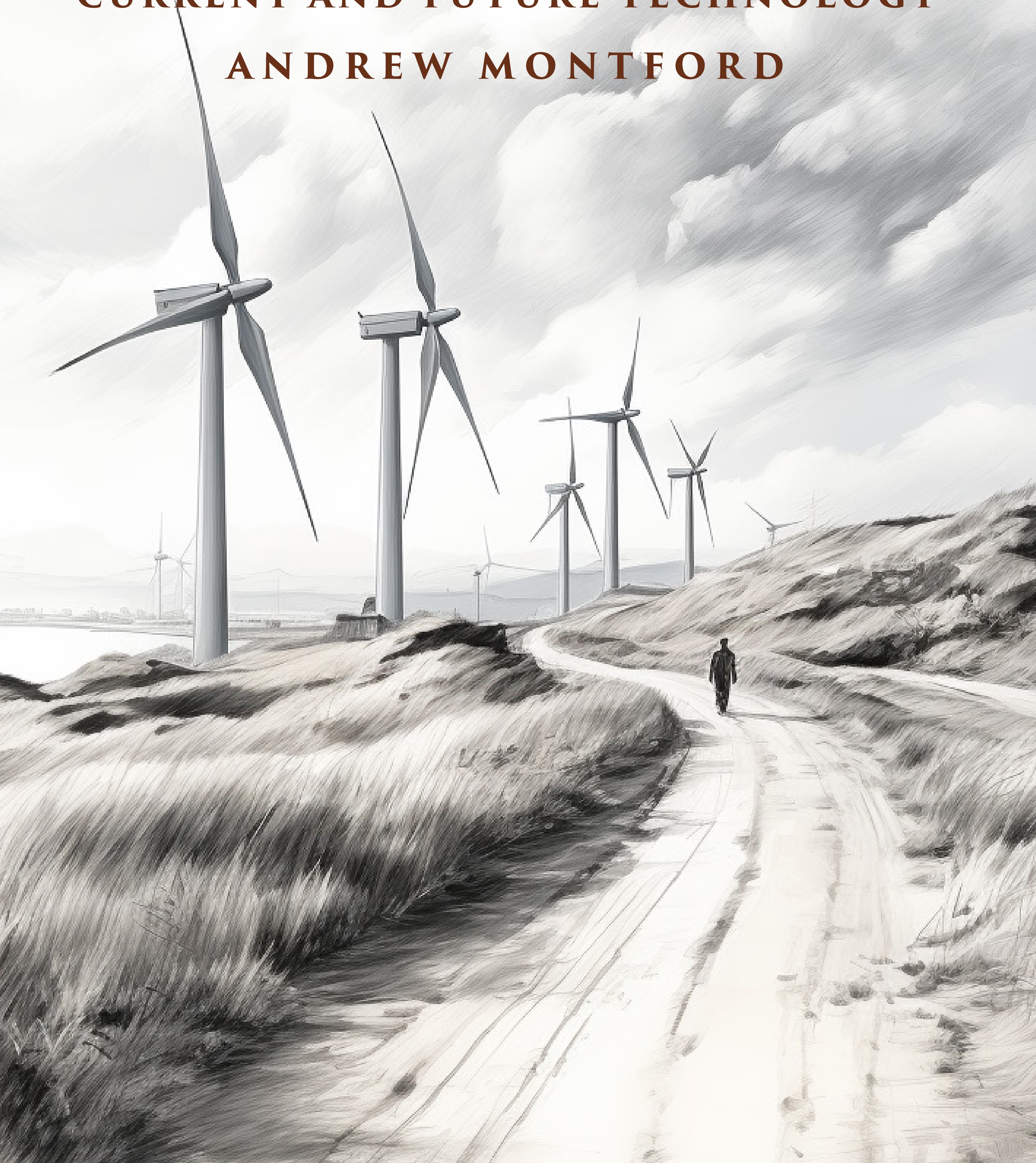
NET ZERO WATCH

COSTING THE GREEN GRID

CURRENT AND FUTURE TECHNOLOGY

ANDREW MONTFORD



Costing the Green Grid: Current and future technology

Andrew Montford

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About the author

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Executive summary

A recent Royal Society report claimed the electricity grid could be decarbonised without materially raising the cost per unit of electricity delivered (the 'system cost'). The annual cost would be of the order of £30 billion. However, this conclusion relied on extraordinary input parameters:

- demand values that are very low, and hardly vary with temperature, apparently through use of an incorrect seasonal demand curve;
- highly optimistic cost and efficiency assumptions.

These assumptions included:

- 60% reduction in offshore wind capital cost
- 70% reduction in offshore wind operating costs
- 50% increase in offshore wind output
- 30% reduction in solar capex
- 70% reduction in solar opex
- 90% reduction in electrolyser capex
- 45% increase in electrolyser efficiency
- 60% reduction in reciprocating engine capex
- 55% increase in reciprocating engine efficiency

compared to levels seen today. In order to deliver a decarbonised grid by 2050 at the overall cost stated in the report, these improvements would have to be delivered in the next 2–3 years.

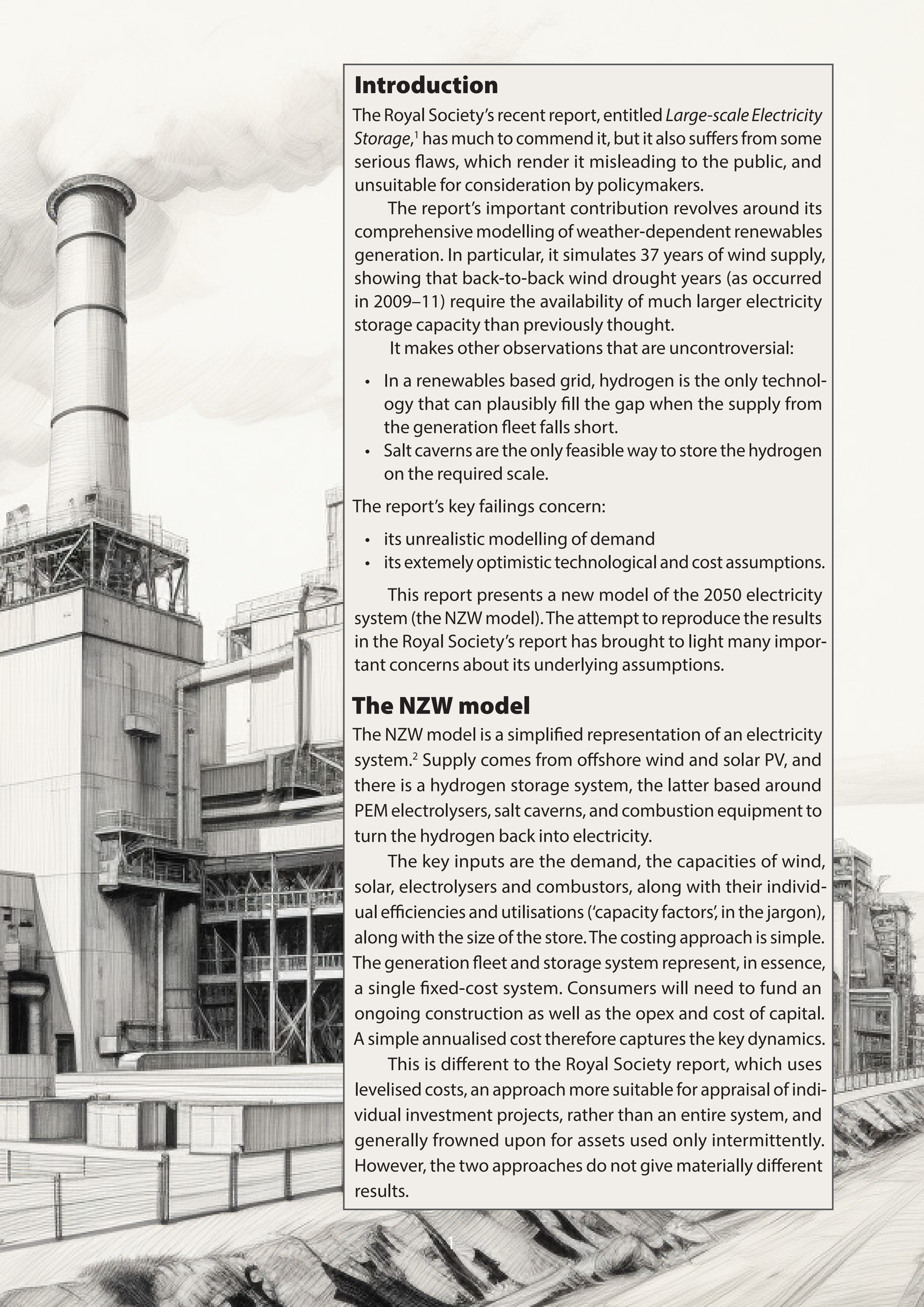
The electricity system model presented in this paper reproduces the Royal Society's results and then examines the effect of correcting the flaws.

- Using the correct seasonal demand curve increases costs by around 10%, to £33 billion per year. The latter figure represents around £1000 per household.
- Introducing interannual variability – that is, allowing for extra demand in cold years – increases annual spend to over £50 billion, or £1700 per household.
- Using assumptions representing current technology and costs, but without allowing for interannual variability, increases annual spend to around £160 billion, or £5000 per household.
- If demand is allowed to vary year by year, then 2023 technology would give an annual spend of around £260 billion (perhaps £8000 per household).

This rate of spend would have to be sustained indefinitely.

Obviously, some reductions in costs should be expected by 2050, so the last scenario only determines the envelope of possible outcomes. However, it is clear that the Royal Society contains a significant error, having apparently used incorrect figures for their seasonal demand curve. The sheer scale of the optimism in its assumptions also means that it is misleading for the policy community.

Together, these flaws mean that the report should be withdrawn.



Introduction

The Royal Society's recent report, entitled *Large-scale Electricity Storage*,[1] has much to commend it, but it also suffers from some serious flaws, which render it misleading to the public, and unsuitable for consideration by policymakers.

The report's important contribution revolves around its comprehensive modelling of weather-dependent renewables generation. In particular, it simulates 37 years of wind supply, showing that back-to-back wind drought years (as occurred in 2009–11) require the availability of much larger electricity storage capacity than previously thought.

It makes other observations that are uncontroversial:

- In a renewables based grid, hydrogen is the only technology that can plausibly fill the gap when the supply from the generation fleet falls short.
- Salt caverns are the only feasible way to store the hydrogen on the required scale.

The report's key failings concern:

- its unrealistic modelling of demand
- its extemely optimistic technological and cost assumptions.

This report presents a new model of the 2050 electricity system (the NZW model). The attempt to reproduce the results in the Royal Society's report has brought to light many important concerns about its underlying assumptions.

The NZW model

The NZW model is a simplified representation of an electricity system.[2] Supply comes from offshore wind and solar PV, and there is a hydrogen storage system, the latter based around PEM electrolysers, salt caverns, and combustion equipment to turn the hydrogen back into electricity.

The key inputs are the demand, the capacities of wind, solar, electrolysers and combustors, along with their individual efficiencies and utilisations ('capacity factors', in the jargon), along with the size of the store. The costing approach is simple. The generation fleet and storage system represent, in essence, a single fixed-cost system. Consumers will need to fund an ongoing construction as well as the opex and cost of capital. A simple annualised cost therefore captures the key dynamics.

This is different to the Royal Society report, which uses levelised costs, an approach more suitable for appraisal of individual investment projects, rather than an entire system, and generally frowned upon for assets used only intermittently. However, the two approaches do not give materially different results.

Reproducing the Royal Society's figures

Demand total

Although the Royal Society report considers hourly weather data for 37 years, this is only applied to the supply side. The same hourly demand curve, with a total of 570 TWh, is always used. This is met by approximately 740 TWh of potential generation, some of which is curtailed, the remainder generating hydrogen for the store.

The lead author of the Royal Society report, Sir Christopher Llewellyn Smith, concedes that using the same figure every year leaves the authors open to criticism:[3] once domestic heat and transport are electrified, they will be strongly temperature dependent, since cold affects:

- heat demand
- heat-pump efficiency
- battery efficiency (notably in EVs).

Sir Christopher argues that 570 TWh is a realistic prediction of annual demand in 2050. At first glance, the figure is implausible:

- It is just 75% above current levels, but would have to include huge new demands from heat and transport.
- It represents a 60% reduction in final energy consumption compared to today, down to levels last seen at the end of the 19th century.[4]
- In the same month that the report was published, Llewellyn-Smith was a co-author of another paper on the future electricity grid, which put 2050 demand at 1,500 TWh.[5]

That said, the number is similar to one of National Grid ESO's Future Energy Scenarios (NGESO; FES); the Consumer Transformation scenario has demand of 550 TWh, met by generation of 726 TWh.[6] So, while the Royal Society report is silent on the assumptions underlying its demand curve, it is possible that these are similar to those in FES.

Unfortunately, not all of the assumptions behind FES are clear either, but enough detail is give to allow some conclusions to be drawn. For example, it says that the Consumer Transformation scenario estimates for electricity for heat, of just 141 TWh per year (compared to 254 TWh of gas in 2022), assumes:

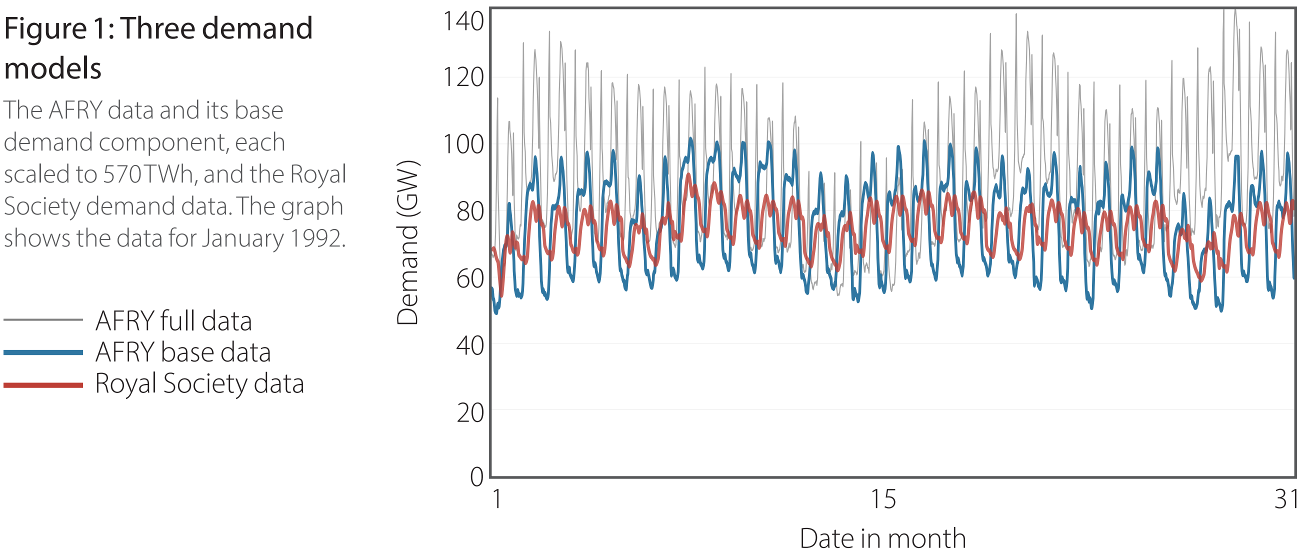
- all homes will be 0.5°C colder than today (in another scenario, the figure is higher);[7]
- a programme of insulation to further reduce demand will have been completed.

Homeowners will presumably be compelled to maintain lower temperatures through their smart meters, although the FES report is, perhaps unsurprisingly, silent on such details.

Some simple calculations suggest that such an insulation

Figure 1: Three demand models

The AFRY data and its base demand component, each scaled to 570 TWh, and the Royal Society demand data. The graph shows the data for January 1992.



programme would need to be extensive, and would thus carry a significant cost – perhaps of the order of £0.5 trillion (Appendix A). This highlights an important issue with all such analyses. Any assumptions made about major reductions in demand will almost certainly be based on actions with major cost implications. But if the subsequent analysis is restricted to the electricity system alone, those costs will be invisible. The cost of the Consumer Transformation scenario was put at around £3 trillion pounds, or about £100,000 per household.

However, even if an ambitious spending programme could produce heat demand reductions on the scale envisaged, another aspect of the Royal Society data reveals a further concern. As well as varying from year to year, the temperature dependence of demand should also give rise to a pronounced seasonal curve. It is therefore surprising that summer demand is only 15–20 GW lower than winter demand in the Royal Society's data (see their Figure 1). This is implausible when sense checked against reasonable assumptions. It is also implausible when compared to the FES2023 Consumer Transformation scenario, which has a seasonal amplitude of around 70 TWh.[8] The more ambitious 'Leading the Way' scenario has amplitude of 57 TWh; see discussion in the Appendix.

Demand curve

Although the total of the Royal Society's demand is known, the report's authors say they are unable to pass on the hourly profile used, which they obtained in confidence from the engineering consultancy AFRY. So apart from the information that the seasonal demand curve appears unduly shallow (see above), there is an immediate difficulty in reproducing the result. Fortunately, another set of AFRY demand data for 2050, which was prepared for the Climate Change Committee's Net Zero report, has been published.[9]

This is split into base demand plus each of the new demands from electrification of the economy.

The total of these separate demands, scaled to 570 TWh, was much more variable than the data in the Royal Society's report (see my Figure 1). This suggested to me that the data used might only be *base* demand – that is, current demand scaled to the 2050 population. Scaling this element of the Net Zero AFRY data to 570 TWh instead gave a curve very similar to the Royal Society's; the absolute value was approximately correct and the variations in the daily totals coincided too, but the diurnal variation was still too large (see my Figure 1).

The total demand figure used by the Royal Society is arguably extraordinarily ambitious, probably requiring mass coercion of the public, but it is at least consistent with the FES scenario. But the pattern of demand is inconsistent and appears to be an error. The impact will be considered below.

Scenario 1: Base case

My surmise about the nature of the demand pattern is strengthened because, using the AFRY base data rescaled to 570 TWh, I was able to get reasonable volumetric agreement with the Royal Society's overall result: overgeneration to an average of around 790 TWh was sufficient to meet demand in any year, with the store not falling below 20% full (the Royal Society figure was 740 TWh). With the more variable AFRY total demand pattern, scaled to the same figure, the store was empty at one point.

The Royal Society does not emphasise the fleet size and capacity factor required to deliver this level of generation, working instead with a volume of electricity generation. They take hourly capacity factors published for the 37 years from 1980 to 2017, scaling them up to give the required 740 TWh average. They do not particularly concern themselves with what nameplate capacities of wind and solar would be required to deliver this output, but they refer in a footnote to a fleet of around 300 GW. In the NZW model, the same output can be generated using 132 GW each of wind and solar, but with the wind capacity factors scaled to 57%. (This is the figure used in the BEIS costings, but is highly optimistic; see below.) Similar results can be obtained with different capacities and capacity factors.

The Royal Society suggests that at a 5% cost of capital, the average cost of electricity supplied to customers will be £65/MWh. This implies an annual cost recovery of £37 billion, equivalent to nearly one HS2 project per year (in terms of its original budget). The NZW model gives slightly lower costs, at £53/MWh, equivalent to £30 billion per year, depending on the assumptions about fleet size and capacity factor. This is around £1000 per household. Given the different costing approaches, this suggests there are no major structural differences between the NZW and Royal Society models.

Scenario 2: With AFRY total demand pattern

Substituting the AFRY total demand pattern for the base demand pattern that appears to have been used by the Royal Society increases the amount of generation required to around 900 TWh. This means a fleet of 150 GW each of wind and solar (assuming the same capacity factor discussed in Scenario 1). The unit cost increases to around £58/MWh, and the total annual cost to £33 billion, 10% higher than in Scenario 1. This suggests the Royal Society's original results may have been understated to a similar extent, so perhaps by £3 billion per year.

Scenario 3: With fully variable demand

The AFRY total demand curve represents a single, average year, and thus is unrealistic in that it fails to account for cold and warm years. In this scenario, I therefore replace the Royal Society/AFRY figures with the NZW model of demand, while leaving their assumptions about costs and efficiencies in place. In parts, the NZW uses figures straight from the published AFRY model, but for the main temperature dependent elements – heat and transport – it uses results reported by Watson et al. and Hao et al. respectively.[10,11] The demand figures it produces are rather higher than the Royal Society's.

The system required to meet this demand is a fleet of 255 GW each of wind and solar, producing output of around 1400 TWh. A 180 TWh store is required. While the unit costs are 20% higher than Scenario 1, at around £64/MWh, the total of around £54 billion, or £1700 per household, is 80% higher.

Parameter values

The Royal Society's cost data appears to have been based on the BEIS 2020 Generation Costs report and, in particular, the values for 2040 in that paper.[12] Those values should be seen as being entirely spurious, on two grounds. Firstly, the recent decision to award huge price increases to renewables generators raises serious question marks over the credibility of BEIS's figures, which are much lower, even at 2025. Secondly, the true current cost of offshore wind, as revealed by analysis of financial accounts, appears to be 2–3 times that put forward by BEIS.[13]

However, it is still worth examining the detail. The subsections below consider the assumptions underlying BEIS's projections and compares them to recent empirical data.

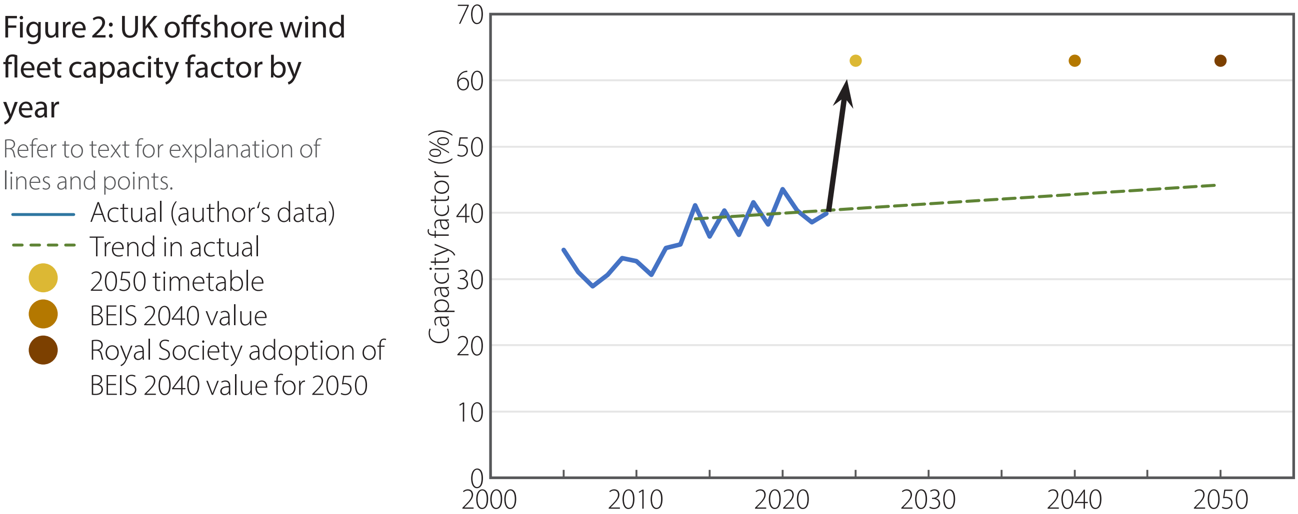
Offshore wind

Output

The average capacity factor of the UK offshore wind fleet has been around 40% for many years (Figure 2; blue line), with only a slight upward trend over that period (green dotted line). However, BEIS's assumption is that capacity factors will reach 63% by 2040 (tan

Figure 2: UK offshore wind fleet capacity factor by year

Refer to text for explanation of lines and points.



point), and the Royal Society adopts this figure as their value for 2050 (brown point). Thus BEIS are expecting a 57% improvement (23 percentage points), which is implausible given the history.

Worse, offshore windfarm lifetimes are around 25 years, so many of those in operation in 2050 will start to be installed in the next few years. As a result, this improvement in output needs to be achieved almost immediately (yellow point). This is beyond plausible.

Similar arguments apply to the capacity factors that BEIS uses for onshore wind. However, since the NZW model does not use any onshore wind, I do not intend to set out the deficiencies here.

Capex

The BEIS assumption for offshore wind capex in 2040 is £1.3m/MW of capacity. The average for the five most-recently commissioned offshore windfarms in the UK is £3.0m/MW. Thus the Royal Society report relies on a 60% reduction in costs. As above, this needs to be an immediate rather than gradual improvement, because windfarms in operation in 2050 will start to be installed in the next few years. This is implausible.

Opex

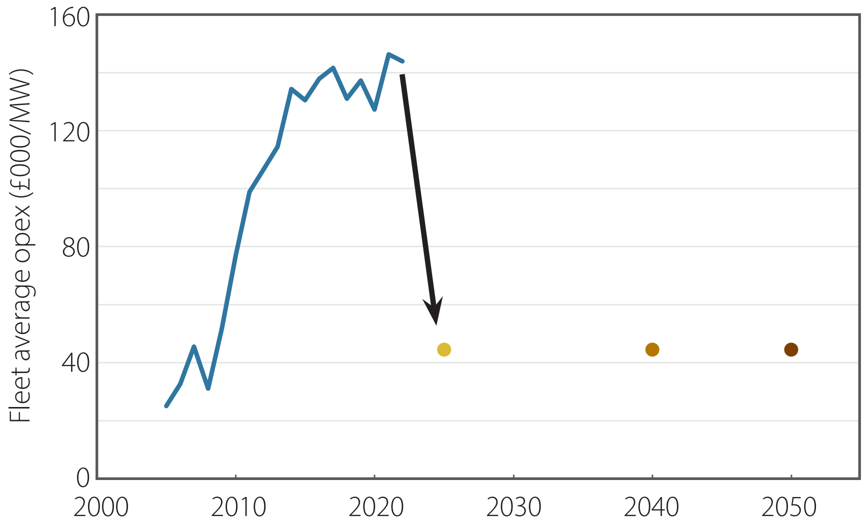
BEIS assumes that lifetime average opex costs for offshore windfarms will be £44,500/MW/year in 2040. However, the financial accounts of offshore wind farms show that opex has been increasing rapidly in recent years, as windfarms move to deeper waters, further offshore, in search of higher capacity factors.

Typical offshore windfarm opex costs are now of the order of £150,000/MW/year (see Figure 3). However, those costs increase as the turbines age, and lifetime averages are likely to be closer to £190,000/MW. Thus, in the face of a recent steep increase in costs, BEIS are assuming a 75% reduction in coming years. This is implausible, particularly since the improvement would again have to be delivered in the next few years.

Figure 3: UK offshore wind fleet opex by year

Refer to text for explanation of lines and points.

Actual (author's data)
2050 timetable
BEIS 2040 value
Royal Society adoption of BEIS 2040 value for 2050



Solar

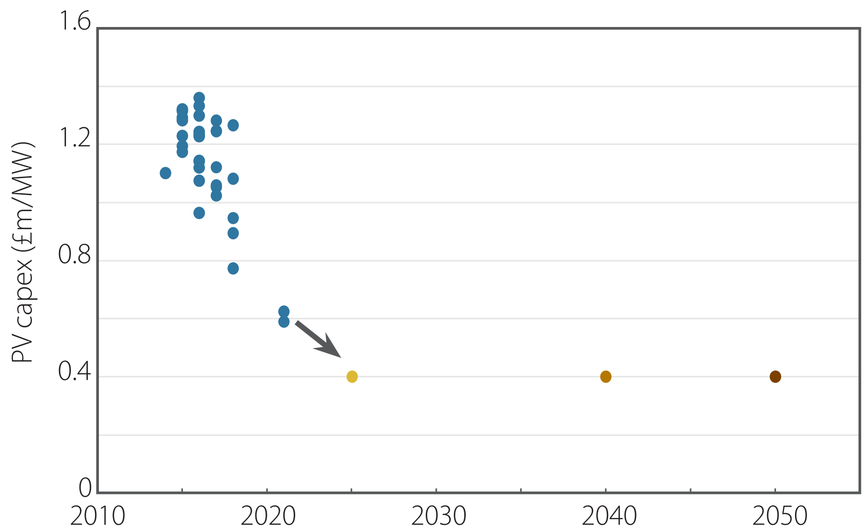
Capex

For solar, BEIS is also predicting major capex reductions by 2040. While recent data on solar costs is less abundant than that for wind, a good case can be made that capital costs have fallen rapidly in recent years (Figure 4), although this conclusion is based on just two recent data points.

Figure 4: UK solar capex by year

Refer to text for explanation of lines and points.

Actual (author's data)
2050 timetable
BEIS 2040 value
Royal Society adoption of BEIS 2040 value for 2050

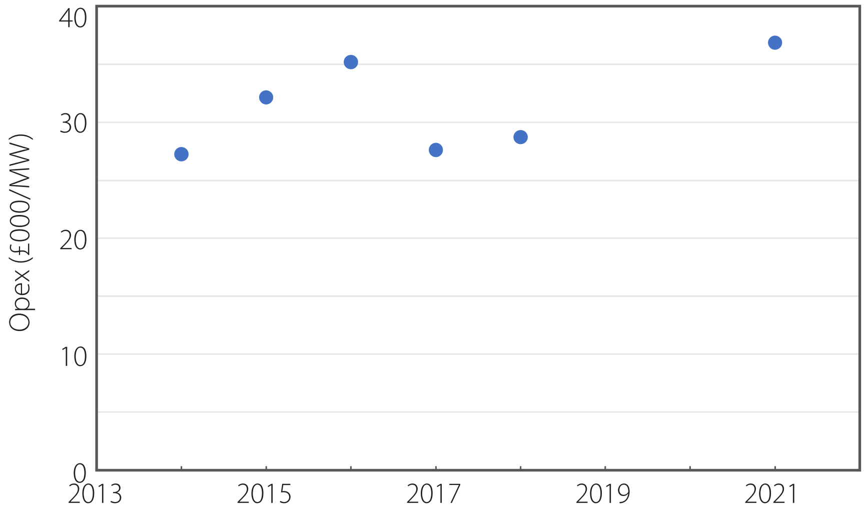


Opex

BEIS predicts opex spend of £8900/MW/year in 2040. However, the typical spend of UK solar farms has been around £30,000/MW for many years, with no sign that more recent ones have lower costs

Figure 5: UK solar opex by year of commission cohort

Source: Author's data, based on audited accounts.



(Figure 5). Thus BEIS's prediction of a 70% reduction in costs is implausible even for 2040, let alone 2025.

Hydrogen system

Hard data to assess the predictions made for the hydrogen system is in short supply. PEM electrolysers are few and far between, and salt cavern storage is in its infancy. There is, however, more information available about the combustion equipment. The Royal Society mentions reciprocating engines, which are already in widespread use, but powered by methane and diesel. Open-cycle gas turbines would be another possibility.

Helpfully, the report provides estimates of current costs and efficiencies, and from these it can be seen that the Royal Society is predicting major improvements across the board. For electrolysers it is predicting:

- a 50% improvement in electrolyser efficiency, from 50% to 73% (23 percentage points)
- a reduction in capital cost of up to 90%.

Since PEM electrolysers are a relatively new technology, this is not impossible, but these changes would need to be achieved in short order to deliver a system of the stated efficiency by 2050.

For salt cavern storage, there is little hard data in the public realm, and the Royal Society report uses figures from the H21 NE hydrogen project. I have accepted the figures used.

For combustion equipment, the report suggests that by 2050 there will be:

- a 60% reduction in capital costs
- a 55% increase in efficiency.

Reciprocating engines (and gas turbines) are both mature technologies, so this appears to be ambitious, to say the least.

Cost of capital

The Royal Society report uses a cost of capital of 5%. This is implausible in the current inflationary environment. While it is likely that these pressures will subside in future, figures of 6% for wind and solar, and 8% for other assets are more likely. The lower values for wind and solar result from their Contracts for Difference, which derisk them for investors.

Scenarios with current technology

Scenario 4: Using 2023 technology

In a fourth scenario, I replace the speculative assumptions used by the Royal Society with figures based on current performance – either from data, or from the RS report itself. I return the system demand to 570 TWh and use the AFRY total demand pattern. This then requires a 180 TWh store, and a fleet of 264 GW each of wind and solar. The cost each year rises to around £156 billion – perhaps £5000 per household – or up to £275/MWh. At these levels, the 2050 grid is a £1.3 trillion project, requiring the equivalent of three HS2 projects to be delivered every year into the future. This theoretically means that the public could be forced to foot the bill for £150 billion per year more than suggested in the original report.

Scenario 5: Full demand and 2023 technology

In this final scenario, the assumptions from Scenario 4 are repeated, except that the NZW demand model is used. The result is a further increase in fleet sizes and costs, with the unit cost up to nearly £300/MWh, and the annual bill for consumers to foot increasing to £255 billion, approximately £8000 per household.

The fleet sizes and the results for all scenarios are set out in Table 1. The underlying costs, efficiencies and capacity factors used can be seen in the Appendix.

Other aspects

From a policymaker's perspective, the true annual cost should be seen as falling into the range defined by the third and fifth scenarios; that is, £54–255 billion per year. While it is unrealistic to expect the 2023 costs to pertain across the board in 2050, it is worthy of note that the costs of both onshore and offshore wind farms commissioned in the last five years are higher than their equivalents commissioned before 2010. In other words, costs can go up as well as down. It should be noted that these figures include nothing for ancillary grid services, nor for transmission and distribution costs, nor the insulation programmes that might make the lower figures possible. Prudence would dictate caution over predictions of dramatic cost reductions.

An annual cost of up to £255 billion, compared to £14 billion today, implies an extra cost of around £240 billion to eliminate the

Table 1: Assumptions and results

	Scenario 1 Royal Society assumptions	Scenario 2 With AFRY full demand pattern	Scenario 3 With NZW demand model	Scenario 4 With AFRY full demand pattern and 2023 technology	Scenario 5 With NZW demand model and 2023 technology
Assumptions					
Offshore wind (GW)	132	150	255	263	407
Solar (GW)	132	150	255	263	407
Store (TWh)	123	123	180	180	240
Electrolysers (GW)	60ᶧ	60	60	60	140
Combustors (GW)	160ᶧ	160	260	160	280
Results					
Fleet output (TWh)*	750–800	850–950	1450–1600	1050–1200	1650–1850
Cost of capital	5%	5%	5%	6–8%†	6–8%†
Annual cost (£bn)	30	38	54	156	255
Cost per MWh consumed (£)	53	67	61–67	275	270–300

* Approximate range, before constraints. †6% for wind and solar, 8% for everything else. ᶧThe Royal Society's assumptions here gave periods with insufficient generation in the NZW model, so the figures have been adjusted.

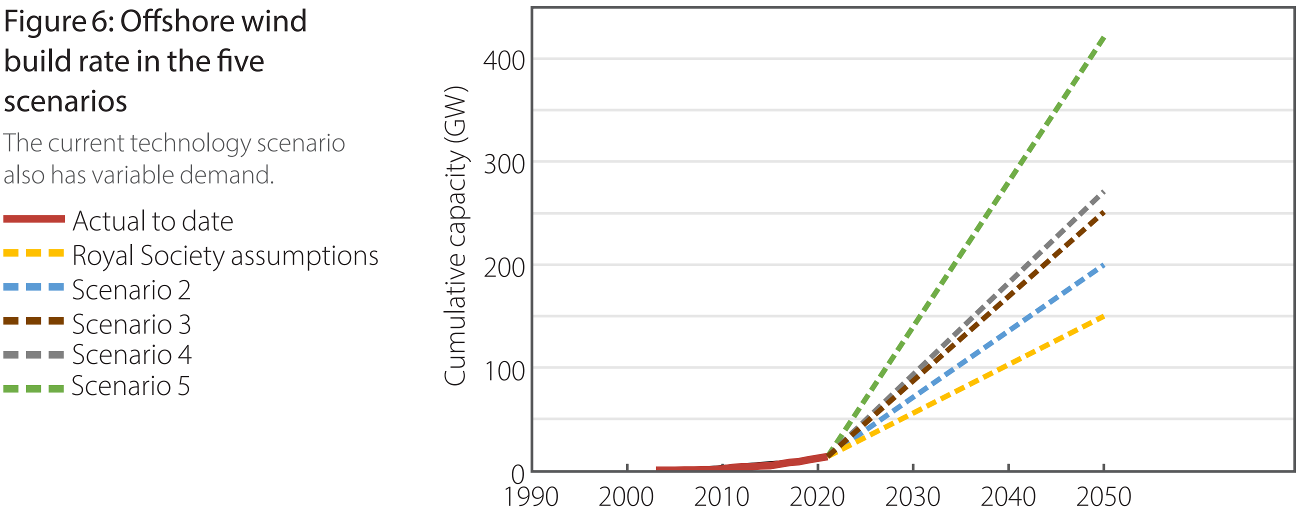
UK's 330 Mt of carbon dioxide emissions, or around £700/t. This greatly exceeds typical estimates of the cost of global warming, the majority of which would be under £100/tCO_2e. Even on the Royal Society's highly optimistic assumptions (Scenario 2), the cost of abatement through renewables and hydrogen is at best only slightly less than the benefits. Thus mitigating climate change through renewables and hydrogen is almost certainly irrational.

Rate of build

Throughout this paper, I have noted that improvements in costs and efficiencies would need to manifest themselves almost immediately if the Royal Society's stated total capital cost of £410 billion were to be met. I have shown that parameter values grounded

Figure 6: Offshore wind build rate in the five scenarios

The current technology scenario also has variable demand.



in empirical data rather than speculation about the future give much larger fleets and much higher costs. However, it is also worth considering the deliverability of the generation fleet necessary. This is shown in Figure 6, which shows the cumulative capacity of offshore windfarms delivered in the last 20 years, and the change in pace necessary to deliver the fleets in the five scenarios in Table 1. It seems unlikely that an engineering project on this scale could even be attempted, let alone delivered.

Conclusions

The Royal Society's report appears to contain a significant error, in that it used an incorrect seasonal demand curve, which led to it understating the costs. This alone should lead to the report's withdrawal.

The report also used a demand assumption that was fixed with respect to temperature and extremely low, further understating the costs. The nature of the assumption – in one respect ambitious, and in another, unrealistic – was not explained to readers.

Finally, the input assumptions for costs and efficiencies were extraordinarily optimistic – so far from today's realities as to be little more than fantasy – and again this was not made plain. This was particularly disappointing because I had corresponded with Professor Llewellyn Smith on the subject of renewables costs before the report's publication.

Policymakers should have been made aware of what the Net Zero project would cost with currently available technology, so as to root its conclusions in empirical reality. Were they to understand the extent to which the Royal Society's conclusions rely on an extraordinary set of improvements in costs and efficiencies, they might well take a different view of the wisdom of continuing with the decarbonisation effort, which appears to be much more damaging than global warming.

Appendix

Achieving demand of 570 TWh

FES2023 says that it will save 15 TWh through reductions in room temperatures of 0.5°C,[6] and 73 TWh per year through improvements to building fabric. Base demand is given as 382 TWh, so the savings figures suggest that insulation measures will be delivering heat demand reductions of the order of 25%. According to NGESO, the heat pump coefficient of performance (CoP) assumed is 3, which, applied to 80% of the building stock, and allowing for an increase in the number of homes, would give a figure commensurate with NGESO's demand for electricity for domestic heat in 2050 of 141 TWh. Calculations approximately in accord with these numbers are set out in Table 2.

The insulation measures would be expensive. FES2023 does not include a costing, but FES2020 did, and the cost of insulation measures for the Consumer Transformation scenarios was, at that time, put at £300 billion, or perhaps £10,000 per property. This is arguably rather small to produce a 25% reduction in heat demand, and presumably does not include any cost for disruption while insulation works are taking place. A pilot project in Cambridge produced average 60% savings in relatively small dwellings at an average cost of £85,000 per house.[14] A cost of perhaps £20,000 per house might therefore be needed to deliver a 25% heat demand reduction in the existing housing stock, amounting to a total of perhaps £0.5 trillion. The extra cost of the new Passivhaus stock would also be significant.

It is reasonable to question whether consumers would be willing to pay such sums and still keep their homes at lower temperatures than they do today.

Daily peak heat demand

FES 2023 reports peak domestic heat demand of around 30 GW.[15] This appears to be in 'normal' weather, since the more extreme 'Average Cold Spell' demand is only reported for gas. This number is broadly consistent with the two scenarios set out in the last subsection, and CoPs of 3 confirms that this is a 'normal-weather' peak.[16] Much lower CoPs would be expected in cold weather.

Peak UK demand for domestic heat is of the order of 200 GW. Applying the savings proportions set out above, and assuming a heat pump efficiency of 2.2 (since peak heat demand occurs in low temperatures, when heat pumps are at their least efficient), the peak in 2050 would be at least 70 GW (Table A1), so the amplitude of the seasonal cycle in total demand should be at least this value. In FES 2023 Consumer Transformation the figure is 72 GW.[17] In the more ambitious Leading the Way scenario, it is 57 GW. Both figures are much higher than the Royal Society's figure of 15–20 GW.'

Table 2: Domestic heat reduction

	Annual total TWh	Peak GW
Heat demand		
Heating	348	182
Hot water	35	18
Total	383	200
Savings		
Temp change 0.5°C = 7%	16	9
Insulation: 25% of remainder	74	43
	90	52
2050 heat after savings		
Heating	221	4
Hot water	31	1
Total	252	5
Plus new homes		
Heating	7	134
Hot water	5	19
Total	12	152
CoPs		
Heating	4	2.5
Hot water	2	1
Electricity demand for domestic heat in 2050		
Heating	57	53
Hot water	18	19
Total	75	72

Endnotes

1 https://royalsociety.org/-/media/policy/projects/large-scale-electricity-storage/Large-scaleelectricity-storage-policy-briefing.pdf

2 The spreadsheet can be downloaded from the web page for this paper.

3 See https://www.youtube.com/watch?v=Y1_gL_XXaQQ&t=1759s.

4 Warde suggests that in 2000, England and Wales consumed around 11,000 PJ of energy. A reduction of 60% would be to around 4,400 PJ, which on Warde's chart is around 1896. See P Warde, *Energy Consumption in England and Wales*, 1560–2000. Consiglio Nazionale della Ricerche, Italy, Figure 4. See https://histecon.fas.harvard.edu/energyhistory/data/Warde_Energy%20 Consumption%20England.pdf.

5 B O'Callaghan et al. 'Could Britain's energy demand be met entirely by wind and solar?' Working Paper No. 23-02 University of Oxford Smith School of Enterprise and the Environment, 2023. https://www.smithschool.ox.ac.uk/sites/default/files/2023-09/Could-Britains-energy-demand-be-met-entirely-by-wind-and-solar-SSEE-working-paper.pdf

6 https://www.nationalgrideso.com/document/283101/download. See p. 13.

7 M Ryland, NGESO, pers. commun.

8 NGESO FES2023 data workbook, sheet ED1. The 2050 peak demand is 113 TWh, while the minimum is 42 TWh.

9 https://www.theccc.org.uk/wp-content/uploads/2021/08/EIR-Technical-working-level-Net-Zero-spreadsheets.zip

10 https://www.sciencedirect.com/science/article/pii/S037877882100061X#s0105

11 https://pdf.sciencedirectassets.com/271750/1-s2.0-S0959652620X00035/1-s2.0-S0959652619342738/am.pdf

12 https://www.gov.uk/government/publications/beis-electricity-generation-costs-2020

13 https://www.thegwpf.org/publications/cheap-offshore-wind-power-claims-are-false-data-reveals/

14 M Kelly. *Decarbonising Housing: The Net Zero Fantasy*. Report 38, The Global Warming Policy Foundation. https://www.thegwpf.org/content/uploads/2020/02/KellyNetZero-2.pdf

15 FES2023 data workbook, sheet ED1.

16 For CoP of 3, it implies delivery of 3 kW of heat, implying a 50% reduction in heat demand from 6 kW today. For CoP of 4, it implies delivery of 1.5 kW of heat, and thus, a 75% reduction in heat demand.

17 FES2023 data workbook, sheet ED1.

For further information about Net Zero Watch, please visit our website at www.netzerowatch.com.