologies are not assumed - the model optimises for these.

Source: National grid (2016).

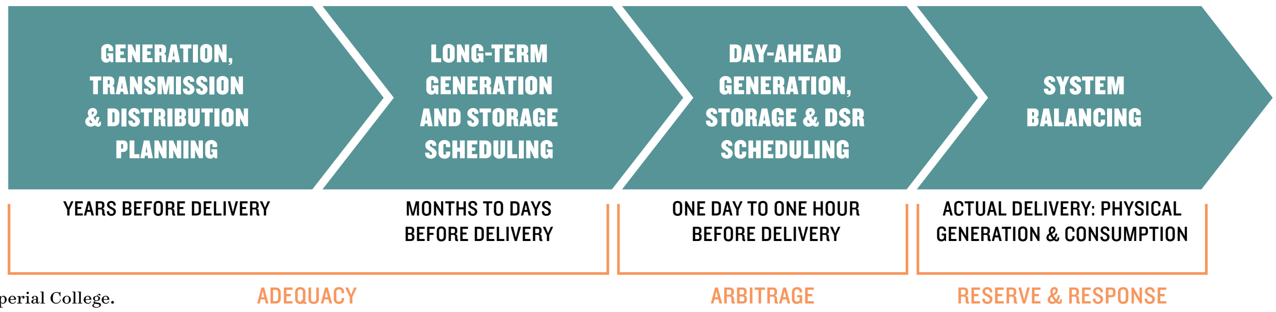
3 Whole Electricity System Investment Model (*WeSIM*)

3.1 Introduction

WeSIM is a comprehensive electricity system analysis model that simultaneously balances long-term investment decisions against short-term operation decisions, across generation, transmission and distribution systems, in an integrated fashion. When considering development of future low carbon electricity systems, including application of alternative smart flexible technologies such as demand side response (DSR), distributed energy storage, flexible network technologies and emerging designs of flexible generation technologies, it is important to consider two key aspects:

- **Different time horizons:** from long-term investment-related time horizon to real-time demand-supply balancing on a second-by-second scale (Figure 7); this is important as, for example, alternative smart technologies can impact system investment and operation cost (and carbon) performance simultaneously.
- **Different assets in the electricity system:** generation assets (from large-scale to distributed small-scale), transmission network (national and interconnections), and local distribution network operating at various voltage levels. This is important as alternative technologies may be located at different sites in the system and at different scales.

FIGURE 7: BALANCING ELECTRICITY SUPPLY AND DEMAND ACROSS DIFFERENT TIME HORIZONS



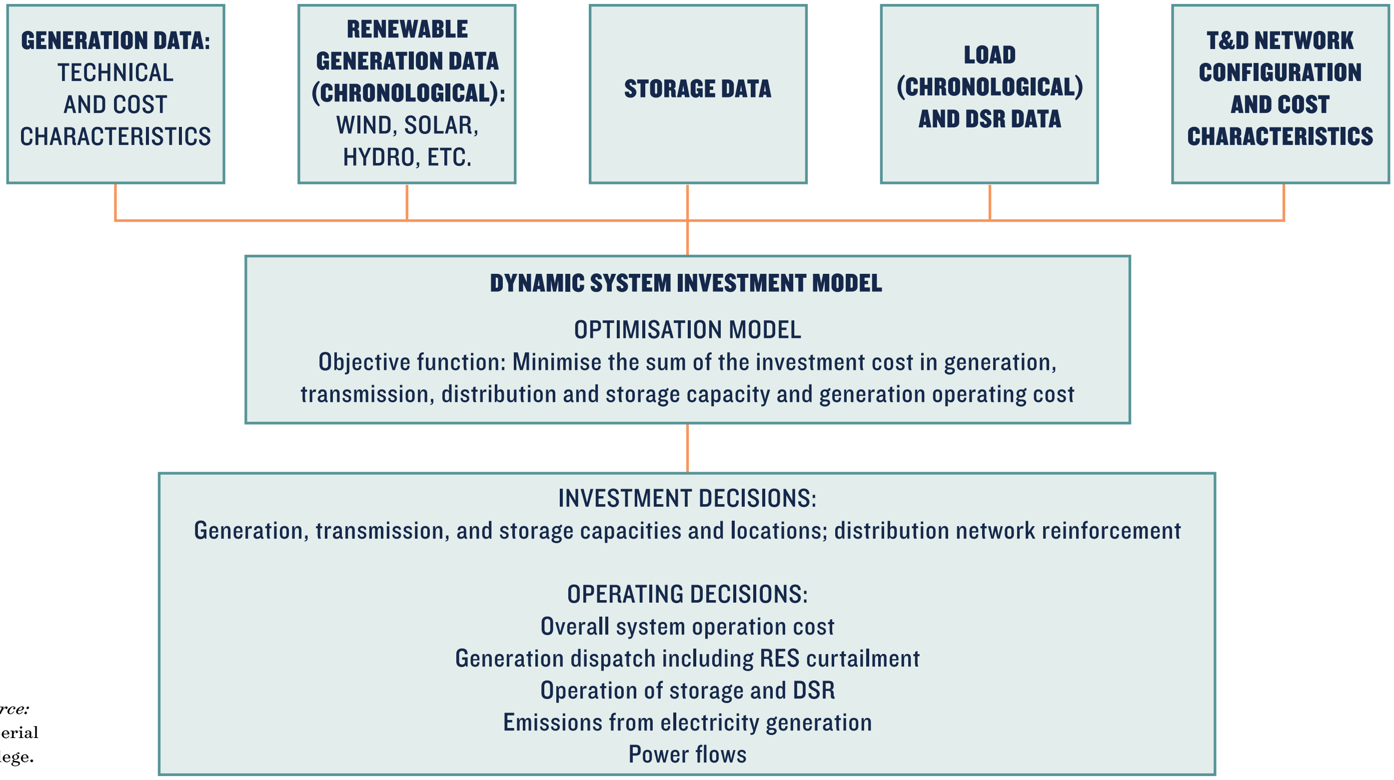
Source: Imperial College.

In this context, *WeSIM* is a holistic model that enables optimal decisions for investing into generation, network and/or storage capacity (both in terms of volume and location), in order to satisfy the real-time supply-demand balance in an economically optimal way, while at the same time ensuring efficient levels of security of supply. A key feature of *WeSIM* is in its capability to simultaneously consider system operation decisions and infrastructure additions to the system, with the ability to quantify trade-offs using alternative smart mitigation measures, such as DSR, new network technologies and distributed energy storage, for real-time balancing and transmission and distribution network and/or generation reinforcement management. The model also captures potential conflicts and synergies between different applications of distributed resources (for example DSR or distributed energy storage) in supporting intermittency management at the national level and reducing necessary reinforcements in the local distribution networks.

3.2 *WeSIM* model structure and features

WeSIM carries out an integrated optimisation of electricity system investment and operation and considers (i) short-term operation with a typical resolution of half an hour or one hour (while also taking into account various frequency regulation requirements), which is coupled with (ii) long-term investment, that is planning decisions with the time horizon of typically one year (the time horizons can be adjusted). An overview of the *WeSIM* model structure is given in Figure 8.

FIGURE 8: STRUCTURE OF *WESIM*



Source: Imperial College.

The objective function of *WeSIM* is to minimise the overall system cost, which consists of cost of investment in generation, network and enabling technologies and cost of operating the system:

- The investment cost includes capital cost of various generating technologies, the cost associated with their flexibility characteristics, investment cost of energy storage technologies, capital cost of new interconnection capacity, the reinforcement cost of transmission and distribution networks including cost of emerging flexible network technologies.
- System operating cost consists of the annual generation operating cost and the cost of interruption driven by capacity inadequacies. The model captures part load efficiency losses and generation start up costs, while taking into account dynamic characteristics of generating plant, which is a key aspect to quantifying system integration cost of renewable generation and role and value of alternative emerging enabling technologies, such as storage.

There are a number of constraints that need to be respected by the model while minimising the overall cost. These include:

- *Power balance constraints*, which ensure that supply and demand are balanced at all times.
- *Operating reserve constraints* include all forms of fast frequency regulation and reserve services needed for secure operation of the electricity system on a second by second basis. The amount of operating reserve services is a complex function of system inertia and uncertainty in generation and demand across various time horizons, driven by dynamic characteristics of different generation technologies, storage and flexible demand. *WeSIM* schedules the optimal provision of reserve and response services, taking into account the capabilities and costs of potential providers of these services (response slopes, efficiency losses and so on). This also considers alternative balancing technologies such as storage and DSR, including, for example, voltage control driven demand response, smart refrigeration / HVAC systems, interruptible charging of electric vehicles and so on.
- The share of spinning and standing reserve and response is optimised ex-ante to minimise the expected cost of providing these services, and we use our advanced Stochastic Unit Commitment model (SUC) to calibrate the amount of reserve and response scheduled in *WeSIM*. Stochastic scheduling is particularly important when allocating storage and DSR resources between energy arbitrage and reserve as this may vary dynamically depending on the system conditions.
- *Generation*: *WeSIM* optimises the investment in generation capacity while considering the generators' operation costs and CO_2 emission constraints, and maintaining the required levels of security of supply. *WeSIM* optimises both the quantity and the location of new generation capacity as a part of the overall cost minimisation. The model can limit the investment in particular generation technologies at given locations.
- *Annual load factor constraints* can be used to limit the utilisation level of thermal generating units, for example to account for the effect of planned annual maintenance on plant utilisation.
- *For wind, solar, marine, and hydro run-of-river* generators, the maximum unit electricity production is limited by the availability of resource that is location specific. The model will maximise the utilisation of these units. In certain conditions when there is oversupply of electricity in the system or reserve/response requirements limit the amount of renewable generation that can be accommodated, it might become necessary to curtail their electricity output in order to balance the system, and the model accounts for this.
- *For hydro generators with reservoirs and pumped-storage units*, the electricity production is limited not only by their maximum power output, but also by the energy available in the reservoir at a particular time (while optimising the operation of storage). The amount of energy in the reservoir at any given time is limited by the size of the reservoir. Minimum energy constraints and efficiency losses are taken into account.
- *Demand-side response constraints* include constraints for various specific types of loads. *WeSIM* broadly distinguishes between the following electricity demand categories: (i) weather-independent demand (ii) heat-driven electricity demand (space heating / cooling and hot water), (iii) transport demand and (iv) smart appliances' demand. Different demand categories are associated with different levels of flexibility. Losses due to temporal shifting of demand are modelled as appropriate. Flexibility parameters associated with various forms of DSR are obtained by using detailed bottom-up modelling of different types of flexible demand.
- *Power flow constraints* limit the energy flowing through the lines between the areas in the system, respecting the installed capacity of the network as an upper bound (*WeSIM* can handle different flow constraints in each flow direction). The model can also invest in enhancing network capacity if this is cost efficient. Expanding transmission and interconnection capacity is generally found to be important for facilitating efficient integration of large intermittent renewable resources, given their location. Interconnectors provide access to renewable energy and improve the diversity of demand and renewable output on both sides of the interconnector, thus reducing the short-term reserve requirement. Interconnection also allows for sharing of reserves, which reduces the long-term capacity requirements.

- *Local distribution network constraints* are devised to determine the level of distribution network reinforcement cost, as informed by detailed modelling of the representative UK electricity distribution networks. *WeSIM* can model different types of distribution networks, for example urban, rural, and so on with their respective reinforcement cost.
- *Emission constraints* limit the amount of annual carbon emissions. Depending on the severity of these constraints, they will have an effect of reducing the electricity production of plants with high emission factors such as oil or coal-fired power plants. Emission constraints may also result in additional investment into low-carbon technologies such as nuclear, CCS or renewables in order to meet the constraints, depending on the cost.
- *Adequacy constraints* ensure that there is sufficient generating capacity in the system to supply the demand with a given level of security. If there is storage in the system, *WeSIM* may use its capacity for security purposes if it can contribute to reducing peak demand, given the energy constraints.
- *WeSIM* allows for the security-related benefits of interconnection to be adequately quantified. Conversely, it is possible to specify in *WeSIM* that no contribution to security is allowed from other regions, which will clearly increase the system cost, but can be used to quantify the benefits of EU wide market. This market integration choice will also impact the value of alternative technologies.

3.3 System topology

WeSIM is used to assess the electricity infrastructure development and system operation within UK or EU. Different network topologies will generally be used to balance the complexity and accuracy of modelling.

Different levels of market integration can be modelled in *WeSIM* through distinctive levels of energy exchanges cross-border, sharing of security or various operating reserves, for example country, regional, EU levels. *WeSIM* optimises the generation, storage, and demand side response dispatches by taking into account diversity of load profiles, renewable energy profiles (hydro, wind, PV, CSP) across Europe, in order to minimise the additional system capacity to meet security requirements. Finally, *WeSIM* simultaneously optimises investment profile in generation infrastructure and transmission networks capacity, while meeting security and CO_2 constraints as appropriate.

3.4 Distribution network and demand-side modelling

Regarding the local distribution networks *WeSIM* uses a set of representative networks that follow the key characteristics of different type of real GB (and EU member states) distribution network. These representative networks are calibrated to match the actual electricity distribution systems.

Understanding the characteristics of flexible demand and quantifying the flexibility they can potentially offer to the system is vital for establishing its economic value. In order to offer flexibility, controlled demand technologies must have access to some form of storage when rescheduling their operation (for example thermal, chemical or mechanical energy, or storage of intermediate products). Load reduction periods are followed or preceded by load recovery, which is a function of the type of interrupted process and the type of storage. This in turn requires bottom-up modelling of each individual demand side technology (appliance) understanding how it performs its actual function, while exploiting the flexibility that may exist without compromising the service that it delivers. In our analysis we consider the following types of flexible demand:

- *Electric vehicles*. EV loads are particularly well placed to support system operation and investment, given the relatively modest amount of energy needed daily, generally short driving times, and relatively high power ratings expected for EV batteries. *WeSIM* modelling of EVs is based on statistics for light-vehicle driving patterns calibrated with the GB and EU driving data patterns.
- *Heat pumps and HVAC systems*. *WeSIM* models the patterns of thermal loads (cooling and heating) for a variety of building types and sizes covering both commercial and domestic sector, construction characteristics and insulation/energy efficiency levels, size, occupancy patterns, indoor temperature settings and outdoor temperatures (this is informed by a detailed thermal building simulation models). The heat demand models take into account hourly temperature variations, considering the temperature dependency of heat pump coefficients of performance. The modelling is then used to investigate building thermal response under different control strategies. Smart appliances. The operation of appliances is scheduled to respond to electricity system conditions (while not compromising the service quality delivered), thus potentially providing support to generation/demand balancing including provision of various types of reserve, peak reduction, and network congestion management. This also includes refrigeration appliances that can potentially contribute to providing frequency regulation services. Bottom up models are used to understand the interdependency between the level and duration of service provided and the corresponding energy payback.

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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.

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