ESO

A week in the life of a Net Zero carbon electricity system in 2035

Every year National Grid Electricity System Operator (ESO) produces our Future Energy Scenarios (FES). These scenarios explore a range of credible pathways for the development of energy supply and demand and how the UK government target of a Net Zero carbon power sector by 2035 can be met. The UK is racing towards more renewable energy supply while increasing system flexibility and ensuring stability. We need to understand how we can operate the energy system with only residual backup unabated natural gas[1] for CCGTs (Combined Cycle Gas Turbines). This will play a critical role in meeting our 2035 target. Jeremy Wardle, in the Energy Insights and Analysis (EIA) team, considers the impact of removing unabated natural gas for CCGTs from the energy mix on our dispatch modelling. Achieving this target requires revolutionary thinking about how the energy system is operated.

Executive Summary

Key insights from the scenario modelling:

- In the future, the electricity system will be supplied by a much greater share of renewable energy, increasing from 29% in 2022 to 78% in 2035 in the Leading the Way scenario
- In 2035, we expect to have flexible, supply-side technologies such as hydrogen generation (7.6GW), bioenergy (3.3GW) and storage (37.3GW) to ensure the system meets demand
- Demand Side Response (DSR) will play a significant role and the system will need to move towards a more supply-led grid, where flexible demand responds according to changes in availability of supply. This could include up to 4 million Battery Electric Vehicles (BEV's) taking part in Vehicle to Grid (V2G)[2]
- Live market reform is a significant enabler and will ensure the right market signals are in place for consumers to respond. This will allow for more responsive shifts in Demand Side Response (DSR), ensuring the system is balanced
- Operating a Net Zero carbon electricity system in 2035 will require a significant amount of negative emissions from Bioenergy with Carbon Capture and Storage (BECCS) to offset the residual CO_2e produced by the power sector, which is around 9.3 million tonnes per year in 2035, down from around 50 million tonnes today[3]. This will require 9.3 million tonnes of CO_2e storage to ensure the power sector is Net Zero carbon
- Within our Leading the Way scenario[4] in 2035, the UK electricity system can meet demand in challenging periods with no unabated natural gas generation[5]

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[1] Unabated Natural Gas use is Natural Gas combustion without the application of carbon capture and storage (CCS) technology

[2] Vehicle to grid charging enables energy to flow bi-directionally. Either from the grid into an electric car or from the electric car to the grid. The number of BEV's that would be able to use this technology are those taking part.

[3] National Grid ESO FES. (2022, July). FES 2022 Data Workbook. Retrieved from National Grid ESO: https://www.nationalgrideso.com/document/263876/download

[4] National Grid ESO. (2022, July). Future Energy Scenarios 2022. Retrieved from National Grid ESO: https://www.nationalgrideso.com/document/263951/download

[5] 2013 weather year (Average weather year), and unconstrained network.

Introduction

The ESO has a key role to play in tackling climate change by transitioning GB's electricity system to Net zero. We already operate the fastest decarbonising electricity system in the world, with an ambition for a zero carbon[6] operation for short periods by 2025. And by 2035, we want to run a fully Net Zero carbon electricity system. On the 4th January this year we operated the system with a record breaking 87.6% of electricity generation being zero carbon.

Currently, when the wind is not blowing and the sun is not shining, we rely on natural gas CCGTs, interconnectors and pumped hydro storage to ensure supply meets demand. Burning natural gas to produce electricity was the largest contributor to the generation mix at 38.5% in 2022, compared to 48.5% of zero carbon generation[7]. Therefore, it is imperative that we explore how the system will operate in 2035 to meet demand without this current reliance.

Electricity systems need to match supply and demand; we call this energy balancing. Electricity system flexibility is the ability to adjust supply and demand to achieve the balance between both[8]. Electricity needs to be moved from where it is generated to where it is required, which can be across a national transmission system. The supply and demand through the transmission system varies as we cannot perfectly predict the flow of electricity, which requires intervention to maintain balance.

Variations in demand occur seasonally, within day due to weather patterns and because of changes in the price of commodities. Variations in supply occur due to weather dependant renewable energy generation and the supply of oil, coal, and gas.

As supply and demand vary throughout the day, season and year there are fluctuations in the flow of energy meaning the system requires flexibility. Furthermore, the system balancing requirements span from a few seconds for surges in TV-pickup[9] to months as we require more energy in winter. There are different systems that provide flexibility over different timeframes to meet those requirements. The type of flexibility differs in how much energy they supply and over what timespan. For more information on the different types see our Introduction to energy system flexibility[10].

Operating an electricity transmission system also comes with challenges to ensure the stability, voltage and constraints are managed second by second. This thought piece will not cover operability in depth, but more information can be found in the operability strategy report[11].

How do we model this?

In this analysis we assessed 2035 using a 2013 weather year which we consider to be an average weather year, focussing on the fourth week of January using an unconstrained network model. An average weather year has the advantage of showing us what technologies are likely to be used regularly rather than a more extreme scenario such as a 1 in 20 weather year where a technology may only be used for a few weeks in the year.

We removed the unabated natural gas from the electricity generation mix, (only a residual was left) but still included gas generation with Carbon Capture and Storage (CCS). This explored the generation and flexibility required to achieve system adequacy. The supply capacity and demand data came out of the Leading the Way scenario from FES 2022[12] which assumes the fastest credible decarbonisation, significant lifestyle changes for consumers and a mixture of hydrogen and electrification for heating. All scenarios meet the

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[6] Zero carbon means that no carbon emissions are being produced from a product or service (for example, a wind farm generating electricity, or a battery deploying electricity).

[7] Zero carbon means that no carbon emissions are being produced from a product or service (for example, a wind farm generating electricity, or a battery deploying electricity).

[8] FES 2022. (2022, July). Flexibility. Retrieved from National Grid ESO: https://www.nationalgrideso.com/future-energy/future-energy-scenarios/flexibility

[9] National Grid ESO. (2020). TV 'pick-up' effect. Retrieved from National Grid ESO: https://www.nationalgrideso.com/news/euro-2020-and-tv-pick-effect

[10] Archie Corliss. (2020, July). Introduction to energy system flexibility. Retrieved from National Grid ESO: https://www.nationalgrideso.com/document/189851/download

[11] National Grid ESO. (2022, December). Operability Strategy Report. Retrieved from National Grid ESO: https://www.nationalgrideso.com/document/273801/download

[12] National Grid ESO. (2022, July). FES Data Workbook. Retrieved from National Grid ESO: https://www.nationalgrideso.com/document/263896/download

reliability standard set by the government - currently three hours per year Loss of Load Expectation (LOLE)[13] - but we chose this scenario because it is more heavily decarbonised by 2035 than other scenarios and meets the condition of having no unabated gas generation by the end of 2035[14]. This model then outputted hourly data for supply and demand for the entire year of 2035.

Finally, we assumed the transmission network could send power wherever it is needed, meaning that the network was unconstrained in its capacity. The impact of this is that power produced in the north of Scotland via wind turbine generation has no issue in travelling to the south of England where demand is highest. We know that this will likely over or underestimate power flows, but we focused on energy limitations to analyse how the system met demand.

Hourly modelling of supply and demand

- We modelled supply and demand on an hourly basis across the year using our dispatch model to simulate the hourly economics of all generating plants on the system, running all hours in the year sequentially, with plant, storage, and interconnector output based on least cost optimisation. The full economics of the system accounts for plant technical characteristics (min stable generation, min on/off etc.) as well as all energy storage constraints and a hydrogen system
- The model works by seeking to find the optimised way to meet demand using available generation, based on minimising total cost. It calculates the hourly electricity mix based on the demand for electricity, the installed capacities and marginal costs of the electricity producing technologies, therefore representing a merit order dispatch. The result of this calculation are the load hours for generation and the amount of excess electricity that is used by the different flexibility technologies. This provides us with an approximation of the market solution at gate closure[15] – this means before actions were taken by the system operator to ensure supply exactly meets demand
- The model analyses the impact of different weather conditions on historic residential demand[16] as well as generating renewable outputs; then heat and EV profiles are used to cater for these demands. From this data we created an hourly time series of demand using the annual value from FES and the relevant historic hourly profile according to:
  Hourly demand = (FES annual demand / 8760[17]) * hourly profile value
- This model then predicts what a future demand will look like under similar weather conditions. All electricity generation is modelled with maintenance and forced outages. This varies on a monthly or quarterly basis to allow for seasonal variations. The electricity generation output is calculated by modelling GB and Europe[18]
- Some demands in the order of price will be satisfied only if consumers are willing to pay for electricity at the current price. These are called "price-sensitive demands" and their behaviour was used to model flexible electricity demand. The model assumes that there will be live market reform, allowing the right market signals to influence Demand Side Response on an hourly basis. Further information on the modelling methods can be found in the FES Modelling Methods document[19].

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[13] LOLE is the expected number of hours when demand is higher than available generation during the year before any mitigating /emergency actions are taken but after all system warnings and System Operator (SO) balancing contracts have been exhausted. It is important to note when interpreting this metric that a certain level of loss of load is not equivalent to the same amount of blackouts; in most cases, loss of load would be managed by actions without significant impacts on consumers. The Reliability Standard set by the Government is a LOLE of 3 hours/year.

[14] Though we did remove all the remaining unabated natural gas from the rest of the year as stated earlier in this paragraph, and only left a negligible amount for security of supply reasons.

[15] National Grid. (2017, Jan). Long-term Market and Network Constraint Modelling. Retrieved from National Grid: https://www.nationalgrid.com/sites/default/files/documents/Long-term%20Market%20and%20Network%20Constraint%20Modelling.pdf

[16] This is derived from BEIS energy trends, and the Elexon 2000 metered homes residential demand. This is then weather corrected to produce a baseline annual demand for each sector in the UK. Where we have our most recent baseline annual demand for GB, we scale the sum of our residential components to match. Whatever level of scaling we use to match these values we gradually phase out over the coming years of forecast until the forecast is purely derived from our sector modelling.

[17] 8760 = number of hours in a year

[18] National Grid ESO FES. (2022, July). FES Modelling Methods. Retrieved from National Grid ESO: https://www.nationalgrideso.com/document/263871/download

[19] National Grid ESO FES. (2022, July). FES Modelling Methods. Retrieved from National Grid ESO: https://www.nationalgrideso.com/document/263871/download

Why did we choose the 4th week in January?

The winter months of the year with cold and cloudy weather often put the largest strain on the system and pose the greatest challenge for the control room to balance supply and demand. This is due to low solar conditions, and greater requirement for home heating, lighting, and indoor appliances. Furthermore, wind in the UK has variability within day, week and season. We explored every week of 2035 from the dispatch model for the Leading the Way scenario using the 2013 weather year. The weeks where the system required the most amount of flexibility to ensure system adequacy occurred in January, February, and November. We specifically chose the 4th week of January as this showed a typical winter week. The system was under the significant stress during the start of the week, and towards the end, generation had to be curtailed. This gives us a good picture of how the system reacts to large scale changes in renewable generation. Therefore, a combination of technologies were required to meet demand during this week. This was primarily due to offshore wind generation dropping from 74GW at the highest point in the week to 7 GW at the lowest point in the week. This is the equivalent of 3 million homes' electricity use for one day.

We conducted this piece of analysis with a weather year from 2013, which was a milder year, to see how the system will manage meeting demand as a Net Zero carbon electricity system. A further piece of analysis will be published later in the year looking at a more extreme weather year to see how supply will meet demand in a Net Zero electricity system. This will explore the impact of less frequent challenging weather events such as extended cold windless periods.

What does generation look like?

Thermal generation from natural gas currently provides between 10% and 50% of our electricity supply each day, depending on the weather. When there is less electricity generation from wind and solar, we rely on natural gas generation to increase output so that supply meets demand. However, when this natural gas is removed what makes up the generation mix? Figure 1 shows the transmission connected generation capacity mix for the week compared with that of 2022 January, to highlight the generation source differences. It is apparent that we have a much higher reliance on wind generation that replaces a significant amount of the natural gas generation.

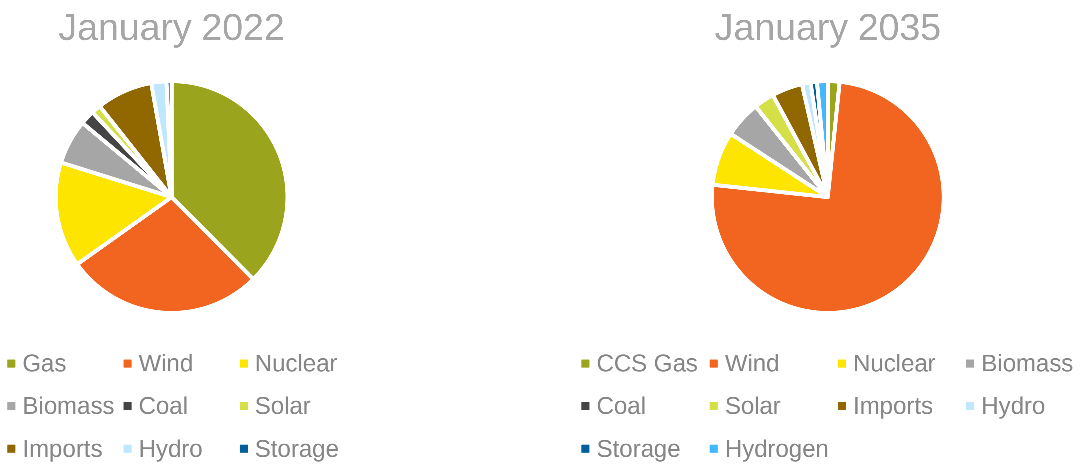

Figure 1 – Shows the transmission connected generation capacity mix January 2022 left hand side and January 2035 right hand side.

Figure 2 shows the transmission connected generation stack per hour for a typical winter week with a particularly stressed period in our model for 2035.

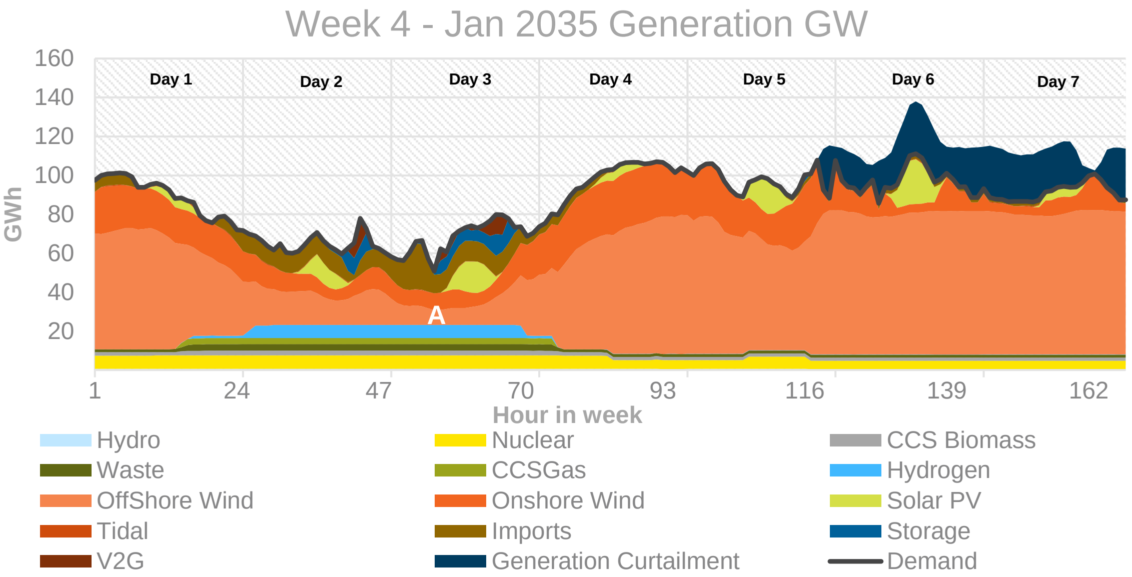

Figure 2 *– shows the transmission connected stacked generation mix for the 4th week of January in 2035 in Gigawatts. Vertical lines show days of the week. The demand line shows all total demand, which includes storage, electrolysis, exports and V2G which is considered embedded generation.*

Point A on Figure 2 shows offshore wind power drops significantly to 10.3% of week peak during day 3 morning's peak. Wind generation in the period drops from 74 to 7 GW. This is equivalent to 3 million medium size households' electricity use for 1 day. The model determined multiple supply side and demand side flexibility options to fill the gap created from the lack of wind in this week. This produced an optimum supply and demand response at each hour of the week.

Figure 3 shows a focus on the most challenging period in the week. As we move through days 1-3, we see different technologies dispatched to meet demand, these are explored in further detail on the next page. Overall, thermal generation ramped significantly during this tough period, with hydrogen, waste and CCS gas all being dispatched. These technologies are used throughout the year by the model, most weeks. Outlined on the next page is the build-up of generation through time.

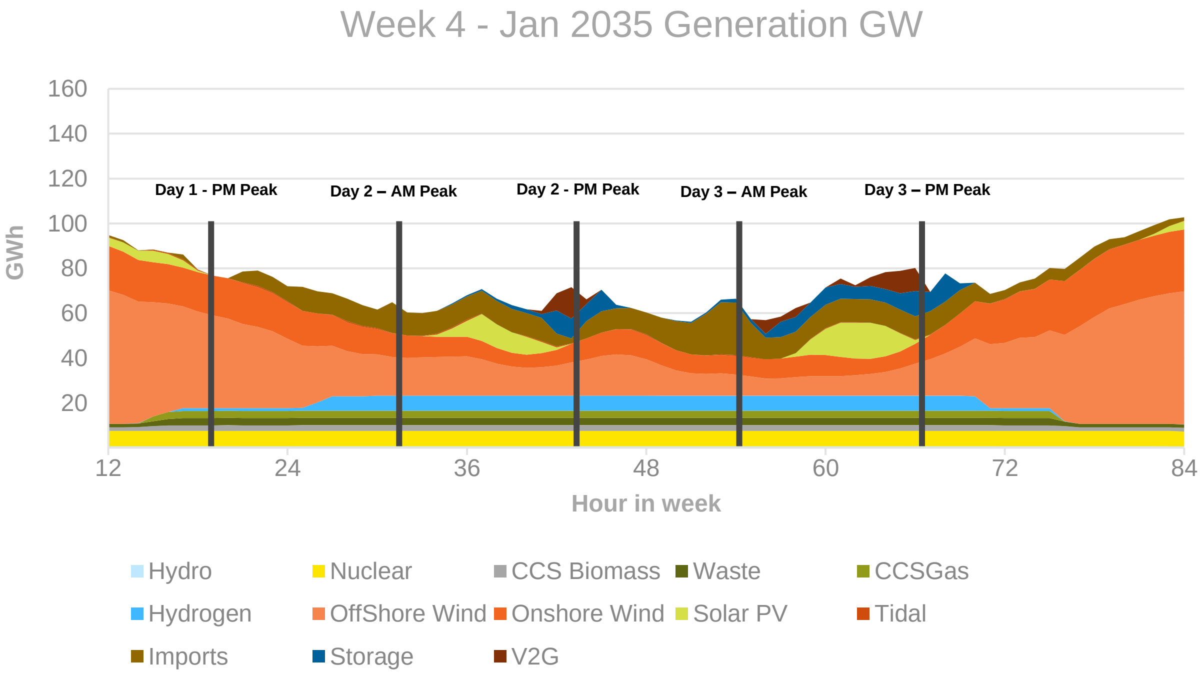

Figure 3 *– shows transmission connected stacked generation mix between midday on day 1 to midday on day 4. The vertical black lines show significant periods where dispatchable supply side generation was deployed.*

Day 1 Evening Peak

Our model dispatched simultaneously bioenergy and CCS gas to ensure that demand is met. This is quickly followed by hydrogen and then finally interconnection to meet the evening peak[20].

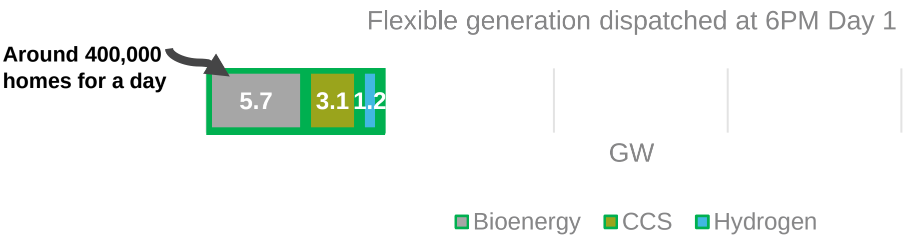

Figure 4 – Day 1 Evening Peak. Green lines show flexible generation dispatched in this hour to meet demand.

Day 2 Morning

Wind continues to drop, and more generation is required. Building on the previous generation stack more hydrogen is then dispatched. There is a greater availability of interconnection in the morning than evening in the UK. Therefore, the model dispatched interconnection here.

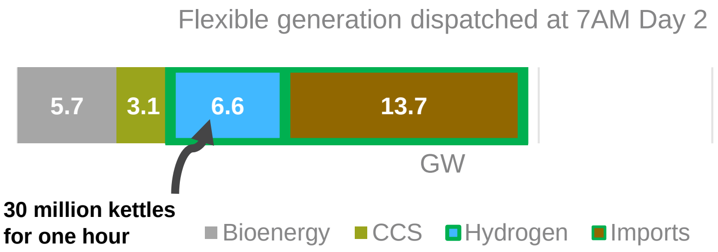

Figure 5 – Day 2 Morning[21].

Day 2 Evening

As the evening peak comes around the model decides to dispatch different technologies. There is less availability of imports in the evening compared to earlier in the day. Therefore, the model begins to dispatch storage, which will be cheaper than imports at this time. In the evening there are also more Electric Vehicles (EVs) parked at home meaning Vehicle to Grid was dispatched.

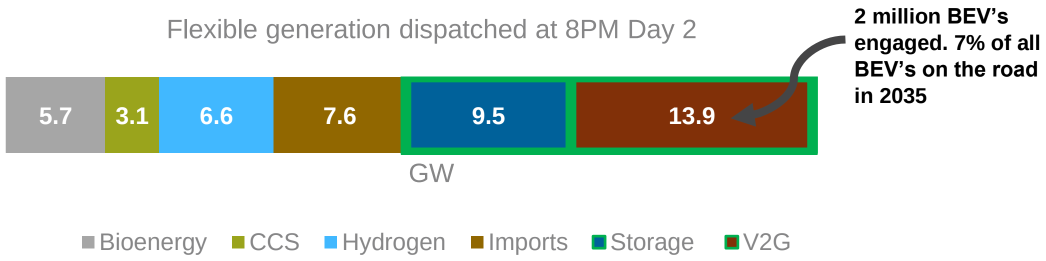

Figure 6 – Day 2 Evening[21].

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[20] The exact figures for the flexibility increase can be found in the appendix on page 16.

[21] Green lines show flexible generation dispatched in this hour to meet demand.

Day 3 Morning

Interconnection was available during the morning peak, and, with surplus from Europe, it was cheaper than dispatching storage.

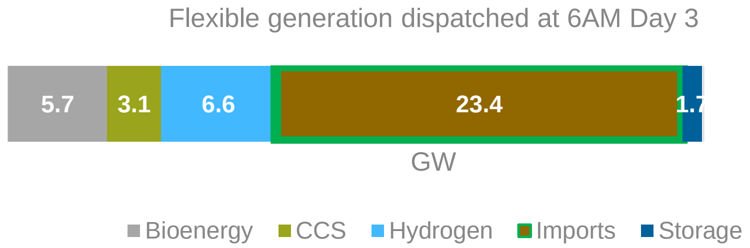

Figure 7 – Day 3 Morning[21].

Day 3 Evening

As the evening peak comes around the system is now under significant stress. With imports being more expensive than earlier in the day a combination of even more storage and V2G are required to meet demand.

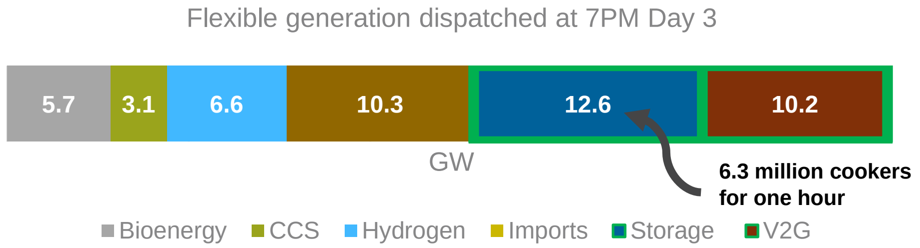

Figure 8 – Day 3 Evening[21].

1 Hour Breakdown

Now that we have seen how the system might cope during a tough period, we wanted to drill down to a 1-hour period where the renewable generation was at its lowest, shown by point A on Figure 9. This is the morning of day 3 at 9AM, with wind generation is at its week low, and all supply side technologies required to balance the

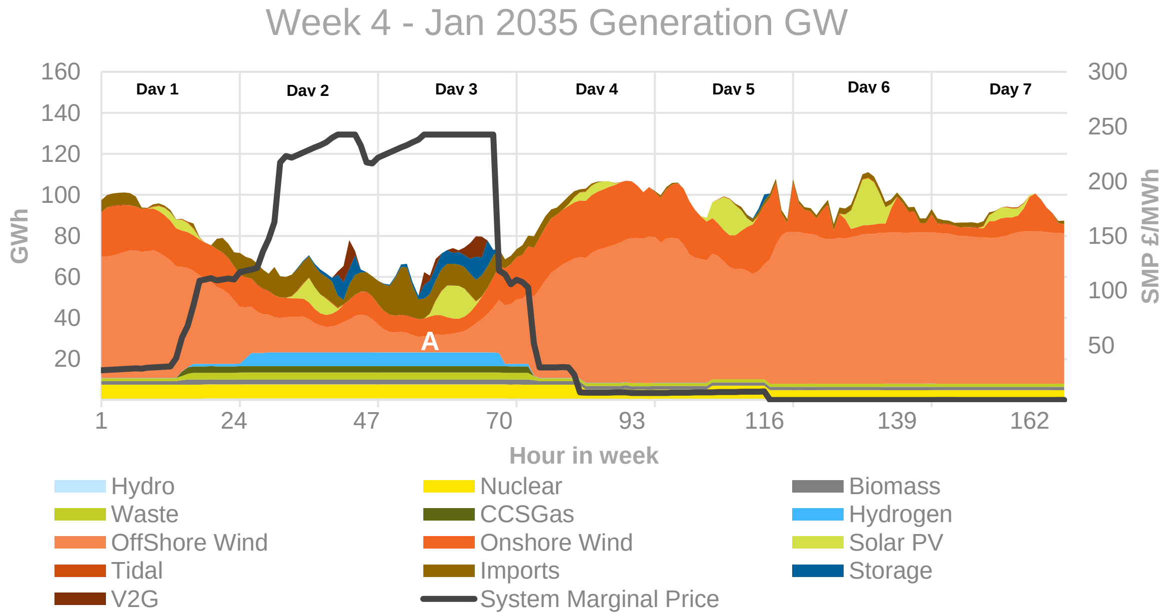

Figure 9 – shows the transmission connected stacked generation mix for the 4th week of January in 2035 in Gigawatts. Vertical lines show days of the week. SMP line in black shows marginal price of electricity generation. Point A shows where the 1-hour breakdown is found in the week.

system. The utilisation of all these technologies was driven by the system marginal price per hour, shown in Figure 9 shown as the black line. As the marginal price increases, different technologies come on the system to meet demand. Therefore, the price hierarchy for the supply side flexible generation for this week is as follows: nuclear, bioenergy, hydro, imports, hydrogen, CCS gas, and finally storage. The smart EV charging, which in this case is supplying power back to the grid (shown as V2G on Figure 9) is dispatched by the model using perfect foresight to reduce consumption where the system marginal price of electricity is more expensive. On the other hand, the model would predict that smart EV charging will fill up when the system marginal price of electricity is cheaper and therefore the model uses car battery capacity to shift its demand.

Figure 10 shows the generation mix for day 3 at 9am, which indicates that storage will become increasingly significant to supply side flexibility. Figure 11 shows the breakdown of storage technologies used in this morning peak hour. It is important to note that all the storage dispatched was long duration lasting over 12 hours. The model throughout this week dispatches storage in long duration periods on multiple days, and therefore is not used for balancing needs in the short term. The total capacity for storage in the Leading the Way scenario is 37.3GW, meaning around 18% has been dispatched in this one hour alone.

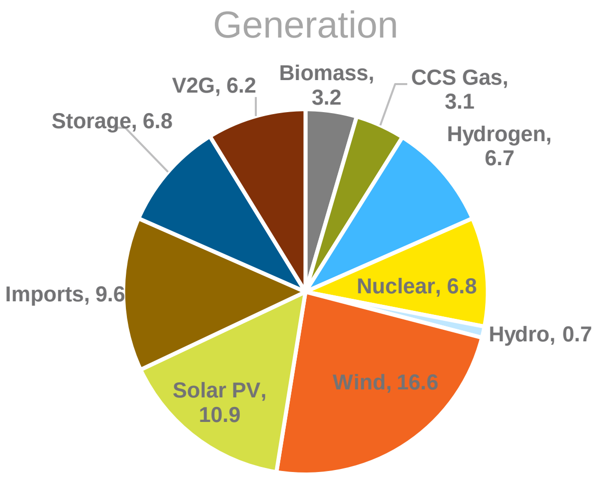

Figure 10 – Generation Mix in GW at 9am on Day 3.

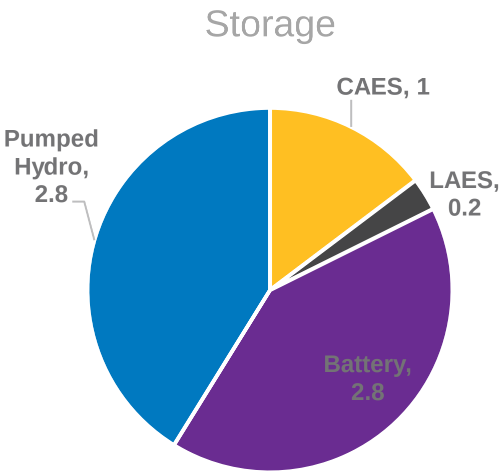

Figure 11 – Storage Breakdown in GW at 9am on Day 3. CAES - Compressed Air Energy Storage. LAES – Liquid Air Energy Storage.

Figure 12 shows the supply side flexibility from the Leading the Way scenario, to highlight how much flexibility was used during this week (at the maximum dispatch of each technology in a given hour) and how much more is still available to dispatch if required.

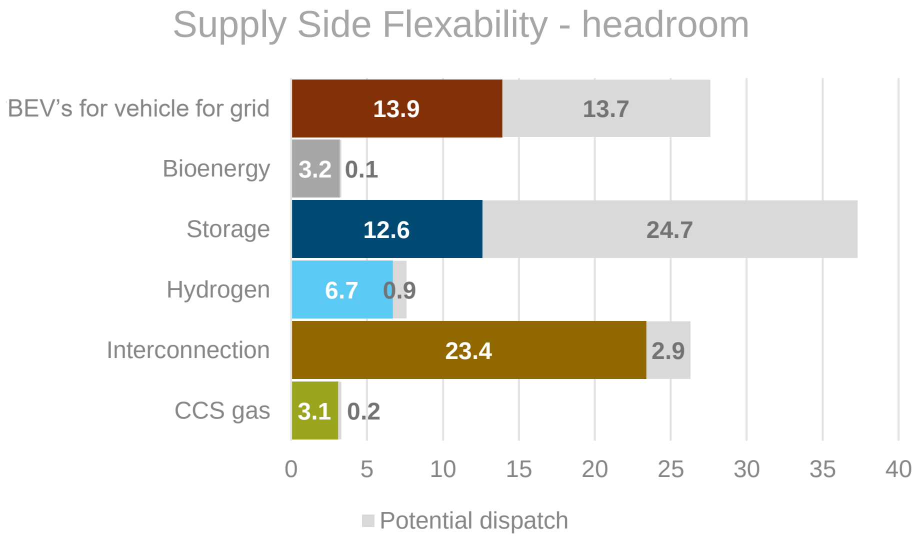

Figure 12 - Shows the maximum supply side flexibility on left hand side that the model dispatch through the week, in the given hour, in GW. The light grey blocks on the right-hand side show the potential if at full capacity the model could have dispatched.

The maximum interconnection dispatched by the model during this week was 23.4GW, which is credible due to this not being a dunkelflaute scenario[22], meaning that renewable generation will not have reduced significantly across western Europe. From Figure 12 13.9GW of Vehicle to Grid, was required by the model at its highest point at 8pm on the second day. The assumed maximum dispatch is 16.6GW at 8pm of Vehicle to Grid. Therefore, we are assuming around 60% of EVs that are willing to participate in V2G[23] could be dispatched at 8pm, the model has dispatched 50% of EVs that are willing to participate.

What does demand look like?

The renewable generation in this week rapidly declines, as explained earlier. However, we also see a drop in demand during this period and explore how this happened. Figure 13 shows the demand stack for the same week.

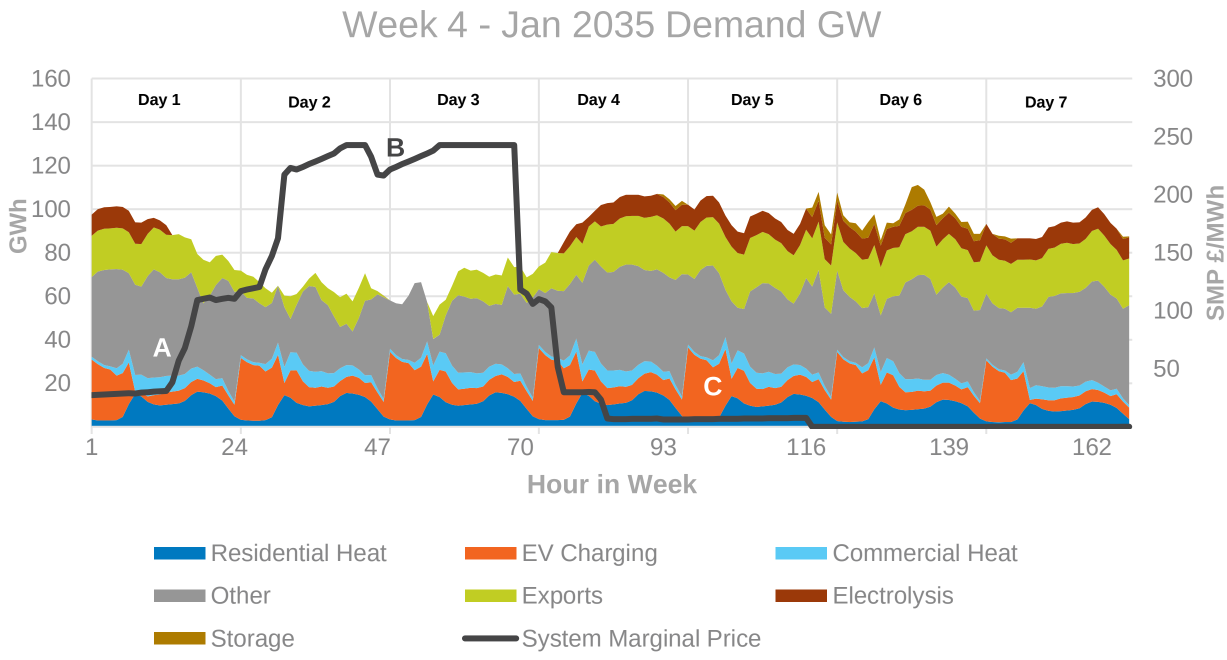

Figure 13 - shows demand stack[24] for the 4th week of January in 2035 in Gigawatts. Vertical lines show days of the week.

Point A on Figure 13, as the marginal price of electricity generation increases, some of the demand side flexible options responded. Firstly, during the period of low wind generation, the model stops generating electricity to fill up storage. There was also a response from electrolysis as green hydrogen was not produced during this period. Exports via interconnectors also dropped significantly, due to this high system price compared with Europe. Finally, there was a response from BEVs, where Vehicle-to-Grid was engaged to ensure the system balanced.

However, several sources of Demand Side Response were not used by the model in this difficult period such as residential, industrial and commercial processes, and commercial heat. Point B on Figure 13 shows the system marginal price as a black line, where days 2 and 3 show an increasing high price or a high flat price of electricity during the day. The model has an assumption that the demand must be met each day and can only be shifted within day by a few hours, it cannot be shifted to another day. Therefore, certain DSR technologies are not utilised, as the system marginal price was not lower further ahead in time[25]. Currently the system

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[22] Dunkelflaute is a German word referring to a period of winter weather with low light and little to no wind across Northern Europe. The Renewable Energy Hub UK. (2023, January). What Will Dunkelflaute Mean for Renewable Energy Surge? Retrieved from The Renewable Energy Hub UK: https://renewableenergyhub.co.uk/blog/what-will-dunkelflaute-mean-for-renewable-energy-surge/#:~:text=What%20Is%20Dunkelflaute%3F,each%20November%2C%20December%20and%20January.

[23] The Leading the Way scenario assumes there are 27,022,908 BEV's on the road, 3,933,761 BEV's will be able to buy and sell their power to the grid using a V2G charging point. Therefore, roughly 4 million BEV's are relevant for V2G.

[24] Specific flexible forms of demand are broken out separately in this chart, including residential heat, commercial heat, EV charging and demand for electrolysis and electricity storage. All other demand, including residential, commercial, and industrial process demand is grouped together under 'Other'. Some of this demand is flexible, but the majority of this category is non-flexible demand and therefore has not been broken down further.

[25] The model always selects the least cost option.

operator has the option to delay demand by a few hours, but in the future, we may be able to shift demand over a longer period of more than 24 hours.

Point C on Figure 13 shows the EV charging pattern which has its daily peak during the night at 28.7GW which is 4 million EV's: around 15% of the total EV's we expect in 2035. Therefore, the model does not delay EV charging from peak as the demand has already been shifted, which is why we see our regular pattern in Figure 13 for EV charging through the week. In the light of the new 'Market Wide Half Hourly Settlement[26]' being implemented over the next few years, we may expect consumers to behave differently. We are looking to further build on our modelling in this area to better reflect the nature of potential EV use shifting its demand beyond a 24-hour period. This could better reflect the behaviour of EV charging in periods of high pricing, resulting in users opting to not charge at all.

1 hour breakdown

As previously analysed in the supply side section we will now explore the demand stack when the renewable generation was at its lowest. Figure 14 shows the demand drop on the 3rd day at the 9am morning peak, compared to the following week at the same time. There is a total of 16.8GW reduction in demand during this single hour. We also saw in this hour stored hydrogen dropped by about 1GWh. However, there is a cost in not producing hydrogen by electrolysis in this period. The store of hydrogen is then depleted going into the next week and therefore is less able to be dispatched.

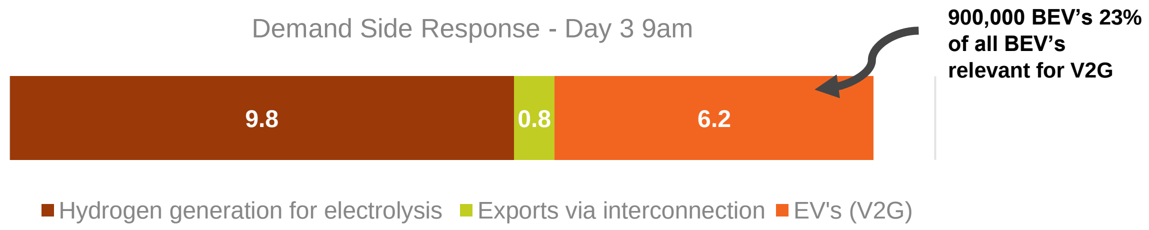

Figure 14 - Shows the reduction in demand, in GW, by technology for the lowest point of wind generation that week, compared to the same time the following week. Day 3 9am.

There are several Demand Side Response technologies that were not dispatched by the model during this hour but are credible in the Leading the Way scenario. These are shown in Figure 15 with the DSR capacities from the Leading the Way scenario, to highlight how much headroom could be available on the system for more flexibility, on top of what the model used in the lowest point of wind for the week. The model did decide to reduce several demands to ensure the system was balanced: the hydrogen production via electrolysis, exports and filling up storage are zero cost reductions, and therefore chosen to reduce demand. The other demands were not shifted by the model, because they had no price incentive to move due to the constant high or rising price throughout the day.[27].

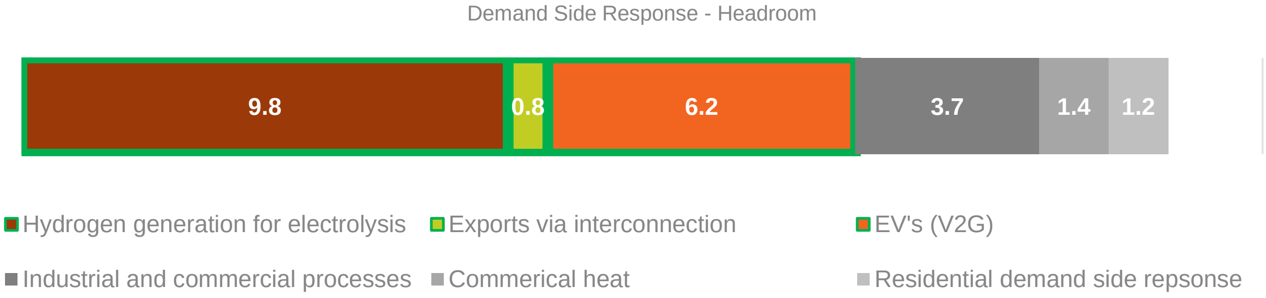

Figure 15 - Shows the demand side response, in GW, used by the model outlined in green and the shades of grey indicate the potential maximum headroom available but was not used by the model.

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[26] OFGEM. (2021). Electricity settlement reform. Retrieved from OFGEM: https://www.ofgem.gov.uk/energy-policy-and-regulation/policy-and-regulatory-programmes/electricity-settlement-reform

[27] Demand must be met fully in each 24-hour period and cannot be shifted to the next day, meaning unless there is a price drop in the next few hours the model will not shift demand.

Implications

For all these technologies to be dispatchable in 2035 there needs to be significant investment in supply and demand side flexibility options, implementation of market reform, network upgrades and implementation of digital infrastructure. However, some of these rely on the development of technologies yet unproven at scale, presenting a risk that some of these options may not be available in 2035.

- Green hydrogen production, for use in CCGTs to create power, has several barriers for it to be scalable. Firstly, there are policy gaps for hydrogen storage, with an ambition but no defined targets. Furthermore, there is currently no government strategy that allows for a hydrogen market, meaning the risk is high for current investors. A new supply chain for electrolysers will need to be developed for green hydrogen production to be ready by 2035. Finally, the Department of Energy Security and Net Zero are due to make a decision on the use of hydrogen for residential heating by 2026. These will all have significant impacts on the future of the energy sector
- Regarding storage, a recent ESO thought piece titled 'Potential Electricity Storage Routes to 2050[28]', considers areas where there are policy gaps and barriers related to storage
- The government report 'Electric Vehicle Infrastructure Strategy[29]' suggests the pace of rollout for charge points may be too slow. There are also challenges regarding charging infrastructure with the distribution networks needing to upgrade the existing capacity to manage the increased demand from EV charging

The model does not consider the new Demand Flexibility Service (DFS), which went live in November 2022, as this was initially implemented as time limited service for winter 2022/23. The rollout of this was developed to allow the ESO to access additional flexibility when the national demand is at its highest during peak winter days. This is flexibility which is not currently accessible to the ESO in real time. This new innovative service allows consumers, as well as some industrial and commercial users (through suppliers/aggregators), to be incentivised for voluntarily flexing the time they use their electricity[30]. We will be reviewing the performance of the DFS at the end of the winter period.

As we look further into the future, the system operator may not need to use DFS in its current form as frequently. With the implementation of 'Market Wide Half Hourly Settlement[31]', we may see consumers taking advantage of lower tariffs throughout the day and night. This could in turn shift some demand away from the peaks and flatten out the daily demand curve.

The dispatch model that we ran using the Leading the Way scenario data in 2035 shows it is possible to meet demand in a challenging week in an average weather year, even with only residual unabated natural gas. However, there are operability challenges that come with operating a system with a large amount of renewable generation, for example lower levels of inertia on the system. Inertia is the ability of a system to resist change and it therefore helps keep frequency stable. This has previously been supplied by synchronous generation such as CCGTs using natural gas. However, if we were to remove a significant amount of the synchronous generation, we will need to find alternative sources for this inertia. These are laid out in more detail in our NOA Stability Pathfinders[32].

To achieve Net Zero in this scenario, the power sector will require a considerable amount of CCUS which removes the carbon dioxide from the electricity generation process. In 2035, the expected emissions from the power sector are 9.3 million tonnes of carbon dioxide equivalent (CO_2e) for the year not including Bioenergy Carbon Capture and Storage (BECCS). Therefore, amount of CO_2e required to be stored in 2035 is 9.3 million tonnes for the power sector to be Net Zero. However, our modelling goes further than this. The electricity

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[28] K, Loukatou. (2022, December). *Potential Electricity Storage.* Retrieved from National Grid ESO: https://www.nationalgrideso.com/document/273166/download

[29] HM Government. (2022, March). Taking charge: the electric vehicle infrastructure strategy. Retrieved from HM Government: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1065576/taking-charge-the-electric-vehicle-infrastructure-strategy.pdf

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[31] OFGEM. (2021). Electricity settlement reform. Retrieved from OFGEM: https://www.ofgem.gov.uk/energy-policy-and-regulation/policy-and-regulatory-programmes/electricity-settlement-reform

[32] National Grid ESO. (2022, September). NOA Stability Pathfinder. Retrieved from National Grid ESO: https://www.nationalgrideso.com/future-energy/projects/pathfinders/stability

generated from BECCS produces a net reduction of 16.6 million tonnes of CO_2e for 2035[33]. This results in an overall net reduction of 7.3 million tonnes of CO_2e, which could help to offset the hard to abate sectors of the UK. The expected carbon storage in the UK by 2035 will be 50 million tonnes per year[34]. Therefore, the power sector could be Net Zero carbon and therefore meet the government target. This would assume the Power CCUS Framework published in July last year will be finalised[35] and we will have built enough storage for the future CO_2e.

By 2050 the expected emissions from the power sector are 6.6 million tonnes of CO_2e for the year, not including BECCS. The electricity generation from BECCS produces a net reduction of 21.1 million tonnes of CO_2e in 2050. This results in a net reduction overall of 14.4 million tonnes of CO_2e. The expected carbon storage requirement for the year of 2050 is between 70 - 180 million tonnes of CO_2e[36]. Therefore, out to 2050 we expect that we will have enough carbon storage capacity to reach Net Zero carbon.

Conclusion

Within our Leading the Way scenario[37] in 2035, the UK electricity system can meet demand in challenging weeks with no unabated natural gas generation. The model runs for the entire year and meets demand every week, every hour of the day[38]. The week chosen at the end of January was one of the most challenging for the system within the average weather year and even with the greatest renewable generation loss at the lowest point of wind in the week the system still meets demand. This is achieved through a combination of existing and new supply side technologies, but also a considerable amount of demand side flexibility.

As of today, we largely operate a demand-led grid, meaning flexibility has been met by adjusting energy supply to meet demand. This is mostly achieved through burning natural gas to produce electricity which was the largest contributor to the generation mix at 38.5% in 2022. However, in 2035 we do not have the same amount of gas generation, and we are more dependent on renewable generation, which is weather sensitive, making it less reliable. In 2035 we expect to have several more supply-side technologies such as hydrogen and V2G, and more bioenergy and storage but this will not be enough to ensure supply meets demand every second of the day. Therefore, there will be a greater emphasis on DSR and the system will need to move towards a more supply-led grid. Our modelling assumes there is market reform to enable DSR; however, this is a complex area and we will be looking at improving our methods to capture the changing nature of the UK energy system.

The level of flexibility on the system will require all technologies to be fully deployed. This creates a need for a whole system approach, where all factors of the power sector are considered. If all these technologies can come together in harmony, then the electricity system will be able to run as Net Zero carbon by 2035.

Get involved in the conversation

We are keen to hear more from stakeholders about your views on different aspects of our FES modelling. If you are interested in sharing your thoughts on a week in the life of a Net Zero carbon electricity system in 2035 and our modelling for FES 2023 and beyond, please email us at FES@nationalgrideso.com.

To access our current and past FES documents, data and multimedia at: nationalgrideso.com/future-energy/future-energy-scenarios

Get involved in the debate on the future of energy and join our LinkedIn group Future of Energy by National Grid ESO

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[33] BECCS generation is assumed to be negative, as the emissions produced are not adding to the overall CO_2 There are simply putting back the CO_2 that the vegetation removed from the atmosphere during its life. Therefore, with the addition of CCS BECCS can be considered to have net negative emissions.

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[37] National Grid ESO. (2022, July). Future Energy Scenarios 2022. Retrieved from National Grid ESO: https://www.nationalgrideso.com/document/263951/download

[38] This assumes an unconstrained network.

ESO

For further information on ESO publications please visit: nationalgrideso.com
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Appendix

Table 1 shows the exact supply side flexibility values for morning and evening peaks on page 6

Time	Dispatched Generation	GW Increase	GW total
Day 1 PM Peak	Bioenergy	1GW	5.7GW
	CCS Gas	3GW	3.1GW
	Hydrogen	1GW	1.2GW
	Interconnection	2GW	10.6GW
Day 2 AM Peak	Hydrogen	5GW	6.6GW
	Interconnection	11GW	13.7GW
Day 2 PM Peak	Storage	9GW	9.5GW
	Vehicle to Grid	14GW	13.9GW
Day 3 AM Peak	Interconnection	11GW	23.4GW
Day 3 PM Peak	Storage	12GW	12.6GW
	Vehicle to Grid	10GW	10.2GW