UK Electricity Strategy: Capacity, Demand and Pricing

Evidence for the BEIS Select Committee, 9th January 2023

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Executive Summary

1. A net zero carbon 2050 implies that almost all UK energy will take the form of electricity. Hydrogen and sustainable aircraft fuel will play important roles but the UK electricity market, assuming total energy needs remain the same, will be five times its present size and its security will be more important than ever.
2. This paper compares the only two feasible strategies for 2050 electricity supply: renewables and nuclear, with and without fossil fuel generation and carbon capture and storage (CCS). This table summarises them:

2050 UK Electricity Market

Sources		Fossil-free		Fossil + CCS	
2018		**Supply 2050**		**Supply 2050**	
Mean GW		**Mean GW**	**%**	**Mean GW**	**%**
	Renewables to grid	126	65		
	Renewables to/from hydrogen	11	6		
12.9	Total renewables	137	71	75	39
20.4	Fossil fuel + CCS	0	0	62	32
7.5	Nuclear	56	29	56	29
3.3	Losses (8%)	16	N/A	16	N/A
41.9	**Total**	**209**	**100**	**209**	**100**

3. The calculations behind this table are complex and set out in the Appendix. The four 3.2GW nuclear reactors, envisaged by BEIS, would supply about 12.8GW. We recommend that no further expensive and unpopular large plants of this kind are commissioned but instead acquire a fleet of about 108 of the more modern small or advanced modular reactors (S/AMRs) generating an average of 400MW each. It seems very unlikely fusion will be in commercial operation by 2050.
4. A key question is how to cope with the National Grid renewables inevitable under-supply days when wind and sun are inadequate. Our model shows this may be feasible and economic by converting over-supply surpluses to green hydrogen, storing it and then using it to generate electricity but that depends on the amount of renewables

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capacity that can be built by 2050 and weather conditions that cannot really be predicted with confidence.

5. The 2050 electricity distribution system will have to carry a load nearly five times higher than currently and using a more complex network. Network scientists should be commissioned to propose the best solution.
6. Electrical capacity will always need to be of the order of three times average demand so that there can be a fully competitive pricing market with government intervention only when competition fails. Ofgem can then be abolished. The Office of Nuclear Regulation should declare S/AMRs hazard-free so they can be sited anywhere, ideally near their consumers, but they can be clustered so the sites required would be far fewer than 108.
7. Our conclusion is that the 39%, 32% and 29% renewables, natural gas + CCS and nuclear (respectively) strategy is by far the better. The other is too risky and requires ten times the 2018 renewables capacity to be built rather than five, and even that will be a challenge.

Introduction

8. This paper considers what we know, or need to know, about:
    a) Electricity generating **capacity**,[4] bearing in mind that all UK energy needs will, in a zero carbon 2050, need to be met by electricity, and **demand**,
    b) Dispatchables (flexible or rampable generation and import/export),
    c) Marine and aviation,
    d) Nuclear generation,
    e) Renewables' peaks and troughs,
    f) Distribution (the National Grid),
    g) Pricing and the 2050 electricity market,
    h) Recommendations.
9. We are aware of the exciting breakthroughs being made with nuclear fusion but it seems highly unlikely it will be in commercial operation by 2050.[5] None of the experiments so far have made the crucial step, i.e. generating electricity.

Capacity and demand

10. To avoid blackouts, electricity capacity on days when the wind does not blow, or is very low, supplemented by stored electricity, must exceed **peak** demand. Climate change is likely to increase volatility[6] and therefore the height and frequency of peaks. US figures for 2021 indicate that capacity was 3.6 times demand, i.e. sales to users.[7] Demand include distribution losses where the UK (8%)[8] exceeds than those of the EU

[4] "Capacity" is the amount of electricity generated, e.g. by a wind turbine, when it is operating at optimum speed, i.e. the maximum it can produce.
[5] https://www.bbc.co.uk/news/science-environment-63950962
[6] https://royalsociety.org/topics-policy/projects/climate-change-evidence-causes/question-13/
[7] https://www.eia.gov/energyexplained/electricity/electricity-in-the-us-generation-capacity-and-sales.php

(6%). UK capacity in 2021 was almost exactly three times average demand (104.9GW vs. 35.7GW)[9] and this would seem a useful yardstick.

11. Predicting 2050 demand, and therefore capacity needs for electricity, is complicated by the zero carbon requirement to convert virtually 100% of UK energy needs to electricity. In 2021, it was only 19.2%.[10] In other words, even if our energy needs do not grow at all and the peak to average ratio remains the same, we will require to meet five times more electricity demand.
12. According to the Committee of Climate Change (CCC), the primary government advisers on these matters, electricity demand will merely double from just over 300TWh per annum to just over 600TWh (Figure 5.5)[11] but this is erroneous as their figure omits any reference to the conversion of other energy sources, such as fossil fuels, to electricity. Furthermore, the Committee confuses demand with capacity. Furthermore, an October 2021 Crown Commercial Service Blog claimed, "According to the National Grid's Future Energy Scenarios, on average, there is a need to increase renewable capacity by just over 4.5 times - from 40GW in 2019 to 88GW in 2030 and 186GW in 2050."[12]
13. Recent **peak** demand in October – December 2021 was 53GW[13] compared with 76.6GW capacity. The National Grid proposed an additional 263GW of renewables by 2050[14] but, as our model will show, we will need 444GW if generating electricity from fossil fuels is eliminated.
14. On 2021 figures, the UK only had enough capacity to cover the winter peak on the *dunkelflaute* days but that was with imports on which the UK has become increasingly reliant. "Total imports were [a record] 28.7TWh in 2021, up 28.4 per cent compared to 2020, while total exports were down 7.0 per cent on 2020 to 4.2TWh."[15]
15. Prime Minister Johnson announced in 2022 that government was "increasing our plans for deployment of civil nuclear to up to 24GW by 2050 – 3 times more than now and representing up to 25% of our projected electricity demand."[16] According

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[8] https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS

[9] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1094025/UK_Energy_in_Brief_2022.pdf

[10] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1094025/UK_Energy_in_Brief_2022.pdf

[11] https://www.theccc.org.uk/wp-content/uploads/2020/12/Sector-summary-Electricity-generation.pdf

[12] https://www.crowncommercial.gov.uk/news/make-way-for-renewable-energy-generation#:~:text=According%20to%20the%20National%20Grid%27s,2030%20and%20186GW%20in%202050

[13] https://protect-eu.mimecast.com/s/uRc1CAQN8tj22NzHG9TSR?domain=bmreports.com

[14] https://www.smart-energy.com/renewable-energy/uk-needs-another-263gw-to-meet-demand-2050-net-zero-target/#:~:text=UK%20needs%20another%20263GW%20to%20meet%202050%20energy%20targets,-By&text=UK%20grid%20operator%20National%20Grid,491%20terrawatt%2Dhours%20by%202050.

[15] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1094025/UK_Energy_in_Brief_2022.pdf

[16] https://www.gov.uk/government/publications/british-energy-security-strategy/british-energy-security-strategy#nuclear

to an observer at the meeting (who obviously does not wish to be named), Mr Johnson just clutched the number out of the air with no rationale. To his credit, he was prepared to take the long view which others in the room were not.

16. We can assume electric vehicle (EV) charging will flatten total electricity demand but not increase the peaks by any significant amount because "to combat peaks in electricity demand, all new chargers sold from 30th June 2022 must be set by default to avoid charging during peak hours, specifically between 8am and 11am and 4pm to 10pm"[17] and smart meters can shift starting times back to 10.30pm. By charging EVs off-peak their impact on the capacity/peak demand relationship will be minimal.
17. The National Grid does not provide a single electricity demand forecast for 2050 but offers four "scenarios" of which "consumer transformation" (CT - electrified heating, consumers willing to change behaviour, high energy efficiency, demand side flexibility) is the most credible, partly because we can eliminate hydrogen, and indeed all forms of gas, from 2050 domestic heating.[18]
18. Renewables deliver electricity at three levels:
    i) The amount required by the National Grid,
    j) Under-supply, e.g. during *dunkelflaute* days when supply is inadequate and has to be filled from other sources and/or storage, and
    k) Over-supply when renewables generate more than the National Grid can use. Wind turbines are switched off or slowed down and this is known as "curtailment", namely this "is the reduction of output of a renewable resource below what it could have otherwise produced. It is calculated by subtracting the energy that was actually produced from the amount of electricity forecasted to be generated and, currently, the operators are compensated with "constraint payments".
19. Renewables "capacity" describes the amount of electricity generated if the turbines ran optimally, year-round, which does not, of course, happen. The "load factor" is the amount generated as a percent of capacity. Over the five years to 2021, according to BEIS (DUKES) data, on + offshore wind load factors averaged 31.6%.[19] Solar was about 10%. In 2021, the first and fourth quarters averaged a 33.3% whereas the second and third were 24%. Such seasonal variation is normal. Separate BEIS figures, indicated the average load factor for the six years to 2021 was spot on 30%.[20]
20. And the BEIS statistical press release gave the 2018 load factor as 34.8% but that figure is clearly too high as BEIS included liquid biofuels for transport as electricity.[21] The National Grid publish lower numbers, i.e. an average 21.7% for the five years to 2021.[22] We consider the higher numbers more credible and consistent with the 3:1

[17] https://blog.evbox.com/uk-en/smart-charging-regulations#:~:text=To%20avoid%20a%20peak%20in,to%20protect%20the%20electricity%20grid.
[18] https://www.thetimes.co.uk/article/hydrogen-too-costly-and-inefficient-to-heat-homes-vlcf2wrkn
[19] https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fassets.publishing.service.gov.uk%2Fgovernment%2Fuploads%2Fsystem%2Fuploads%2Fattachment_data%2Ffile%2F1094495%2FDUKES_6.3.xlsx&wdOrigin=BROWSELINK
[20] https://www.gov.uk/government/statistics/energy-trends-section-6-renewables
[21] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/791297/Press_Notice_March_2019.pdf

capacity to demand ratio and therefore use a load factor of 30% in our model. It would be good if BEIS took more care to arrange consistency in their published data. Whilst we cannot know how productive future sites, or future turbines, will be, BEIS expects load factors will be as high as 58.4%.[23]

Dispatchables

21. At least four of the available advanced nuclear reactors are load following[24] and another three are semi-load following in that they use molten salt as a coolant and have the capability of storing heat to be used at times of peak demand[25] but, for the purposes of this paper, we will consider nuclear as supplying the baseload. There are five types of dispatchable, i.e. means of generating electricity when renewables plus baseload are inadequate:
    - l) **Fossil fuels with CCS**. By 2050, the remaining fossil fuel generation is likely to be limited to natural gas but it could be reduced by converting gas power stations to using green hydrogen produced from surplus electricity arising during renewables over-supply days. It should not be wasted as now.
    - **m) Biomass with CCS**. At the BEIS Select Committee on 22nd November 2022, Will Gardiner, CEO of Drax, said "In the UK, when we were using coal, we were emitting about 20 million tonnes.[26] Now, effectively, we are emitting less than 3 tonnes."[27] The International Energy Association (IEA) supports this view and believes it will play a 5% role in 2050 electricity generation.[28] On the other hand "Some biofuels, like Ethanol, is relatively inefficient as compared to gasoline. In fact, "it has to be fortified with fossil fuels to increase its efficiency and the use of animal and human waste escalates the amount of methane gases, which are also damaging to the environment. Additionally, the pollution created from burning wood and other natural materials can be considered just as bad as that resulting from burning coal and other types of energy resources."[29] Euractiv, in December 2022, was even more negative.[30] Whilst it remains a possibility to be considered, biomass should be ruled out of the main electricity generating strategy. It should not be treated as, or called, a renewable on the specious grounds that is only recycling CO_2.

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[22] https://www.bmreports.com/bmrs/?q=generation/fueltype/current
[23] https://www.renewableuk.com/page/UKWEDExplained/Statistics-Explained.htm
[24] Arc Energy, NuScale, Terrestrial Energy and Thorcon
[25] Kairos, Moltex, Terrapower,
[26] Presumably of CO_2.
[27] https://committees.parliament.uk/oralevidence/11606/pdf/
[28] https://www.iea.org/articles/what-does-net-zero-emissions-by-2050-mean-for-bioenergy-and-land-use
[29] https://www.syntechbioenergy.com/blog/biomass-advantages-disadvantages
[30] https://www.euractiv.com/section/biomass/opinion/why-burning-primary-woody-biomass-is-worse-than-fossil-fuels-for-climate/

n) **Green hydrogen** should become, alongside batteries in EVs, the most important way to store electricity. It can use the surplus electricity from renewables over-supply times and replace natural gas in generators. It is also a valid fuel for some land and marine transport although rechargeable electric batteries are more cost efficient for most land transport, but probably not for heavy duty transport. Other uses proclaimed for hydrogen, e.g. replacing or being blended with natural gas for home heating, or aviation fuel are misplaced and the BEIS "Hydrogen Strategy update to the market: July 2022" is wholly misleading. In essence, hydrogen needs electricity for its production and the energy it provides is far less than the energy required to produce it. Using electricity directly does have some generation and distribution losses but it is over 90% efficient, whereas hydrogen is only 38% efficient, excluding the costs of conversion, reconversion and storage.[31] ***The bottom line is that hydrogen will play a very important part in 2050 electricity supply but only as a storage medium.***

o) **Batteries** are also much vaunted but irrelevant for large-scale storage applications due to their high cost and limited capacity.[32] Ofgem's idea of using EV batteries as storage[33] would not find favour with drivers wishing to start a journey and finding their car batteries drained.

p) **Imports.** The National Grid reported "by 2024 we will be operating at least six interconnectors and 7.8GW of power between Great Britain and Europe. This is enough to supply 25% of our electricity requirements"[34], providing good back-up but **net imports** are expected to be less than one percent of demand by 2050.[35] In the 1990s, the UK was a net exporter of electricity but the tide turned and net imports have been steadily increasing to 28.7TWh (5.7%) in 2021.[36] Gross imports were 8.6%. There are two problems with reliance on imports: cost/balance of payments and supplier compliance. In 2022, for example, France, a traditional net supplier from their strong nuclear baseload, announced that it needed to keep its own electricity[37] and, also thanks to Mr Putin, the UK became a net electricity exporter for the first time in a decade.[38] "A 2021 survey conducted by the UK Department for Business Energy & Industrial Strategy (BEIS) found that 71 percent of

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[31] https://theconversation.com/hydrogen-cars-wont-overtake-electric-vehicles-because-theyre-hampered-by-the-laws-of-science-139899
[32] The London Gateway battery cost is £300M/GWh so 30GWh costs £9bn.
[33] https://cleantechnica.com/2021/09/05/uk-energy-regulator-supports-vehicle-to-grid-proposal/
[34] https://www.nationalgrid.com/stories/energy-explained/what-are-electricity-interconnectors
[35] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/943714/Modelling-2050-Electricity-System-Analysis.pdf
[36] https://www.statista.com/statistics/550304/electricity-imports-uk/
[37] https://www.telegraph.co.uk/business/2022/12/12/ftse-100-markets-live-news-uk-economy-strikes-energy/ .
[38] https://www.thenationalnews.com/world/uk-news/2022/12/29/renewables-power-up-uk-electricity-exports-to-europe/

UK's residents [had] concern about foreign energy dependence."[39] It would be sensible to aim to balance imports and exports of electricity by 2050 but that should still provide some back-up for *dunkelflaute* days if climate volatility does not match the rest of Europe's.

22. In essence, this analysis indicates that the UK should use renewables to the full extent of availability. Curtailment is wasteful today and the growth of renewables would further grow that was unless over-supply is put to green hydrogen production.

Marine and aviation

23. The two sectors that cannot be fuelled by land generated electricity are marine and aviation. Shipping could use green hydrogen where the weight to energy ratio is not really a problem. Ammonia has been advanced as an option but safety issues with this hazardous chemical and NO2 from combustion are major negatives. Hydrogen is not a feasible aviation fuel for medium/long haul flights.[40,41]
24. The Department of Transport's "Jet Zero" (July 2022) provides 83 pages of piety with only one key action: developing and promoting "sustainable aviation fuel" (SAF) to replace kerosene. It is mostly about the UK's international leadership of, and partnership in, aviation; SAF gets 16 mentions. The paper claims aviation fuel amounted to 12.4 mtoe in 2019[42] which looks about right, but gives no data on the forecast UK 2050 air mileage relative to now, or relative SAF efficiency per kg, or how much SAF the UK will then need, or how much electricity is needed to make SAF, or its costs.
25. Carbon sucked from the air and combined with green hydrogen, extracted by electrolysis from water, to yield SAF which "emits a minimum of 75% less emissions compared to fossil jet fuel, including from production, distribution, transportation and combustion. It also reduces other harmful emissions [from biomass-derived sources] like particulates and sulfur by 90% and 100% respectively."[43] It is promoted as net zero because the CO2 emissions are balanced by the CO2 captured in its manufacture. The process of Direct Air Capture has yet to be proven at scale, nor have running costs, nor plant longevity.
26. All this, really, is beside the point as this paper is about electricity generation and supply, Apart from the amount needed to manufacture SAF, the marine and aviation sectors seem unlikely to substantially affect overall electricity demand.

[39] https://www.statista.com/statistics/426960/united-kingdom-uk-concern-about-depending-on-foreign-energy/
[40] https://www.airportwatch.org.uk/2021/03/hydrogen-very-unlikely-to-be-used-in-long-haul-planes-huge-problems-even-for-short-haul/
[41] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/637662/dft_f4c-feasibility_final_report.pdf
[42] https://www.gov.uk/government/statistical-data-sets/energy-and-environment-data-tables-env#fuel-cons
[43] https://skynrg.com/sustainable-aviation-fuel/

Nuclear generation

27. HM Treasury, understandably, is reluctant to spend taxpayer money on nuclear reactors. Moving to S/AMRs would allow nuclear financing and development to transfer to the private sector. As the first one or two of any type will cost more to develop than subsequent models, HM Treasury may need to grease the wheels with some subsidies for those initiating costs but these would be, relatively, small.
28. There is considerable divergence between the government's 24GW requirement and the Grid prediction of 10.5GW for 2050. We consider that the 2050 baseload, i.e. nuclear, needs to be in the region of 27%, and arguably more, i.e. at least 56GW. The three 3.2GW plants envisaged now[44] (Hinkley Point C, Sizewell B and, perhaps, Wylfa B[45]) and one more (12.8GW) would leave 35GW baseload/nuclear to be met by small/advanced modular reactors (S/AMRs) which generate 300MW to 470MW each,[46] say 400MW. That translates to 108 S/AMRs or £200bn if Rolls Royce's figures are right and excluding initial excesses. That would be quite enough for a competitive market to develop as Treasury rules require with, say, four UK manufacturers – some, perhaps, under licence from international.
29. Nuclear load factors are well over 90%[47] but since the numbers above are rough estimates, we can assume that would be the equivalent of one more S/AMR for this paper, i.e. 109. Rolls Royce are already making proposals for SMRs and the comparable GE Hitachi Boiling Water 300MW Reactor (BWRX300)[48] should be considered alongside that. The Ontario Power Generation have selected it for one site. Licence for UK manufacture should be negotiated.
30. The main problem with nuclear is not money but the length of time taken from initiation to active generating, i.e. the timeline. It was expected, way back, that as governments became familiar with nuclear, build times would speed up but, as the 6th December 2022 Gordian Knot News reports,[49] the reverse has proved more often the case. The US deteriorated from four to 16 years between 1966 and 1973 starts. Government and regulators were most of the problem. France did well, maintaining six year build times up to 1985 and then they doubled because "EDF is a monopoly, beset by strong unions." China and Japan are far better disciplined: Japan averages 3.8 years.
31. The UK probably holds the record for delays with Sizewell C first mooted in 2010[50] and by the end of 2022, still had not been finally approved, still less built. Research by the University of Greenwich Business School indicates it will take another 15 – 17 years to build and cost twice as much as its twin, Hinkley Point C.[51] The delays, of course, add immensely to the costs. The moral of the history is that build times have

[44] https://www.ft.com/content/21a54a90-1b51-4561-ba9e-c1677e0262ed
[45] https://committees.parliament.uk/committee/162/welsh-affairs-committee/news/171129/could-wylfa-be-the-uks-next-nuclear-power-station-mps-launch-new-inquiry/
[46] https://namrc.co.uk/intelligence/smr/
[47] https://www.energy.gov/ne/articles/what-generation-capacity
[48] https://nuclear.gepower.com/build-a-plant/products/nuclear-power-plants-overview/bwrx-300
[49] https://jackdevanney.substack.com/p/nuclear-power-is-too-slow
[50] "Nuclear power: Eight sites identified for future plants". BBC News. 18 October 2010.
[51] https://www.theguardian.com/environment/2022/aug/31/who-will-fund-sizewell-c-nuclear-plant-when-will-it-be-built-explainer

little to do with technology and everything to do with national culture and indecisive government.

32. Probably the most wasteful delays (£1bn and two years) were caused by the Environment Agency (EA) objecting to the removal of an acoustic fish deterrent from the Bristol Channel.[52,53] The EA insisted nonetheless, but with no evidence that it would make the slightest difference to anything.
33. The Office for Nuclear Regulation which must be commended for participating in international and industry discussions about modernisation, should only need to approve the first of each **type** of S/AMR. Subsequent builds of the same model should only require site approval, and the Department for Levelling Up, Housing and Communities should facilitate local planning.
34. The government needs to give the Great British Nuclear recommendations full backing immediately. Any delays will not just cost money but, given nuclear approval and commissioning lead times, compromise the net carbon zero 2050 target.

Renewables' peaks and troughs

35. Ideally, the surplus electricity that the Grid cannot accept during peaks could be used to generate green hydrogen to be burned in place of natural gas to provide enough electricity to meet the shortfalls during the inevitable under-supply days. This section considers the feasibility of that and the cost implications relative to the alternative, natural gas with carbon captures and storage (CCS).
36. Massive storage tanks would be needed and refrigeration, if hydrogen is to be kept liquid. Of the numerous ways of storing hydrogen to generate electricity,[54] salt caverns presently look to be best value for money (about $0.6 per kg, Figure 5)[55] and a large number of caverns would be needed for the no fossil fuel strategy.
37. So far as comparative costs are concerned, according to Bloomberg New Energy Finance, green hydrogen could be produced for $0.70 – $1.60 per kg in most parts of the world by 2050, a price competitive with natural gas. NEL, the world's largest producer and manufacturer of electrolyzers, believes that green hydrogen production cost parity (or even superiority) with fossil fuels could be achieved as early as 2025."[56] "Production costs are also very sensitive to electricity prices: for instance, for a utilization of 40–50% and average electricity prices of 40–50 €/MWhel, electricity costs account for more than 50% of hydrogen costs."[57] In other words, using effectively "free" electricity from over-supply days, would reduce the price of green hydrogen from parity with natural gas to about half. Our conclusion is that, in price

[52] https://www.edfenergy.com/energy/nuclear-new-build-projects/hinkley-point-c/news-views/fish-protection-measures-and-removal-acoustic-fish-deterrent
[53] https://www.edfenergy.com/energy/nuclear-new-build-projects/hinkley-point-c/about/acoustic-fish-deterrent
[54] https://journals.sagepub.com/doi/pdf/10.1260/014459806779367455
[55] https://www.researchgate.net/publication/352286454_A_Review_of_Seasonal_Hydrogen_Storage_Multi-Energy_Systems_Based_on_Temporal_and_Spatial_Characteristics/figures?lo=1
[56] https://blogs.worldbank.org/ppps/green-hydrogen-key-investment-energy-transition
[57] https://www.sciencedirect.com/topics/engineering/hydrogen-production-cost

terms, green hydrogen is a least no more expensive than gas with CCS. Where green hydrogen is produced from over-supply, i.e. no extra capacity is required, the electricity to make the hydrogen is, in effect, free and it is massively cheaper.

38. The no-fossil-fuel strategy assumes short-supply days to be the equivalent of one month a year, 92% of renewables electricity supply should come direct from the turbines and 8%, via hydrogen storage, to top up those days.

Distribution

39. The National Grid, in England and Wales, consists of high voltage cables carrying electricity to 330 substations where it is converted to a lower voltage for 14 geographically defined local distribution networks (DNOs) to deliver to homes and businesses.[58] It also serves 20M people in New York and Massachusetts.[59] There are also 13 free-ranging independent DNOs which are not geographically centred. The other UK operators are: Scottish Power Transmission, Scottish Hydro Electric Transmission Limited and Northern Ireland Electricity.
40. "In 2021, transmission losses amounted to around 25 terawatt-hours, or approximately nine percent" of UK electricity generation.[60] We have allowed eight percent but it is only six percent on the continent.
41. The government 2050 distribution strategy[61] owes more to Voltaire's Dr Pangloss than considered development. The joint Ofgem and BEIS August 2022 paper "Electricity Frameworks Strategic Network"[62] forecasts 2050 electricity demand be about double 2020, i.e. 570 – 770TWh whereas five times seems far more likely. Basically, it expects everything to remain much the same (including Ofgem's role) when it will clearly all be very different.
42. The National Grid and local distribution networks approach has worked well in the 20th century but maybe somewhat simplistic for the 21st. Electricity in the 20th century could be conceived, with no renewables and few nuclear or other generators, as a centralised system. In 2050, most electricity will be arising around the UK coastline and from up to 112 nuclear power plants. Scotland is developing an electricity supply strategy which differs from England's.[63] A new network will be needed with many more inputs and the potential to locate renewable generation collectors and nuclear (S/AMRs) closer to users. Optimising that distribution network will require sophisticated specialist expertise beyond anything the National Grid, with no disrespect, currently employs.

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[58] https://www.nationwideutilities.com/service/dno-idno/
[59] https:could foresee//www.nationalgrid.com/us
[60] https://www.statista.com/statistics/550583/electricity-losses-in-transmission-uk/
[61] https://www.gov.uk/government/publications/british-energy-security-strategy/british-energy-security-strategy#networks-storage-and-flexibility
[62] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1096283/electricity-networks-strategic-framework.pdf
[63] https://www.gov.scot/publications/scotlands-energy-strategy-position-statement/

43. Hungarian thinker, Albert-Lázló Barabási, created "network science"[64] about 20 years ago and its application is now growing. **A team of network scientists should be commissioned to model the most efficient UK distribution options bearing in mind the implications for a price competitive market** (see below). The recommended network should reduce distribution losses to the EU average six percent.

Pricing and the 2050 electricity market

44. In March 2022 the Public Accounts Committee reported "that after taking two years to publish its plan for achieving the target, set in law, of 'Net Zero by 2050', Government still has "no clear plan for how the transition to net zero will be funded" or "how it will replace income from taxes such as fuel duty", and "no reliable estimate of what the process of implementing the net zero policy is actually likely to cost British consumers, households, businesses or government itself".[65]
45. With characteristic myopia, HM Treasury (HMT)[66] and the Office for Budget Responsibility (OBR)[67] do not look at pricing or market effects for consumers, businesses or the UK economy in any depth but at the effect on the tax take, which is minimal, and of little interest to anyone else.
46. The 2022 energy prices hiatus was mostly caused by two things: the reduction in Russian supplies and misplaced UK government interventions, such as selling off gas storage, cutting North Sea production and allowing generators of renewables to sell at natural gas generation prices. Ofgem proved useless and was rightly taken to task by the BEIS Select Committee. Ofgem's governing "Framework Document" was promised (Para 65) by December 2022 but has not appeared.[68]
47. If capacity sufficiently exceeds demand and regulations (government meddling) are sufficiently removed, prices will naturally fall towards costs which for both renewables and nuclear are low. That is why France built so much nuclear capacity.
48. These market and pricing problems can be avoided in 2050 by:
    q) Keeping capacity at something like three times demand that would renewables capacity to be 10 and 5 times the 2018 levels for the fossil free and natural gas strategies respectively,
    r) Balancing electricity imports with exports, with net imports being below 1%,
    s) Ceasing all constraint or curtailment payments to renewables generators when winds and/or sun are strong but encouraging them to make saleable green hydrogen instead,

[64] http://www.network-science.org/
[65] https://committees.parliament.uk/committee/127/public-accounts-committee/news/161405/uk-net-zero-2050-government-without-answers-to-key-questions-on-costs-or-funding-target-set-in-law/
[66] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1026725/NZR_-_Final_Report_-_Published_version.pdf
[67] https://obr.uk/docs/dlm_uploads/Fiscal_risks_report_July_2021.pdf
[68] https://committees.parliament.uk/publications/30191/documents/174915/default/

t) Providing adequate storage for green hydrogen and converting fossil fuel generation to hydrogen,
u) Restructuring the distribution network so that it can operate as a classic, competitive market,
v) Streamlining renewables and nuclear plant development safety rules (ONR working with the Canadians for nuclear) and planning approvals,
w) Transitioning from an ineffectively regulated to a classic competitive market. When Margaret Thatcher announced, in 1986, that electricity would be denationalised, she fudged the issues. All electricity has to come down the same cables which put the National Grid and Ofgem in charge of everything apart from dealing with consumers – a small and fragile part of the value chain. How to abolish Ofgem and stop government meddling (beyond the conventional policing of competition) in the electricity market should be the subject of a separate paper.

2050 Electricity Market Model

49. Zero carbon 2050 can certainly be achieved if electricity demand can be successfully met just by renewables, green hydrogen, produced by surplus renewables, and nuclear. The alternative is to continue with natural gas generation with CCS. The calculations for those alternatives are set out in the Appendix.

Sources		**Fossil-free**		**Fossil + CCS**	
2018		**Supply 2050**		**Supply 2050**	
Mean GW		**Mean GW**	**%**	**Mean GW**	**%**
	Renewables to grid	126	65		
	Renewables to/from hydrogen	11	6		
12.9	Total renewables	137	71	75	39
20.4	Fossil fuel + CCS	0	0	62	32
7.5	Nuclear	56	29	56	29
3.3	Losses (8%)	16	N/A	16	N/A
41.9	**Total**	**209**	**100**	**209**	**100**

2050 UK Electricity Market

50. As noted above, this two strategies model translates the 56GW nuclear baseload into the existing, or planned, four 3.2GWs and 108 S/AMRs. That is roughly one S/AMR for each three of the 330 electricity substations[69] although it may be advantageous to cluster them. A senior nuclear government adviser told us that S/AMRs would be

[69] https://www.nationalgrid.com/electricity-transmission/document/119636/download#:~:text=National%20Grid%20owns%20the%20high,cable%20and%20around%20330%20substations.

confined to approved nuclear sites of which there are only eight[70] so more 3.2GW generators, i.e. six, would make better use of them. That would still leave about 100 homeless S/AMRs so we are sticking with our arithmetic.

51. In September 2022, a Japanese team published similar analysis to this paper. They included 25.4GW and 50.7GW options for nuclear for example. They included biomass as renewable, which we reject, but it played a very small part in their analysis. More relevant was "simulation shows that a 100% renewable electricity supply can be technically feasible but economically challenging." We reached much the same conclusion. "As requested by the Japanese government, we calculated Japan's optimal power generation mix in 2050, in which renewables (wind, solar, hydro, geothermal, and biomass) account for 50 to 60%, while nuclear, natural gas (+CCS), and ammonia collectively account for 40-50%."[71]
52. We found no other reports of optimal 2050 electricity mix so had to resort to the Delphi Technique to reach the division of the 71% between renewables and fossil fuel + CCS. That division will not greatly matter as humans have the control over fossil fuel generation that they lack with renewables. The important thing is not to decommission fossil fuel generators that appear to be surplus to requirements.

Recommendations

53. Electrical capacity should remain about three times average demand and, assuming **energy** demand remains around the same, should be expected to rise by about five times by 2050.
54. Competitive electricity pricing would help prevent the continuing decline in British industry. The global reduction in CO2 emissions is not helped by off-shoring industry.
55. Biomass should be ruled out of the main electricity generating strategy.
56. Imports and exports of electricity should be balanced by 2050 but that should still provide some back-up for *dunkelflaute* days.
57. The four 3.2GW nuclear reactors under consideration would supply about 12.8GW but no furthermore such machines should be commissioned. Instead, we need a fleet of about 108 (+ one to cover for maintenance) S/AMRs generating an average of 400MW each.
58. The government should give the Great British Nuclear (GBN) recommendations full backing immediately.
59. GBN should work with the ONR and DLUHC (the department for planning) to bring the times from commitment to operation down to the Japanese level of under four years. Any delays will not just cost money but, given nuclear approval and commissioning lead times, compromise the net carbon zero 2050 target.
60. To comply with HM Treasury competition rules, GBN should begin with Rolls Royce and one other SMR, before venturing into the more modern world with two AMR suppliers. HMT should only subsidise the first one or two of each type, leaving the rest to the private sector under the supervision of GBN. This plan, or

[70] https://www.energy-uk.org.uk/our-work/generation/nuclear-generation.html
[71] https://doi.org/10.1002/eej.23396

something like it, should be put in hand immediately as the lead times on nuclear are notorious and the programme would be dealing with many unknowns.

61. Net zero seems to imply major investment in renewables to about five times current capacity. It is high time the UK insisted on home manufactured turbines and insisted on installing them with UK labour.
62. Curtailment and constraint payments should be discontinued and surplus electricity from Grid over-supply days used to make hydrogen.
63. A team of network scientists should be commissioned to model the most efficient UK distribution options bearing in mind the complexities of a future electricity distribution network and the implications for a price competitive market.
64. The Office for Nuclear Regulation should declare S/AMRs hazard-free (as they are beyond very brief boundary) so they can be sited anywhere, ideally near their users.
65. An independent committee of top scientists and technologists should review BEIS strategies and plans securely developing the electricity/energy market through 2050 and publish their conclusions so that those in turn can be peer reviewed.
66. How to transition the electricity market to full competition, eliminating government intervention (apart from policing competition) and terminating Ofgem should be the subject of a separate paper.
67. Our conclusion is that the 39%, 32% and 29% renewables, natural gas + CCS and nuclear (respectively) strategy is by far the better. The other is too risky and requires ten times the 2018 renewables capacity to be built rather than five.

Appendix

How we built the 2050 Electricity Market Model

Disclaimer: This paper has been difficult to assemble due to the astonishing inconsistencies of the published data from BEIS and its associates. We have had to be selective.

2018 Baseline

68. Energy usage has been declining in the UK since 1990 (147 to 121 mtoe) but this is mainly due to the decline in UK industry (39 to 21 mtoe).[72] Domestic, commercial and services have been static. Marine and aviation transport are irrelevant as they will not be fuelled by electricity and have to be taken out of the model. We have to hope that Britain industry will stop declining, given the fillip of rescuing renewables turbines construction from imports (if we do). Accordingly, we projected static demand for energy overall.
69. Using 2018 as the base line to avoid the Covid hiatus, demand (334TWh[73]) grosses up to 362TWh (average 41.9GW) which included 8% distribution (Grid) losses.

2050 Fossil-free Strategy

70. "Electricity accounts for nearly 20% of UK's total energy use, a figure which is largely stable over time. In 2019 43% of electricity was from fossil fuels and 37% from renewables. The remainder was provided by nuclear and imports."[74] T hen because we are hypothesising all energy will be electricity in 2050, we multiplied by five to give 1,810TWh for 2050, average 209GW, including 8% distribution losses.[75]
71. Though the curtailment figures should give us some indication of over-supply recently, they give us no indication at all of any potential over-supply in 2050, still less under-supply. It matters not how many *dunkelflaute* days a year there are; what matters is the total amounts of under- and over-availability across a year. So long as the latter exceeds the former and a year's worth of green hydrogen can be stored, there should be no blackouts.
72. 65% of mean 209GW gives us 161GW for renewables and 8% (one month equivalent of under-supply days) gives us an average 13GW shortfall. Because only 0.38% electricity survives conversion to green hydrogen and back again, a 30 day shortfall requires 79 days equivalent over-supply to make it up. We use the current

[72] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1094025/UK_Energy_in_Brief_2022.pdf
[73] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/877047/Press_Notice_March_2020.pdf
[74] https://eciu.net/analysis/briefings/uk-energy-policies-and-prices/uk-energy-and-emissions
[75] https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS

load factor of 30%. Those figures give us a 493GW capacity need for Direct to Grid sales and 114GW for Green Hydrogen production. All this leads to the Fossil-free mode which has some hydrogen production except it leads to a very high number for renewables capacity: a minimum of 444GW versus 44.4GW in 2018,[76] i.e. 10 times. The greater problem is whether there would be enough surplus electricity to provide the Green Hydrogen from the over- supply days for the under- supply days. Current figures make that highly unlikely and even if there were, how would UK industry cope with the critical, massive storage requirements? And that scenario makes electricity supply highly vulnerable to changing weather conditions.

With Fossil Natural Gas +CCS strategy

73. The only substantive development was to divide the non-nuclear 71% between renewables and fossil fuel (natural gas) and CCS. As noted above, the literature was not much help so we had recourse to the Delphi Technique, or an informal version thereof. The conclusion was that the renewables share should be slightly higher. It is cheaper but less reliable.

[76] https://www.gov.uk/government/statistics/electricity-chapter-5-digest-of-united-kingdom-energy-statistics-dukes