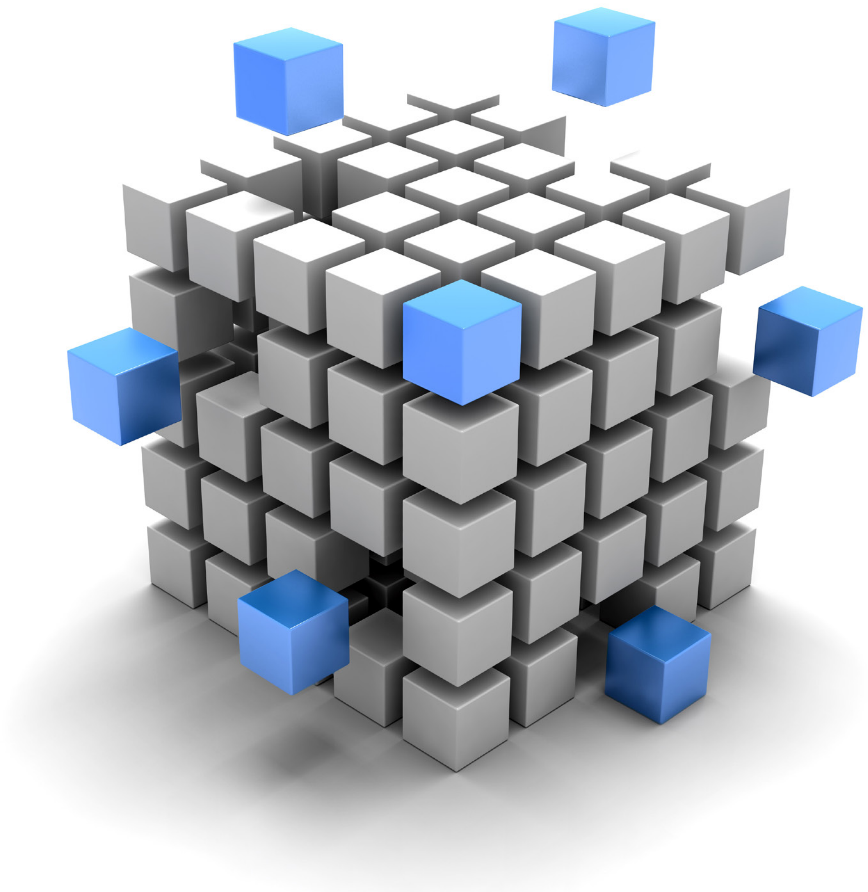
Small Modular Reactors

The next big thing in energy?

Matt Rooney



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About the Author

Matt Rooney joined Policy Exchange in 2017 as a Research Fellow in the Energy and Environment Unit. From 2011 to 2017, he studied for an MPhil in Technology Policy and a PhD in Energy Policy at the University of Cambridge, where he researched strategies for the deployment of new energy technologies, with a particular focus on carbon capture and storage and nuclear power. Prior to this, he was employed for six years at the STFC Rutherford Appleton Laboratory, where he designed components for international particle physics experiments. He is a British Science Association Media Fellow, having worked briefly as a science policy journalist with Times Higher Education. He is a fully chartered member of the Institution of Mechanical Engineers and holds an MEng in Mechanical Engineering from the Queen's University Belfast.

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Glossary

Term	Definition
BEIS	Department for Business, Energy and Industrial Strategy.
CCGT	Combined-cycle gas turbine – used to produce electricity from natural gas.
CCS	Carbon capture and storage – collective term for technologies that capture carbon dioxide, which is subsequently compressed and stored underground indefinitely.
CO_2	Carbon dioxide, the main greenhouse gas. The vast majority of CO_2 emissions come from the burning of fossil fuels such as coal, gas and oil.
DECC	Department for Energy and Climate Change – a predecessor to BEIS
ETI	Energy Technologies Institute.
gCO_2/kWh	Grams of carbon dioxide emissions per kilowatt hour of energy used or produced. A measure of 'carbon intensity' of a fuel.
GW	Gigawatt: a measure of power or electrical output. 1 GW = 1,000 megawatts = 1,000,000 kilowatts.
Gen III & Gen IV	Third- and fourth-generation nuclear reactors. Gen III comprises current designs used in most of the nuclear power stations around the world today, whilst Gen IV are more speculative future designs under development.
IEA	International Energy Agency.
IPCC	Inter-governmental Panel on Climate Change.
Ktoe, Mtoe	Kiotonnes or megatonnes of oil equivalent – a common unit of energy
LCOE	Levelised cost of electricity – a method of comparing the total lifetime cost of different electricity technologies that takes into account the time value of money
$MtCO_2e$	Megatonnes of carbon dioxide equivalent – a standard unit of greenhouse gas emissions
OCGT	Open-cycle gas turbine – like a CCGT. Less efficient, but with a faster response time.
PWR	Pressurised water reactor – the most common type of nuclear reactor used in power stations
RED	Renewable Energy Directive – an EU regulation that set targets for renewable energy deployment in member states.
SMR	Small modular reactor.
TWh	Terawatt-hour: a measure of energy equivalent to the power consumption of one terawatt for one hour. One TWh equals 1,000,000,000 kWh.

Executive Summary

Given the anticipated rise in demand for low-carbon electricity in the coming decades, the various limitations of renewable sources of energy, and the difficulties in financing and reducing costs of large nuclear power plants, small modular reactors could be a crucial technology for the UK in decarbonising our energy system and rejuvenating our nuclear industry.

Context

The magnitude of task facing the UK in its transition to a low-carbon economy is daunting. By 2030, 14 of the UK's 15 nuclear power plants will have closed. Combined with the Government's decision to phase out coal power by 2025, this means that around 40% of the UK's reliable electricity capacity will have disappeared. The risk of blackouts can be managed in the short term, but in the medium to long term large quantities of new low-carbon electricity capacity will be required. The Committee on Climate Change estimate that the UK will need **80-100 terawatt-hours of low carbon electricity supply to meet our legally binding decarbonisation target – almost a third of current demand.**[1]

Beyond 2030, the scale of the challenge will increase. The Government have recently announced that it will ban the sale of petrol and diesel from 2040, but the astonishing pace of electric vehicle development means the market may deliver this outcome before then, thus making the 2040 ban almost redundant. **National Grid estimate that if our entire light vehicle fleet is electrified this could add more than a quarter to current electricity demand.**[2]

The energy required for domestic heating is much greater than transport, currently being double that to power our entire electricity grid. The majority of houses in Britain are heated by burning methane that is delivered through our extensive natural gas network. A possible decarbonisation solution is to use our existing gas network to deliver hydrogen to homes instead of methane as hydrogen combustion produces no carbon emissions. In the short term the hydrogen could be produced through steam methane reformation of natural gas (perhaps combined with carbon capture to reduce carbon dioxide emissions). A more sustainable solution in the longer term, however, is hydrogen production through hydrolysis of water. **Producing enough hydrogen to heat the country using hydrolysis would require electricity production to treble from current levels.**

We are going to need previously unthinkable levels of new low-carbon electricity capacity.

1 The Committee on Climate Change (2017) *Reducing emissions and preparing for climate change: 2017 Report to Parliament, Summary and recommendations*

2 National Grid (2017) *Future Energy Scenarios*

The limits of renewable energy

Decarbonising our existing electricity system with 100% renewable energy would be possible, but unnecessarily expensive and perhaps unsustainable. The intermittent nature of solar and wind would mean that large amounts of under-utilised backup capacity and storage would be required at great expense to the consumer/taxpayer. Biomass could be used to provide some backup power supply, but this is unlikely to be a sustainable solution for more than a small part of our electricity system.

Decarbonising our whole *energy* system using renewable sources would test the limits of the possible. Electricity comprises just one fifth of final energy demand in the UK, so creating a 100% renewable energy economy would be an order of magnitude more difficult than the already challenging task of powering our existing electricity grid with 100% renewable sources.

Nuclear power – bigger is not necessarily better

It is clear that in meeting our low-carbon energy needs that nuclear power should play a crucial role. The energy density of nuclear fission means that just a few plants can provide a large percentage of our electricity requirements. In Western liberalised economies, however, traditional large nuclear power plants are not thriving. Struggling utility companies now have difficulty financing projects that can cost upwards of ten billion pounds and reactor vendors do not have a good record in reducing costs or bringing new plants online on schedule.

Small modular reactors (SMRs) could be a solution. Each unit would require a smaller investment than large reactors and their modular nature means that they can be built in a controlled factory environment where, with increased deployment, costs can be brought down over time through improved manufacturing processes and economies of volume. This learning-by-doing effect has helped the offshore wind industry achieve impressive cost reductions and the nuclear industry could replicate their success.

SMRs could offer a number of advantages in a flexible power system, including the potential for dual output, producing other useful services in addition to electricity, like hydrogen or heat. SMRs could, for example, provide a demand/grid management solution by redirecting the power from an SMR to hydrogen production when renewable output is high.

A new fleet of British SMRs would also provide a large quantity of secure low-carbon energy, thus reducing reliance on imports of natural gas, electricity via interconnectors, and biomass. Uranium, the main source of nuclear fuel, is an inexpensive commodity traded worldwide, and the UK has the capability to both enrich uranium and manufacture its own nuclear fuel. Nuclear power reduces import dependency.

The UK Government recognised the potential of SMRs in 2016 and provided funding to seek companies that would be interested in leading the development of a British small modular reactor.[3] A decision on how to proceed with the second phase of the process is due in the Spring of 2018.

SMR technology options

The first big decision to be made with regard to the development of a new design of nuclear reactor is whether to stick to tried and tested technology with an aim to bring down cost, or to expend more effort in order to develop revolutionary technology that may offer extra benefits like proliferation resistance or providing process heat for heavy industry. **We argue that in the short-to-medium term the priority for the UK should be to focus on the technology that can bring low cost, low carbon electricity to the grid in a timely manner.** This is likely to be third generation ('Gen III') pressurised water reactors (PWRs). At whatever scale, this is a proven technology with an excellent safety record. Incremental design improvements should focus on simplification to bring down costs (without compromising the already excellent safety record of PWRs), not new revolutionary concepts that will be unlikely to deliver power to the grid until the 2040s.

This does not mean that investment in research and development into fourth generation ('Gen IV') concepts is not necessary and the recently announced £4 million innovation fund made available to conduct feasibility studies into Gen IV designs is welcome. They could produce benefits for the UK in the longer term that would be worth the expense incurred through their development. They could lay the foundation for the development of a future fast neutron reactor that could use plutonium as fuel, thereby gradually disposing of the UK's stockpile of high level nuclear waste and reducing the associated costs of ongoing management of this resource. They could also contribute towards the decarbonisation of heavy industry. Investment into Gen IV research programmes in our universities will also ensure a pipeline of scientists and engineers to deliver the skills required to maintain the nuclear industry tomorrow.

A new strategy for the deployment of British SMRs

The UK should proceed swiftly with the development of at least one Gen III small modular reactor design. The initial support will involve providing funding for front end engineering design studies. There is a good argument for enabling the development of more than one design at this stage as this will help reduce development risk (one project could fail to meet expectations), but this must be balanced against constraints on the overall R&D budget, the capability of UK industry to concurrently develop more than one technology, and the ability of the Office for Nuclear Regulation to process multiple Generic Design Assessments for SMRs alongside their current work in processing the designs of larger reactors.

Finally, the UK Government should ask potential SMR vendors to take into consideration our evolving energy system. With increased penetration

3 BEIS (2016) Small Modular Reactors competition: phase one

of intermittent renewable technologies, like solar and wind, nuclear power plants will need to find new and inventive ways of adding value to the system. SMR design studies should at least be asked to consider how they could contribute to such a system, be it for hydrogen production, energy storage or combined heat and power. **The long-term future of nuclear power will depend on its ability to adapt to the new world of flexible power systems and low marginal cost renewable electricity.**

Policy recommendations

The report makes a number of detailed policy recommendations, including:

Small modular reactor deployment

- **Fund SMR design studies:** The Government should choose at least one Gen III design SMR to take forward through detailed design stages to enable deployment in the 2020s. The metrics on which to judge the best SMR should be simplicity of design, potential for cost reductions and the speed of deployment, with no compromise on safety.
- **Emphasise our flexible future:** Vendors in receipt of innovation funding should be asked to submit a plan to Government detailing how they think their plant could fit into a flexible and distributed low carbon electricity system in the long term.
- **Bolster the ONR:** Ensure the Office for Nuclear Regulation has the capacity to process multiple generic design assessments, of both large and small reactors, concurrently. The £7 million extra funding made available for the nuclear regulation announced in the Clean Growth Strategy is a welcome step in this direction.[4]
- **Conduct extensive polling into public perception of SMRs:** The Government should commission polling of the populations closest to potential sites for small modular reactors. This can be used to inform future SMR siting studies and feed into the Government's existing energy and climate change public attitudes tracker.

Nuclear R&D policies

- **Funding Gen IV reactor research:** Research into Gen IV reactor designs in the UK should continue in order to ensure that the UK has the capability and skills to maintain a vibrant and successful nuclear industry into the 2040s.
- **Continued membership of GIF:** Continued UK membership of the Generation IV International Forum (GIF) will facilitate collaboration in this regard and save the British taxpayers money through effort sharing.[5]
- **Industrial uses:** Launch a consultation with heavy industry into what services advanced reactor designs could bring that would be most useful to them (heat, electricity for hydrolysis, etc).
- **A new research reactor:** The UK should consider funding the development of a nuclear fission reactor that would be used for

4 UK Government policy paper, *Clean Growth Strategy*, October 2017

5 https://www.gen-4.org/gif/jcms/c_9260/public

academic research and development. This could be sited on one of our existing secure civil nuclear power or research sites and universities and other research organisations could apply for time on the reactor for experimentation.

Strategies for large nuclear power plants

- **Review existing nuclear deployment strategies:** The Government should maintain its current ambition to deploy up to 16 GW of large nuclear by the 2030s in order to meet our legally binding decarbonisation targets under the Climate Change Act, but it should review the current strategy for deployment in order to ensure the country is getting value for money.

General energy policy

- **Scrap renewable-specific energy targets:** When the UK leaves the EU it should abandon renewable energy targets and focus energy policy on the objectives of sustainable, low carbon and affordable energy.
- **Assess UK energy storage capacity:** The Government should commission research into the potential for long term energy storage in the UK. As a first step this should evaluate the most feasible sites for pumped hydro, compressed air and heat storage to determine how much storage capacity is available.
- **Properly assess the future costs of intermittency:** BEIS should commission a consultancy to design an economic model that fully assesses the value of the electricity produced by dispatchable and non-dispatchable sources of electricity. This could be an adaption of the Dynamic Dispatch Model, which was used to model scenarios for the Energy Market Reform process.
- **Create a carbon capture and storage hub:** The UK Government should partner with industry to create an initial CCS hub close to a suitable geological storage site and focus initial deployment of carbon capture technologies on industrial uses and hydrogen production, not electricity.

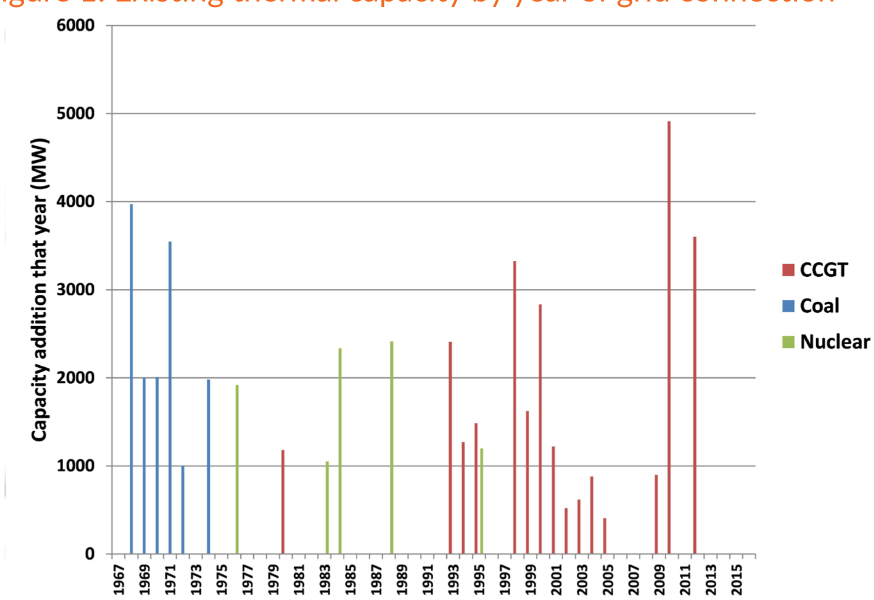
The Case for SMRs

The challenge of decarbonisation

The scale of the challenge facing the UK in its transition to a low carbon economy is staggering. In the short-to-medium term, the major issue is in simply replacing the generating capacity that is due to fall off the system in the next decade. The coal and nuclear power plants in the UK were mostly built in the 1970s (see Figure 1) and are due for retirement or replacement imminently. 14 of the UK's 15 nuclear reactors are due to reach the end of their operating lives by 2030, whilst the Government have announced plans to phase out coal power in the UK by 2025.[6] This amounts to a combined loss of 22 gigawatts (GW) of secure generating capacity (40% of peak electricity demand).[7] Most of the combined cycle gas turbines (CCGT) built since the 'dash for gas' in the 1990s could continue operating beyond this date, but their fate depends upon the economic viability of keeping them open, which in turn will depend on the price of natural gas, the level of carbon taxation and the availability of government subsides for maintaining backup capacity for intermittent renewable sources of electricity.

Although electricity demand in the UK has fallen some 12% since 2005, primarily due to the recession and energy efficiency measures, it could increase again in the next decade due to a rising population and the uptake of electric vehicles. National Grid's Future Energy Scenarios suggest that power demand could increase by 15% by 2030.[9]

Figure 1: Existing thermal capacity by year of grid connection[8]



6 https://www.gov.uk/government/speeches/pm-press-conference-with-canadian-prime-minister-justin-trudeau-18-september

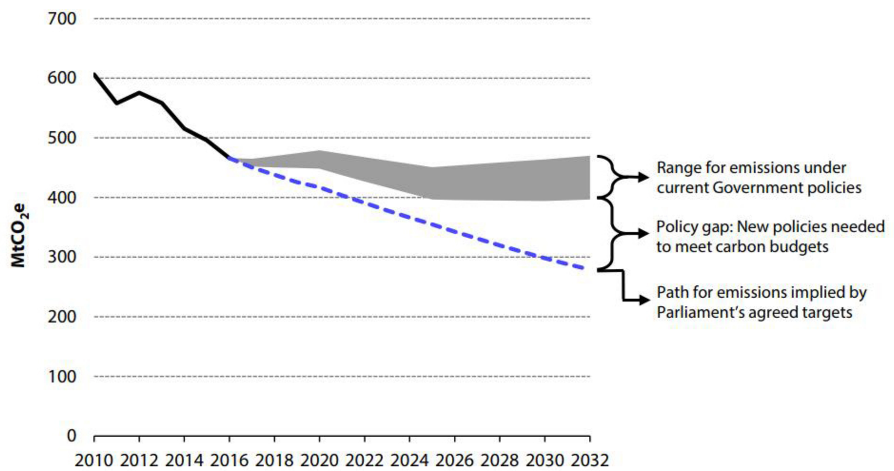
7 BEIS (2016) Historical electricity data: 1920 to 2016

8 Digest of UK Energy Statistics (DUKES) 2017, Plant loads, demand and efficiency (DUKES 5.10)

The loss of 22 GW of reliable, dispatchable power, therefore, presents a serious challenge to our energy system. The Committee on Climate Change (CCC) estimate that the UK needs to replace almost one third of existing supply with new low carbon electricity capacity by 2030 in order to meet decarbonisation targets in the fifth carbon budget.[10] The CCC estimate that the UK is currently on course to miss decarbonisation targets under the fifth carbon budget, as shown in Figure 2.

Decarbonising other sectors of the economy presents even more of a challenge than that of electric power. Domestic heating in Britain is almost

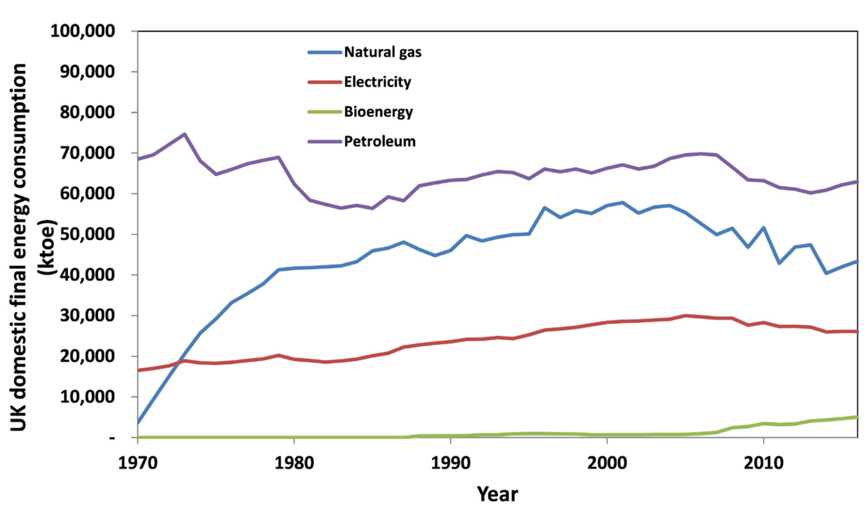
Figure 2: The Committee on Climate Change's assessment of the UK's decarbonisation trajectory[11]



entirely fuelled by natural gas and the energy required to heat Britain's homes is almost double that of domestic electricity consumption, as shown in Figure 3.

The challenge is not just in providing so much new low carbon electricity, but also in the infrastructure transition that will be required. For new

Figure 3: UK final energy consumption by year[12]



9 National Grid (2017) *Future Energy Scenarios*

10 Committee on Climate Change (2017) *Meeting Carbon Budgets: Closing the policy gap 2017 Report to Parliament*

11 Committee on Climate Change (2017) *Reducing emissions and preparing for climate change: 2017 Report to Parliament*

12 BEIS (2017) Energy Consumption in the UK, data table 1.02

housing developments it would be relatively straightforward to install a district heating scheme or ground/air heat pumps, but this would be much more difficult with the existing housing stock. The Energy Technologies Institute (ETI) estimate that a full retrofit of UK housing stock could cost £1 trillion.[13] The least disruptive way to decarbonise the majority of domestic heating is likely to be through using the existing natural gas network to deliver hydrogen instead of methane. The combustion of hydrogen does not produce carbon dioxide as a by-product. However, its production can result in significant emissions.

Most of the world's hydrogen is currently produced through steam methane reformation of natural gas, a process that results in significant carbon emissions unless paired with carbon capture and storage (CCS). In the longer term, producing hydrogen sustainably will require more advanced techniques such as electrolysis or thermo-splitting of water. The electricity or heat to power this process will have to be provided by nuclear reactors or renewable electricity if carbon emissions are to be avoided. Assuming the hydrogen was to be made by electrolysers with an efficiency of 70%, the electrical energy required to produce enough hydrogen to replace our natural gas supply to homes and industry would be in the region of 729 TWh. The total demand for electricity in the UK in 2016 was 336 TWh, meaning that electricity supply could have to more than treble in order to sustainably replace UK natural gas with hydrogen.

The task of decarbonising our energy system is daunting then, but which technologies should be a part of our energy mix in the future? And should we, like Germany, pursue a 100% renewable energy strategy?

100% renewable energy in the UK

In his final public interview, the late Sir David MacKay, ex-Chief Scientist to the (now defunct) Department for Energy and Climate Change (DECC) called the idea that the UK could power itself on 100% renewable energy an 'appalling delusional'.[14] His reasons for reaching this conclusion were numerous. Firstly, solar and wind are incredibly diffuse sources of energy and, therefore, a large proportion of land and sea would need to be set aside for them to provide more than a small percentage of our energy needs. Secondly, the combination of our climate and our seasonal demand profile makes solar power particularly unsuited to the UK. Solar output is highest on a summer afternoon when electricity demand is low and lowest on a winter evening when peak demand occurs. Long term storage of solar power from summer to winter would be inefficient and expensive. Finally, the UK does not have vast swathes of unused land on which to produce sustainable biofuels.

100% renewable energy would be more challenging for some countries than others. Those with low population densities that are blessed with the right terrain for hydroelectric power, for example, have a better chance of completely ditching fossil fuels and forgoing nuclear power than those that don't. In 2015, 96% of electricity in Norway came from hydroelectric

13 ETI (2017) *Housing Retrofits – A New Start*

14 The Guardian (2017) *Idea of renewables powering UK is an 'appalling delusion' – David MacKay*

power stations.[15] The Skagerrak interconnector between Norway and Denmark has also helped to enable Denmark to incorporate the 49% of intermittent wind power on their grid without blackouts on calm days.[16] When the wind doesn't blow, they purchase hydroelectric power from Norway to fill the gap.

For most major countries, however, powering their economies with 100% renewable energy would be incredibly difficult, even just from a physical and technical point-of-view before economics and politics are also taken into account.

In academia, many have tried to map out what a 100% renewable energy system would look like, but these studies are usually plagued by unrealistic technical assumptions or they are devoid of any consideration of costs or politics. In *Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems*[17], Heard et al critically reviewed 24 studies that proposed plans for 100% renewable electricity in various different regions around the globe. Note that these were electricity only and not total energy, therefore largely excluding the energy requirements of heating, transport and industry. The authors set four tests that the studies would have to pass in order to demonstrate that they were credible plans and not merely back of the envelope calculations. They found that none of the studies passed their credibility test.

Similarly, the Energy Innovation Reform Project conducted a literature review of 30 deep decarbonisation studies that have been published since 2014.[18] They found a strong consensus that near 100% decarbonisation is much more challenging than making it to 50-70%: 'While it is theoretically possible to rely primarily (or even entirely) on variable renewable energy resources such as wind and solar, it would be significantly more challenging and costly than pathways that employ a diverse portfolio of resources. In particular, including dispatchable low-carbon resources in the portfolio such as nuclear energy or fossil energy with carbon capture and storage would significantly reduce the cost and technical challenges of deep decarbonisation.'

Crucially, these studies focussed only on electricity, which typically makes up much less than half the energy demand of a major industrialised country. Studies proclaiming the feasibility of 100% renewable energy also exist. The most well-known proponent of such a plan is Prof Mark Jacobson of the University of California, Berkeley in the USA. His research teams have put out plans that proclaim that many countries, including the USA, would have no trouble in moving to an energy system powered by wind, water (hydro), and solar.[19] This WWS plan, however, assumes that hydro-electric power can be scaled up massively from its present output – an unrealistic assumption in most countries.

There are two main challenges with moving to a 100% renewable energy system. The first is simply in producing enough electricity from sources of energy that are very diffuse. Powering a country by wind, water and biomass, for example, would require hundreds of times more land (or sea) than doing so with fossil fuels or especially nuclear power. The

15 https://www.iea.org/media/countries/Norway.pdf

16 https://www.iea.org/media/countries/Denmark.pdf

17 Heard et al (2017) 'Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems', *Renewable and Sustainable Energy Reviews*

18 EIRP (2017) Deep Decarbonization of the Electric Power Sector

19 Jacobson et al (2017) '100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World', *Joule*

second challenge is in coping with the intermittent nature of wind and solar power, which we will now explore in a UK context.

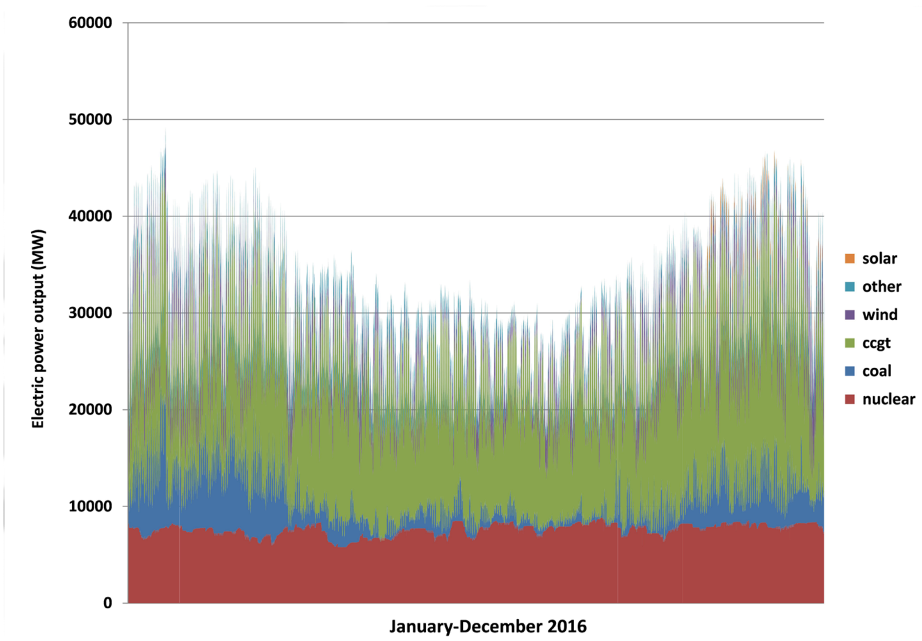
The problem of intermittency

Calculating the additional costs of integrating intermittent renewable electricity sources, mostly solar and wind, into an energy system is complicated. The most accurate way to attempt to make this calculation is with whole system modelling, but even then there is disagreement about the implications of moving towards a world largely powered by solar and wind. Integrating low percentages of renewable electricity incurs low costs, but the expense increases with increasing penetration and the relationship is non-linear. The integration costs imposed on an electricity system powered by 80% solar and wind would be much higher than one with 40% penetration, for example. The cost would be more than double, but exactly how much more is uncertain and depends on various factors, including the characteristics of the existing energy system.

Another major factor is the demand profile of the country or region in question, combined with the climate and weather of the region. Electricity demand in the UK varies over the course of a day, between weekdays and weekends and, most importantly, between summer and winter, and supply and demand must remain constantly in balance. Figure 4 below shows how the UK's electricity supply varies over the course of a year (not including small, distributed sources).

Average demand is higher in winter than in summer and annual peak demand usually occurs on a cold, dark evening in winter. (The seasonal variation of demand for natural gas for domestic heating is even more pronounced, so any move towards the electrification of heat will

Figure 4: Large-scale electricity supply in the UK in 2016[20]



20 Data source: http://www.gridwatch.templar.co.uk

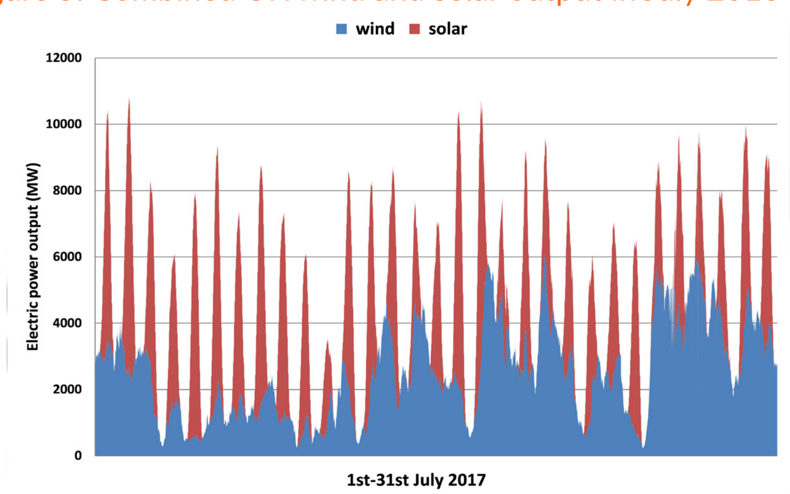
accentuate this seasonal disparity.) This, unfortunately, makes solar power less useful in the UK than in countries that have peak electricity demand occur in the summer time. These are warm countries that use a lot of air conditioning. Ironically, the UK may become one of these countries if summer temperatures keep increasing due to global warming, but we are many decades away from this becoming a possibility.[21]

A recent report by Bloomberg New Energy Finance, Beyond the Tipping Point, estimates that solar and wind could be meeting 55% of electricity demand in the UK by 2040.[21] Although extremely positive about the progress made by solar and wind energy, the Bloomberg report does point to the fact that there will be 'entire weeks and months where wind and solar produce little energy', so other backup resources must be able to meet up to 80% of demand. They believe that the UK will still require 70 GW of dispatchable power through some combination of generation, storage, flexible demand and interconnectors.

The problem of intermittency can be illustrated by looking at the output of the UK's solar and wind capacity for a month in winter and a month in summer. Figures 5 and 6 show the combined wind and solar output in the UK for July 2017 and January 2017. There are a few important points to note from comparing these graphs. Firstly, solar output in July is much higher than in January. Secondly, total average wind output is slightly higher in January than in July. In this respect, wind and solar are complementary in that they have their highest output at different times of the year. The problem, however, is illustrated in Figure 6 in which wind output is six times lower in one week than in the one that preceded it. As the UK attempts to integrate more and more wind into their electricity grid, it is times of the year like this week in January that present the greatest challenge for system integration and 'keeping the lights on'. These long periods of low wind output can occur at any time of year. Solar output is slightly more predictable, but can also vary primarily due to different levels of cloud cover.

Managing this intermittency is possible, but the more intermittent capacity that is added to the system, the more it costs to deal with the

Figure 5: Combined UK wind and solar output in July 2016[23]

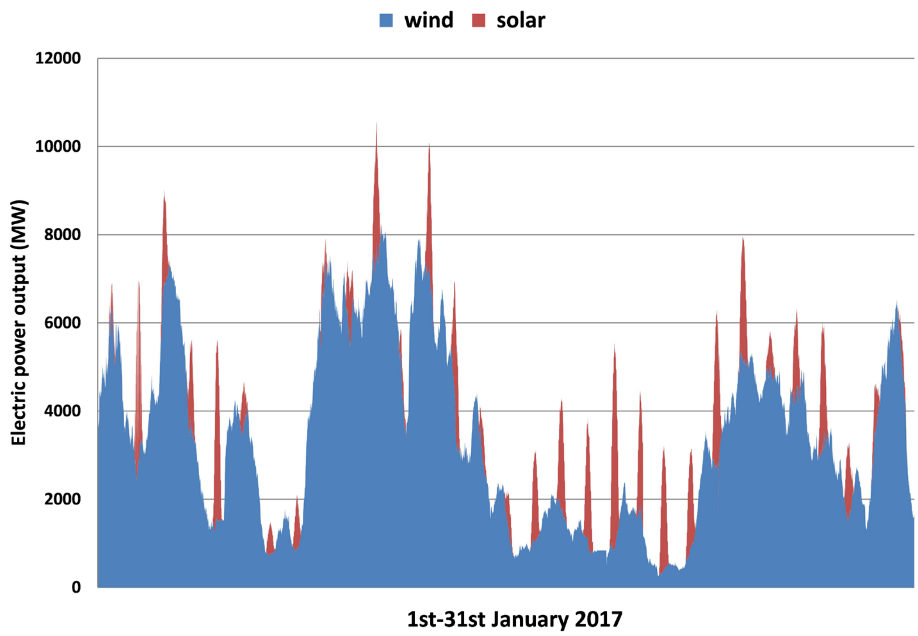


21 https://www.carbonbrief.org/climate-change-could-flip-european-peak-power-demand-to-summer-study-says

22 Bloomberg New Energy Finance (2017) *Beyond the tipping point*

23 Data source: http://www.gridwatch.templar.co.uk

Figure 6: Combined UK wind and solar output in January 2017[24]



variability and, as previously mentioned, it is not a linear relationship. Managing 10 GW of wind capacity on the grid will incur system integration costs more than double that of managing 5 GW. The costs of managing 20 GW would be more than double 10 GW, and so on. This is because every additional unit of storage added to the system will be utilised less often than the one that preceded it, which reduces its economic value and would increase the level of subsidy required to keep such facilities operating. If we invest in large-scale storage facilities that need to be maintained all year round, but are only used for a few days in January, this is likely to be inefficient from a whole system point of view.

Britain's electricity grid is not a closed system. We currently have the capacity to import or export up to 4 GW at any given time through interconnectors with France, the Netherlands and Ireland, and further interconnectors are planned with other countries.[25] They are bi-directional and which way the electricity flows will depend on the relative supply-demand balance and electricity price in each country. These interconnectors have been presented as a solution to the problem of wind and solar intermittency and in some cases they can indeed help to fill the gap. However, interconnectors work best when the neighbouring countries have different and complimentary sources of electricity supply, as is the case with Norwegian hydro and Danish wind. But if the whole of Western Europe continue their push to systems with large amounts of solar and wind, the value of interconnectors will begin to diminish. France recently planned to cut the share of nuclear power on their grid from 75% to 50% and expand solar and wind capacity, but watered down proposals citing security of supply as a major concern with such a plan.

Figures 7 and 8 below show the wind output for Germany and France for January 2017. Comparing these with Figure 6 above shows that the

24 Data source: http://www.gridwatch.templar.co.uk

25 https://www.ofgem.gov.uk/electricity/transmission-networks/electricity-interconnectors

wind output from each country is similar and all three suffer from severely diminished output in the third week. Although interconnectors will still add value to a nation's electricity system, in a world of high solar and wind capacity they cannot be relied upon to fill major gaps in supply. The main value of interconnectors lies in lowering consumer prices and preventing renewables curtailment, not in providing large backup capacity for periods of high demand and/or low renewable output.

The intermittency of renewable sources of energy should increasingly be taken into account as our low carbon energy system evolves. Solar

Figure 7: Combined German wind and solar output in January 2017[26]

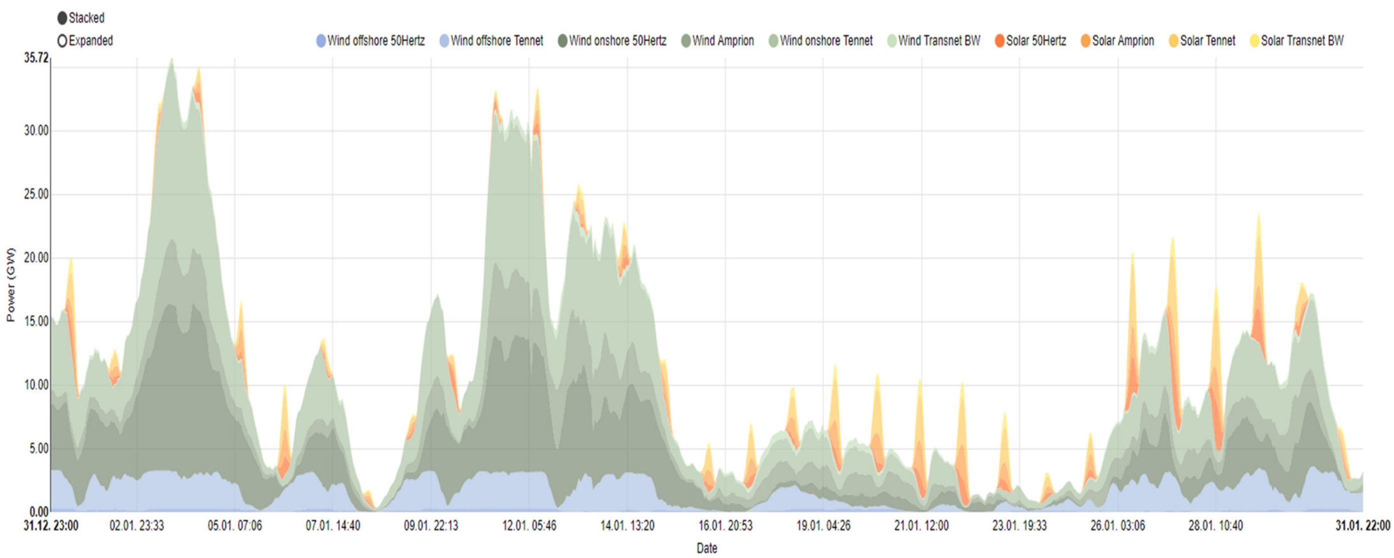
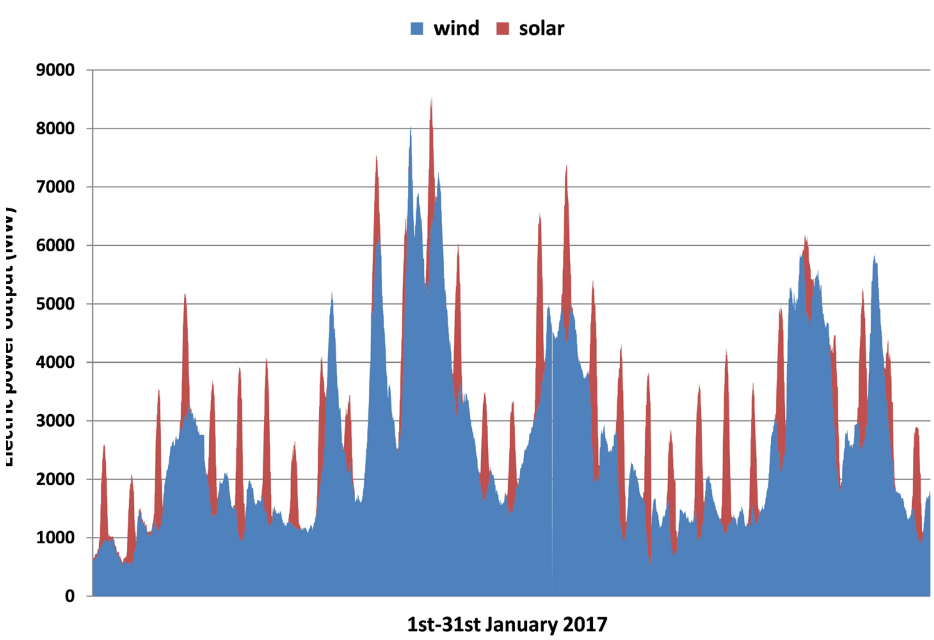


Figure 8: Combined French wind and solar output in January 2017[27]



26 Source: https://www.netztransparenz.de

27 Data source: http://www.gridwatch.templar.co.uk

power provides most electricity at the time of the year when electricity demand is lowest and it provides zero electricity at the period of yearly peak demand, whilst wind power in unreliable all year round. The most common method of comparing the cost of different electricity generation technologies, the levelised cost of electricity (LCOE), does not take this into account. New methods of measuring the economic value of electricity produced by different generation technologies are required.

Policy recommendation: *BEIS should commission a consultancy to design an economic model that fully assesses the value of the electricity produced by dispatchable and non-dispatchable sources of electricity. This could be an adaption of the Dynamic Dispatch Model, which was used to model scenarios for the Energy Market Reform process.*

The German Energiewende ('energy transition') recognised the difficulty they would have in balancing supply and demand in their high renewable system and planned to fill supply shortages with power stations converted to run on biomass from wood sources (or 'woody biomass'). This is a technically feasible solution to the problem of intermittency, but is it sustainable?

The limits of biomass

A component of the EU's 2020 climate and energy strategy were targets for renewable energy generation. Through the Renewable Energy Directive (RED), the European Commission set the aim that 20% of energy in the EU should come from renewable sources by 2020.[28] One consequence of the RED has been the wide-scale deployment of power stations fuelled by forest-derived wood pellets. This is particularly prevalent in Germany where wood combustion was until recently the largest source of renewable electricity (now overtaken by offshore wind).[29] But this is a controversial way of producing electricity as the environmental effects of burning biomass are difficult to quantify accurately.

In theory the process of burning wood can be carbon neutral, but in reality there are emissions associated with the processing and transport of wood pellets and the effect of any land use changes can be particularly significant. Calculating the full life cycle carbon emissions associated with biomass power stations is complicated and estimates vary wildly depending on the input assumptions. In the best case scenario the wood that is burned would be waste that would have been left to rot on the ground (thereby releasing greenhouse gases anyway). In the worst case scenario mature woodlands would be cut down with no replanting of trees, in which case the life cycle emissions could be higher than an unabated coal power station.[30]

The uncertainty about the sustainability and associated carbon emissions of biomass power plants has led the EU to tighten its sustainability guidelines.[31] In the UK it has led the Government to reconsider support for new large-scale biomass power plants, the only major facility at the moment being the 1.935 GW capacity Drax plant in Yorkshire. While Germany, who previously had planned to replace their fossil fuel power stations with biomass, have quietly rolled back this ambition due to

28 European Commission (2009) *Renewable Energy Directive*

29 https://www.cleanenergywire.org/factsheets/germanys-energy-consumption-and-power-mix-charts

30 NRDC (2015) *Think Wood Pellets are Green? Think Again*

31 European Commission (2017) *Definition of input data to assess GHG default emissions from biofuels in EU legislation*

uncertainty about the sustainability.[32]

Care should be taken by the UK Government before approving large new capacity additions of biomass power plants that use imported wood, the hidden carbon emissions of which could be high. We can most easily regulate the sourcing of biomass for power in the UK to ensure it is sustainably produced if the material is also sourced here, so small-scale biomass projects, ideally combined heat and power, using local and sustainably sourced wood should be the focus for the time being. But how much of our power system could be fuelled sustainably by UK wood?

Research by the Tyndall Centre for Climate Change Research at the University of Manchester has estimated that waste residues from agriculture, forestry and industry could provide up to 6.5% of the UK's energy needs by 2050.[33] Liquid biofuels and biogas derived from energy crops and food waste can play a much larger role, but they are more suited for the decarbonisation of transport and heating than for electricity production, sectors of the economy that are more difficult to decarbonise through electrification. So woody biomass may have a role to play in our energy system, but it will likely be a limited role. In the electricity sector it would be most useful for contributing extra capacity at times of peak demand after our natural gas power plants are phased out and in small-scale combined heat and power (CHP) projects. It cannot provide large amounts of low carbon heat and power at a scale capable of matching nuclear power.

In terms of decarbonising every part of the economy, it is also the case that biomass could be more valuable in other sectors other than electric power. Aviation and shipping in particular, but also home heating, are very difficult to electrify, so biofuels may be a better path to decarbonisation in these sectors whereas in electricity production there are many alternatives to biomass. Given that there is a finite amount of biomass worldwide that can be harvested sustainably in any given year (though this stock can grow over time by planting more trees), relying on a secure supply of low cost source material for electricity production may not be a sensible strategy.

The recent growth of power stations in Europe that are fuelled by woody biomass has been driven by a major flaw in EU energy policy: it made the *a priori* assumption that almost anything renewable is good. This is not the case. Large-scale biomass is technically renewable, but not necessarily sustainable – not without extremely tight safeguards and regulations. The aims of a sensible energy policy should be low-carbon, sustainable and affordable. Renewable energy sources should only be included in the mix to the extent that they meet these three criteria.

Policy recommendation: *When the UK leaves the EU it should abandon renewable energy targets and focus energy policy on the objectives of sustainable, low-carbon and affordable energy.*

The focus on mass deployment of renewables has been an expensive and inefficient method for reducing carbon emissions and it has resulted in the questionable practice of burning large quantities of wood for electricity. Having a more technology neutral approach would allow for a more efficient use of government resources and would be a more cost-

32 https://energytransition.org/2015/07/biomass-growth-is-over

33 http://biomassmagazine.com/articles/10041/study-unveils-vast-potential-of-uk-biomass-resources

effective strategy in our drive to reduce carbon emissions.

Energy storage

Renewable sources of electricity, like solar and wind, have reduced in cost to the extent that on a per-kilowatt-hour of energy produced basis they are becoming cost competitive with fossil fuel power plants. However, although solar and wind add low carbon electricity to the system, they provide almost zero in terms of system capacity. For that a power source that can provide electricity on demand is required. The main low carbon options to provide capacity are hydroelectric and nuclear, but large-scale energy storage is also an option for meeting demand when solar and wind output is low.

With the increased penetration of these intermittent power sources in recent years, it is clear that developing better energy storage technologies should be a priority. There are already times of year when the wholesale price of electricity goes negative due to oversupply and wind and/or solar power has to be curtailed to prevent damage to infrastructure. This energy is being wasted and the development of low cost storage technologies will make the whole system more efficient. Policy Exchange studied the value of energy storage in our 2016 report *Power 2.0: Building a smarter, greener, cheaper electricity system*[34], in which we estimated that the value of system flexibility (demand response, energy storage, interconnectors) could deliver savings of £8 billion per year by 2030.

Battery technology gets most of the attention when it comes to energy storage, but while innovation in this field is proceeding at impressive speed, batteries are more suited to providing frequency response and short term backup supply on a small scale. They are less suited to filling the huge week-long gaps in our energy needs that would occur if we moved towards a system with very high levels of wind and solar penetration. Similarly, demand response, where large consumers of energy will agree to curtail their usage during periods of high demand, is a useful tool to prevent blackouts in the short term, but cannot be relied upon for long periods of time.

A simple calculation can illustrate the amount of battery storage that might be required to meet our winter electricity needs. To power our current electricity system for a typical five day work week in January using batteries alone would require the capacity equivalent to approximately 200 million Tesla Power Walls, which at current recommended retail prices would cost approximately £1 trillion. Similarly, Tesla has just completed the construction of the 'world's largest lithium-ion' in Australia.[35] But if this 100 MW (129 MWh) were to be built in the UK, it would store enough energy to meet peak demand for just a few seconds. Batteries may also not be an environmentally friendly way to meet our storage needs. Although estimates vary, lifecycle emissions from batteries can be significant as manufacturing them is an energy-intensive activity.

Backup power may never have to meet 100% of demand, but as discussed earlier if we are going to decarbonise heat and transport, then electricity

34 Policy Exchange (2015) *Power 2.0: Building a smarter, greener, cheaper electricity system*

35 The Guardian (2017), *Elon Musk's Tesla battery in South Australia poised for final testing*

demand could treble, so a requirement for that scale of backup power is not unimaginable. Battery storage is not likely to be the best way to fill this gap. Although battery technology is improving and costs are falling, it is unlikely to become the technology of choice for large-scale, long term energy storage. Other technologies like compressed air, pumped hydro, heat storage, and hydrogen are more promising for large-scale long-term storage. However, we first need to produce enough low carbon electricity in the first place to generate a large surplus to store. We are a long way from achieving this and that is a very convincing reason why new nuclear should not be ruled out.

The case for nuclear

The most respected energy systems studies conclude that in order to decarbonise whole energy systems, including heat and industry, it is at the very least sub-optimal to pursue a 100% renewable energy strategy and it may even be unsustainable and infeasible. The inclusion of nuclear power and carbon capture and storage (CCS) in the mix make the low carbon transition more feasible and reduces whole system costs. The International Energy Agency (IEA), the Intergovernmental Panel on Climate Change (IPCC) and the UK's Energy Technologies Institute (ETI) are all in favour of nuclear power being part of the energy mix.[36, 37, 38] This is because it is the only technologically mature source of low carbon power that is scalable and dispatchable (hydroelectric power is low carbon and dispatchable, but it is limited by suitable geography). Nuclear provides benefits to the system that no other technology can currently provide.

Carbon capture and storage is also considered to be a key decarbonisation technology, but it is of most use in reducing emissions from industrial processes that cannot easily be electrified, like cement and steel production.[39] The use of CCS for reducing emissions from power stations fuelled by coal or natural gas is less beneficial, as the process is currently costly (though innovations may reduce costs over time) and because no CCS process captures 100% of CO_2. Therefore, there are typically higher emissions associated with electricity produced in power stations combined with CCS than with nuclear power plants, wind turbines or solar panels.

Policy recommendation: *The UK Government should partner with industry to create an initial CCS hub close to a suitable geological storage site and focus initial deployment of carbon capture technologies on industrial uses and hydrogen production, not electricity.*

Nuclear power can also play a role in decarbonising heavy industry, but this would mostly be through the use of immature Gen IV technologies, like the high temperature gas-cooled reactor, which could provide the requisite heat that is needed for many industrial processes (for an explanation of the evolution of nuclear power from Gen I to Gen IV, see the box at the end of this subsection). In the medium-term, nuclear can be most useful in providing large quantities of low carbon electricity, something CCS is less suited for.

Having nuclear power as part of the energy mix is certainly desirable, but recent examples of cost and schedule over-runs of large nuclear reactor

36 IPCC (2014) Summary for Policymakers. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*

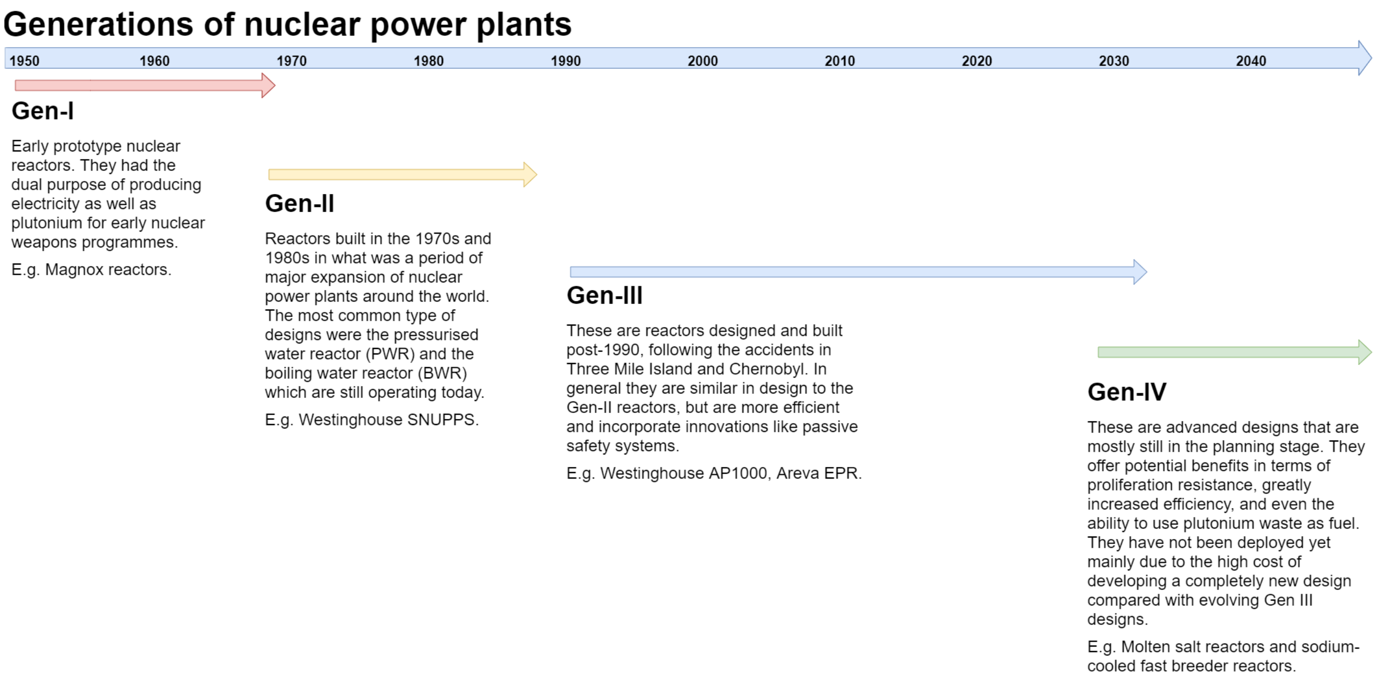
37 ETI (2016) *The role for nuclear within a low carbon energy system*

38 https://www.oecd-nea.org/news/2012/2012-08-QA.html

39 IPCC (2014) Summary for Policymakers. In: Climate Change 2014: Mitigation of Climate Change. *Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*

construction,[40, 41] at least in the Western world, have led some to question whether nuclear power is worth the expense.

Box 1: The evolution of nuclear power



Diseconomies of scale: the woes of large nuclear

An infamous research paper by Professor Arnulf Grubler, *The costs of the French nuclear scale-up: A case of negative learning by doing*, looked into the cost of building nuclear power plants in France during their massive building programme from the 1970s to the 1990s.[42] Grubler claims that as France built more and more nuclear reactors, and as they got bigger, the cost actually got higher over time. He calls this 'negative learning-by-doing'. Traditionally, what economists refer to as technological learning means the opposite: a reduction in costs that are achieved through increased deployment.

More successful examples of learning-by-doing in the energy industry include the cost reductions achieved in wind turbine and solar panel production in recent years. Figure 9 below shows how the cost of solar power has declined in the USA over the last decade. Similar cost reductions are now also being seen in the wind energy sector. Table 1 shows how auction prices for offshore wind have decreased in the UK since the introduction of a competitive auction process in 2014.

The general average trend for nuclear power has been for costs to go in the opposite direction. There are a number of explanations put forward for this:

40 Financial Times (2017) *Nuclear plant nears completion after huge delays*

41Reuters (2017). *How two cutting edge U.S. nuclear projects bankrupted Westinghouse*

42 Arnulf Grubler (2010) 'The costs of the French nuclear scale-up: A case of negative learning by doing', *Energy Policy*

- Increased safety requirements following the accidents at Chernobyl, Three Mile Island and, more recently, Fukushima.
- Economies of scale effects being offset by increased build durations.
- Frequent design changes meaning that learning and fleet effect benefits did not materialise.

There were good reasons for moving towards larger reactors in the early 70s and 80s. The economies-of-scale effect is real. In the absence of any countervailing forces, building larger power stations should bring down the cost of the plant on a per-megawatt energy basis. Building one large power station should be less costly than building two that are half the size, but in the nuclear industry the economies of scale effect did not offset the upwards pressure on costs of regulatory changes, frequent design modifications and lengthy build times.

The effect of schedule over-runs in power plant construction has been a particular feature of nuclear reactors as they have become larger. Cost and schedule over-runs are not a feature limited to nuclear power, however, they are inherent to large and complicated infrastructure projects. Various factors mean that project developers have a susceptibility to underestimate the true cost of large infrastructure projects. This is such a common problem that the National Audit Office produce guidance on how to mitigate the optimism

Figure 9: Cost reductions of solar power over time in the USA[43]

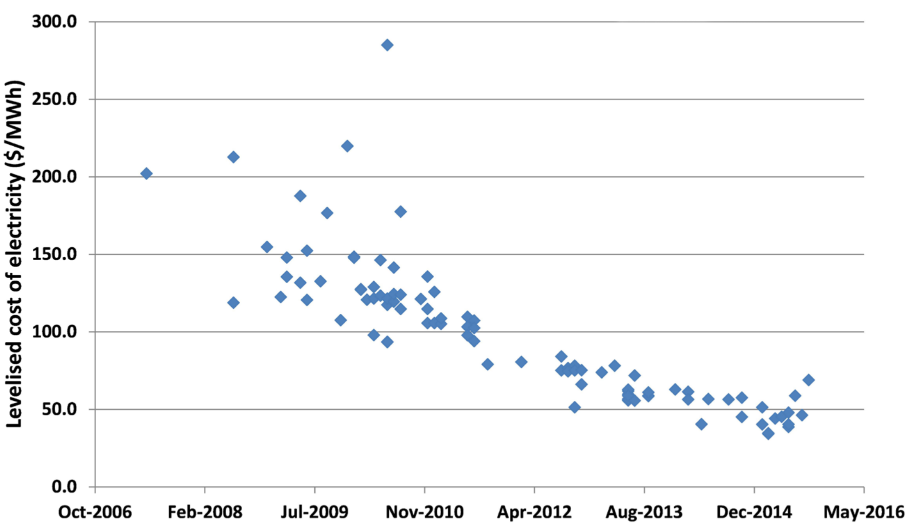


Table 1: Auction price of electricity for offshore wind in the UK by year of project delivery[44]

Delivery year	Strike price (£/MWh)
2017	119.89
2018	114.39
2021	74.75
2022	57.5

43 Data source: Data source: https://emp.lbl.gov/sites/all/files/lbnl-1000917_data_file.xls

44 Data sources: https://www.gov.uk/government/publications/contracts-for-difference-cfd-allocation-round-one-outcome https://www.gov.uk/government/publications/contracts-for-difference-cfd-second-allocation-round-results

bias effect[45] and the Government has merged two existing bodies to create a single organisation, the Infrastructure and Projects Authority, to attempt to better manage the delivery of large projects.[46] Although optimism bias is not limited to nuclear power, analysis by Professor Benjamin Sovacool and colleagues has suggested that the nuclear industry has been the worst offender in the power industry. Studying the construction of large electricity projects built between 1936 and 2014 in 57 countries, they found that large nuclear power plants were more likely to go over budget and by a greater percentage than any other electricity generation technology.[47]

It should be noted that the liberalisation of energy markets also made life more difficult for nuclear. The economics of a capital intensive, long term investment, like a nuclear power plant, is much more favourable when financed at a government borrowing rate of ~3.5%, rather than the >10% rate that private businesses would face. Table 2 shows the levelised cost of electricity for a typical nuclear power station assuming they are financed at borrowing rate of 3%, 7% and 10%.

The data in Table 2 make a strong case for some sort of government assistance in reducing the financing costs of new nuclear power plants. The

Table 2: Projected LCOE for nuclear power plants built 2015–2020 for varying discount rates ($/Mwh)[48]

Country	At 3% discount rate	At 7%	At 10%
Belgium	51.5	84.2	116.8
Finland	46.1	77.6	109.1
France	50.0	82.6	115.2
Hungary	53.9	89.9	125.0
Japan	62.6	87.6	112.5
South Korea	28.6	40.4	51.4
Slovakia	53.9	84.0	116.5
UK	64.4	100.8	135.7
USA	54.3	77.7	101.8
China	25.6–30.8	37.2–47.6	48.8–64.4

privatisation of British energy in the 80s and 90s was broadly a success in terms of improving efficiency and reducing costs for consumers, but it was not an environment in which it was easy for nuclear power to thrive, especially in the absence of a carbon tax. Both today and historically the places where nuclear power has thrived have been where the Government has taken an active role in a large-scale deployment programme through the use of a national champion.

Figure 10 shows the astounding scale-up of nuclear power that was achieved in France in the 1980s. Although the costs of the French roll-out have been criticised by some, the chart below shows that there really is no other low carbon technology that can match nuclear power for scale. The nuclear power plants that France built in just over a decade during

45 HM Treasury (2013) *Supplementary Green Book Guidance: Optimism Bias*

46 https://www.gov.uk/government/news/government-creates-new-body-to-help-manage-and-deliver-major-projects-for-uk-economy

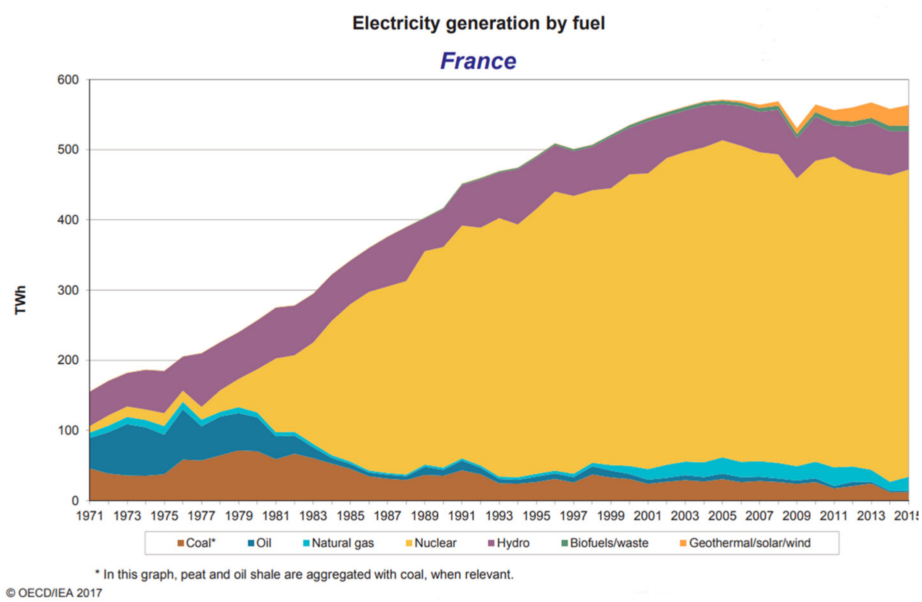
47 Sovacool et al (2014) 'Risk, innovation, electricity infrastructure and construction cost overruns: Testing six hypotheses', *Energy*

48 IEA-OECD-NEA (2015) *Projected Costs of Generating Electricity*

this period would be enough to completely decarbonise the UK's current electricity system.

Even with large nuclear power plants, costs can be controlled with standardisation and replication of one design with the same project

Figure 10: The evolution of electricity supply in France since 1980[49]



management team overseeing the roll-out. However, even if the UK had a government sympathetic to such a statist strategy, having not constructed a large nuclear power plant in decades we would not have the capability to pursue it independently.

In the short-to-medium term, the UK Government has a dilemma with regard to large nuclear power plants. As well as the Hinkley Point C power station, which is based on the European Pressurized Water Reactor design, three other reactor designs are being considered with a possible outcome being that four large nuclear power stations are built based on four different designs by four different companies. This is a very good strategy for getting a large amount of low carbon electricity on to the grid quite quickly, but it is not a good strategy for bringing down the cost of nuclear power.

Every new reactor design will have first-of-a-kind costs associated with the fact that it always more challenging to build something for the first time in a new country (estimated as a 20% premium by Tony Roulstone[50]). Diversification at the beginning of a large deployment programme is a good idea as it reduces the risk of being locked-in to an inferior technology and competition can also drive down costs. But if the UK builds four different nuclear power stations and stops at that point, then that is likely to be an expensive strategy. This puts the Government in a difficult position. Studies have suggested that the UK is unlikely to meet legally binding

49 Source: http://www.iea.org/stats/WebGraphs/FRANCE2.pdf

50 http://www.nuclearinst.com/write/MediaUploads/TR.pdf

emission reduction targets without these nuclear power stations, so large nuclear should not be taken off the table completely, but costs need to come down.[51]

Policy recommendation: *The Government should maintain its current ambition to deploy up to 16 GW of large nuclear by the 2030s in order to meet our legally binding decarbonisation targets under the Climate Change Act, but it should review the current strategy for deployment in order to ensure the country is getting value for money.*

51 Institution of Mechanical Engineers (2017), *Nuclear power stations 'must be built on time to maintain UK climate targets'*

Small Modular Reactors

The case for modular production

Given the difficulty of the UK moving to a 100% renewable energy system and the considerable challenges facing the deployment of large nuclear reactors in the UK, there is a strong case for Britain developing a small modular reactor (SMR) programme. They offer an extra potential tool in the drive to decarbonise our energy system in a cost-effective manner. They could also help to revitalise our domestic nuclear industry.

The 'SMR' acronym originally meant 'small and medium reactors', meaning any size up to 300 MWe (for comparison, the two reactors under construction at Hinkley Point in Somerset will be 1600 MWe each). It now more commonly is taken to mean 'small modular reactors'. Indeed it is modular that is the key word, rather than small. When building a power plant based one or more SMRs, the reactor vessel(s) and as much of the associated equipment is manufactured in a factory environment and then transported to the site to be connected to the grid. On a per megawatt output basis, the first SMR built may not provide much of a cost advantage over traditional large reactors. However, with a standardised design and factory production, the cost of producing each subsequent reactor should be lower than that of the one that precedes it. This is the learning-by-doing effect. A metric used in energy policy to determine how fast the costs of a given technology fall with increased deployment is known as the learning rate. Learning rates will vary for different technologies depending on various characteristics, as shown in Figure 10 in the previous section. As explained in Chapter 1, learning rates for large nuclear reactors have typically been low compared to other technologies. Through standardisation of design and factory production SMRs could change that.

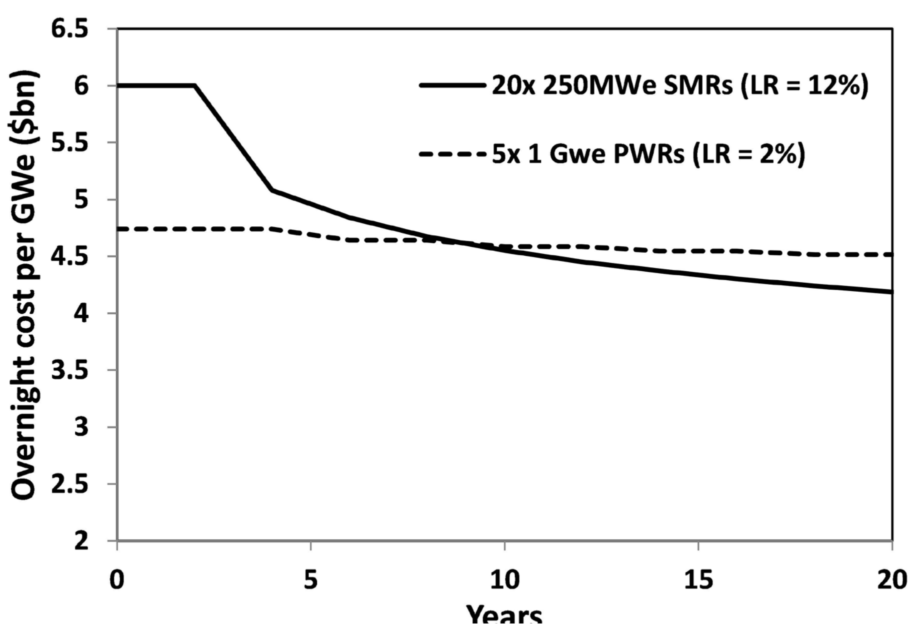
Achievable learning rates for immature and novel technologies are notoriously difficult to predict. In a report to the Electric Power Research Institute, academics at Carnegie Mellon University in the USA attempted to look back and quantify cost reductions in energy technologies through a literature review of studies on the topic.[52] Table 1 shows an overview of their results. Estimates for learning rates vary substantially, even for a single technology, but there is a clear trend. Large infrastructure projects like coal, nuclear and hydroelectric power plants have low rates of learning, whilst factory produced items like solar panels and wind turbines have achieved very high cost reductions in some instances.

In a research paper published in the journal *Energy Policy* looking at historical learning rates for flue gas desulphurisation and selective catalytic reduction systems for coal fired power stations, Dr Ed Rubin and colleagues estimated the historical learning rates for these technologies over a 30 year period. They estimated the learning rate to be 11% and 12% for each. Such numbers are not implausible for a novel, factory produced energy technology like a small modular reactor. If such progress in cost reduction could be achieved with small modular reactors, even if the first SMR had 25% higher capital cost per GW than an equivalent larger reactor, a crossover point would be achieved quite quickly in which the 'overnight' capital cost of an SMR would be lower than that of a large reactor. Figure 11 illustrates how the costs of a large reactor and an SMR might evolve with the same capacity of deployment over time, but with the SMR having the higher learning rate (numbers are indicative and for illustration purposes only).

Table 3: Historical learning rates for electricity-generation technologies

Technology	Years covered by study	Range of learning rates (%)
Coal (PC)	1902–2006	5.6 to 12
Natural gas	1980–1998	-11 to 34
Nuclear	1975–1993	0 to 6
Wind (onshore)	1980–2010	-3 to 32
Solar PV	1959–2001	10 to 53
Bioenergy	1976–2005	0 to 24
Hydropower	1980–2001	0.48 to 11.4

Figure 11: How the cost of an SMR would evolve with a 12% learning rate, compared with a PWR with a learning rate of 2% (illustrative numbers only)



52 Azeveda at al (2013) *Modelling Technology Learning for Electricity Supply Technologies*

An analogous process of bringing down cost has been seen in the offshore wind industry. Offshore wind turbine manufacturers have been able to take advantage of economies of scale effects (wind turbines blades have become much larger, increasing from typically 20 metres in 1990 to over 70 meters today[53]) and economies of volume effects (you still need a lot of wind turbines, even if each one is huge, to produce a significant amount of electrical power, so manufacturers have been able to improve manufacturing processes over time). With a suitable reactor design, good project management and a large enough market for low carbon electricity, a British SMR design could replicate the success of the wind industry.

In order for SMRs to do this it is important to make the right choices early on. The deployment programme should:

- Focus on design simplicity with as few unproven concepts, techniques or materials as possible whilst not compromising on safety.
- Only make design changes during deployment that are absolutely crucial to operating efficiency or safety.
- As much as possible use the same project management team for the whole deployment process.

Policy recommendations:

Fund SMR design studies: The Government should choose at least one Gen III design SMR to take forward through detailed design stages to enable deployment in the 2020s. The metrics on which to judge the best SMR should be simplicity of design, potential for cost reductions and the speed of deployment, with no compromise on safety.

The Office for Nuclear Regulation will be crucial in the smooth roll out of a new generation of nuclear power plants, large and small. It is important that they be adequately resourced. In order to do this the Government should ensure that the Office for Nuclear Regulation (ONR) will have the capacity to process perhaps as many as four Generic Design Assessments (GDAs) at the same time.

Bolster the ONR: Ensure the Office for Nuclear Regulation has the capacity to process multiple generic design assessments, of both large and small reactors, concurrently. The £7 million extra funding made available for the nuclear regulation announced in the Clean Growth Strategy is a welcome step in this direction.

Flexibility

Load following refers to when a power plant ramps up and down to balance supply and demand. In the UK, National Grid has the responsibility for ensuring the country constantly has an adequate supply of electricity. It is occasionally said that nuclear power plants cannot load follow and that this

53 https://www.researchgate.net/figure/221911675_fig1_Fig-1-Size-evolution-of-wind-turbines-over-time

is a major downside of the technology, but this is untrue. Whilst they may not have the 'ramp rate' of natural gas power plants, nuclear reactors are able to cycle their power output up and down. France, due to its abundance of nuclear power plants built in the 70s and 80s, at times of the year does cycle the output from plants to match demand. Modern reactor designs have improved capability in this respect and SMRs even more so. The table below shows the typical ramp rates of a nuclear power plant compared with those fuelled by gas and coal.

Table 4: Typical load following ability of power plants[54]

	Startup time	Maximal change in 30 sec (%)	Max ramp rate (%/min)
OCGT	10–20 min	20–30	20
CCGT	30–60 min	10–20	5–10
Coal	1–10 hours	5–10	1–5
Nuclear	2 hours – 2 days	Up to 5	1–5

With a power plant comprised of multiple SMRs, the ability to respond instantly to changes in demand would be enhanced through being able to divert the electrical power from one or more of the reactors into electrical storage facilities and vice versa. In effect, step changes in supply to the grid could occur instantly that would be equal to the power output from one SMR unit.

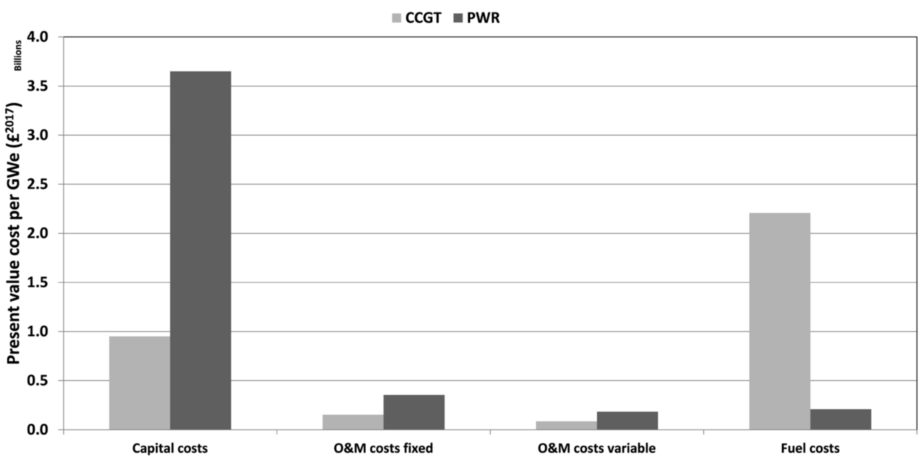
Modern Gen III reactors, large and small, could be set up to load follow, but in reality it makes little economic sense to do this. The largest component of the total life cost is the up-front capital required to build the plant. Once producing power the fuel costs are very low and the operating and maintenance (O&M) expenses relating to staff, etc. will have to be paid whether the plant is operating at 100% or 50% of its rated power. Once a nuclear power plant is built it makes sense to operate at the highest load factor possible, with the only downtime being for scheduled maintenance and refuelling. This cost profile of a natural gas power plant, typically a closed cycle gas turbine or CCGT, is the opposite – low capital costs and relatively high fuel costs – making them much more suited to meeting intermittent peak loads.

Figure 12 illustrates the difference in cost profiles of a CCGT plant versus a large nuclear power plant on a levelised cost basis (assuming 10% discount rate and 30-year operating life). As can be seen they have opposite cost profiles with regard to capital and fuel expense.

So although nuclear power plants can load follow, the economics of nuclear fission do not make it a good idea to do so. A nuclear reactor is so cheap to run on a per-unit of energy produced basis that the wholesale electricity price has to become very low before it is below the marginal cost of producing electricity from the power station. In traditional electricity systems, this is referred to as providing 'base-load' electricity. Power plants fuelled by natural gas provide 'peaking load' (cycling to match demand).

54 OECD-NEA (2012) *System Effects in Low Carbon Electricity Systems: Executive Summary*

Figure 12: Levelised cost breakdown of CCGT versus PWR[55, 56, 57]



However, the traditional business model of operating in base-load may eventually be disrupted by increased penetration of intermittent solar and wind power. The marginal cost of nuclear power is low, but it is not quite as low as that of solar panels and wind turbines. With increased deployment of these intermittent technologies, there will be times of the year when nuclear power plants are displaced from the merit order and electricity from nuclear plants will not be required by National Grid. It will make more sense to use this electricity in some way than to reduce the output from nuclear power plants.

The Government are right to make investment in battery storage a priority, but more attention is needed on the important area of long term storage, something batteries are less suited to than other technologies. If the Government is going to decarbonise our energy system, it should focus more on large-scale storage of energy and on how we are to meet our energy needs in the winter when the output from solar panels will be substantially reduced compared to summer days.

It is clear, however, that in a future with increasing penetration of intermittent renewable power there will be times that nuclear power will be displaced. These periods of the year are likely to become longer and more frequent.

Any long term plan for nuclear power must consider how the energy from a nuclear power plant could be used when it is not required for meeting our national electricity needs. The options include:

- Hydrogen production by electrolysis
- Hydrogen production by thermal 'cracking'
- Electricity storage (e.g. pumping water into a reservoir to be used for hydroelectric power later when required)
- Heat storage (e.g. storing energy in underground rock formations)
- District heating (using excess waste heat to warm up a network of water pipes that can be used to heats homes in towns or cities)

Which of these technologies becomes the norm for large-scale energy

55 Capital costs taken from: Parsons Brinckerhoff (2013) *Electricity Generation Model: 2013 Update of Non-Renewable Technologies*

56 Gas price taken from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/663101/BEIS_2017_Fossil_Fuel_Price_Assumptions.pdf

57 Fuel cycle costs estimated from: http://www.world-nuclear.org/information-library/economic-aspects/economics-of-nuclear-power.aspx

storage will depend on how our energy system evolves and whether the costs of different storage facilities and of hydrogen production decline significantly with increased research and deployment.

Policy recommendation: *The Government should commission research into the potential for long term energy storage in the UK. As a first step this should evaluate the most feasible sites for pumped hydro, compressed air and heat storage to determine how much storage capacity is available.*

This will allow some estimation of the backup capacity that will be required from conventional thermal generation. In the short-to-medium term, our low carbon electricity needs are so great that this need not be a major consideration for the first large and small reactors built. An electricity only business model is viable for these plants, but any forward-thinking energy company should be planning for beyond then.

Policy recommendation: *Vendors in receipt of innovation funding should be asked to submit a plan to Government detailing how they think their plant could fit into a flexible and distributed low carbon electricity system in the long term.*

Lowering cost versus advancing technology

In tech sectors there is often a drive to push the boundaries of what is possible and always strive towards what is new and innovative. In the nuclear sector, however, this has been one of its major flaws. Frequent design changes (often driven by regulatory changes as much as the companies themselves), have meant that cost reductions through replication of a single design have rarely been achieved. There are many who advocate ditching existing Gen III reactor designs and moving to Gen IV; however, this would be a mistake.

The Gen IV International Forum was set up by the UK and other nations to collaborate on research into advanced nuclear reactors. They have selected six potential designs to take forward for further study:

- Gas-cooled Fast Reactor (GFR)
- Lead-cooled Fast Reactor (LFR)
- Molten Salt Reactor (MSR)
- Super-Critical Water-cooled Reactor (SCWR)
- Sodium-cooled Fast Reactor (SFR)
- Very High Temperature Reactor (VHTR)

Details of how these designs would differ from a conventional pressurised water reactor can be found on the World Nuclear Association website.[58] For the purposes of this report, we are more interested in why a company or country might be motivated to advance to Gen IV reactors. Their advantages differ between the various proposed designs, but in general the potential benefits are said to be:

58 http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/generation-iv-nuclear-reactors.aspx

- Safety
- Enhanced uranium 'burn-up'
- Ability to use nuclear waste as fuel
- Enhanced proliferation resistance
- High temperature process heat for industry and desalination

These advantages are overstated to varying degrees, however. Taking each of them one-by-one:

- **The safety record of Gen III nuclear power plants is outstanding.** On a per-unit of electricity produced basis, including full life cycle and fuel effects, nuclear power in general, and especially the pressurised water reactor, is one of the safest sources of energy we have. Estimates vary on deaths per kilowatt-hour energy produced for different energy technologies, but nuclear power is much safer than energy from fossil fuels[59] and generally on par with or safer than wind and solar.[60] One may wonder how people die from wind and solar power, but because they are diffuse sources of energy, large quantities of materials need to be mined, manufactured, installed and regularly maintained. There is plenty of scope for injuries and deaths to occur during these processes.

- Enhanced burn-up refers to making better use of the nuclear fuel in terms of extracting more energy from each kilogram of uranium. A typical Gen III reactor operating today will only make use of around 5% of the energy that could potentially be extracted from the uranium. Gen IV fast reactors make this much higher, thereby lowering the fuel costs. However, as **the cost of uranium is already very low as a fraction of the total cost of nuclear power,** reduced fuel costs do not yet justify the huge expense that would be required to develop and deploy a Gen IV fast reactor. Worries about 'peak uranium' have also faded as forecasts for nuclear power plant construction have been downgraded. The world has more than enough easily obtainable uranium to comfortably supply our nuclear power plants for many decades, even if there is strong growth in the nuclear power sector.[61, 62] Even if these resources become scarce, much larger reserves of uranium could be obtained through recycling of nuclear waste and various unconventional sources (like uranium from seawater) that would extend the resource base into centuries. Gen IV fast neutron reactors could even extend this to thousands of years, but due to the abundance of natural uranium in the world their development is not something that is required in the near term.

- The UK currently has around 100 tonnes of plutonium stored at Sellafield with no clear plan for what to do with it. It is not even clear if this is a liability or a resource. Technically it is high level nuclear waste that will need to be dealt with in some manner

59 https://ourworldindata.org/what-is-the-safest-form-of-energy

60 Forbes (2012), *How Deadly Is Your Kilowatt? We Rank The Killer Energy Sources*

61 Rooney et al (2013) 'A dynamic model of the global uranium market and the nuclear fuel cycle', *Resources Policy*

62 http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/uranium-resources/supply-of-uranium.aspx

eventually. However, this **plutonium can be recycled and reused as fuel in nuclear reactors**. One way of making use of this plutonium would be to use it to fuel a sodium fast reactor, as had been proposed with the GE Hitachi PRISM design.[63] Their proposed design could provide around 1.5% of our electricity demand, whilst also disposing of our most dangerous nuclear waste in a matter of decades. However, this plutonium could also be used in today's Gen III reactors if combined with uranium in the form of mixed oxide (MOx) fuel. So a Gen IV reactor is not necessarily required to make use of our plutonium stockpile as a fuel.

- Thorium is more abundant in the earth's crust that uranium and it could theoretically replace uranium as the fission fuel of choice in our nuclear power plants in the future if uranium becomes scarce. Moving to a nuclear fuel cycle that replaces uranium with thorium is also put forward as a way to enhance proliferation resistance as it is more difficult to make a nuclear weapon if using a thorium fuel cycle. However, as Dr Stephen Ashley and colleagues from the University of Cambridge and Imperial College showed in a 2012 research paper published in the journal *Nature*, **moving to a thorium-based fuel cycle does not eliminate the proliferation risk**.[64] The main proponent of thorium in the world today is the Indian Government, as they have vast thorium deposits.

- Finally, advanced reactor designs could be used for industrial process heat and desalinisation. Unlike some of the hotter, dryer countries around the world, the **UK is unlikely to require desalination of water any time soon**. Process heat for industrial applications could be useful in contributing to the decarbonisation of heavy industry in the longer term, and that is one reason why research into Gen IV concepts is still worthwhile, but that alone is not enough of a justification to press ahead at speed with an immediate shift to Gen IV reactors.

In the near term, what the UK and the world requires is large quantities of low-carbon, low-cost electricity. As Gen IV designs have not been deployed at scale yet, they would be slower to develop and deploy. The priority in the short-to-medium term should be to develop simple low-cost Gen III reactors and build many of them in order to take advantage of learning-by-doing and fleet effects.

There is still value in research into more advanced nuclear technologies. Funding advanced research in our universities and national laboratories will help build up a skills base for the domestic nuclear industry. It will also maintain the capability to develop a Gen IV reactor in the future. Reviving the UK's civil nuclear power industry through SMRs should work in parallel with a thriving research environment in which universities and national research labs are at the forefront of innovation into advanced

63 http://gehitachiprism.com

64 Ashley et al (2015) 'Nuclear energy: Thorium fuel has risks', *Nature*

nuclear power. This will maintain a steady pipeline of university graduates for the civil nuclear industry and ensure that the UK has the capability to deploy Gen IV reactors in the 2040s.

Policy recommendations:

Funding Gen IV reactor research: Research into Gen IV reactor designs in the UK should continue in order to ensure that the UK has the capability and skills to maintain a vibrant and successful nuclear industry into the 2040s.

Continued membership of GIF: Continued membership of the Generation IV International Forum (IV) will facilitate collaboration with our European neighbours in this regard and save the British taxpayers money through effort sharing.

Consult with heavy industry: Launch a consultation with heavy industry into what services advanced reactor designs could bring that would be most useful to them (process heat, hydrogen production, etc).

A new research reactor: The UK should consider funding the development of a nuclear fission reactor that would be used for academic research and development. This could be sited on one of our existing secure civil nuclear power or research sites and universities and other research organisations could apply for time on the reactor for experimentation.

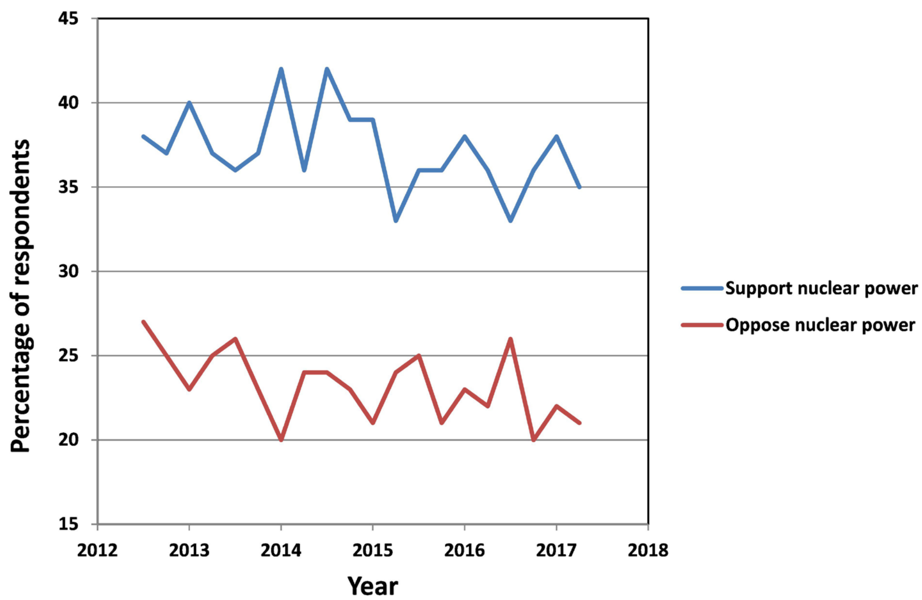
Such a facility could also be used to produce medical isotopes. The issue of the UK having no indigenous production of these crucial materials, which are used for the diagnosis and treatment of various diseases, was highlighted in the recent debate over whether the UK should leave Euratom (the EU body that regulates civil nuclear power).

Public acceptance of nuclear power

The British public generally has a more favourable view of nuclear power than unfavourable. The Department for Business, Energy and Industrial Strategy periodically poll the general public to measure attitudes to various issues in the area of energy and climate change. Polls are conducted four times per year and began in March 2012. Figure 13 shows results from 2012 to 2017. The percentage of respondents who say they support nuclear power has never fallen below those who oppose it during that time.

Polling from America suggests that the closer you live to a nuclear power station the more likely you are to have a favourable opinion of the technology.[65] This is because if a person lives near a nuclear power station they are more likely to have friends or family employed directly or indirectly by the plant. Even if they do not, they will be more familiar with the concept of nuclear power than the average citizen and therefore less likely to believe common misconceptions around safety and nuclear waste.

Figure 13: Public attitudes to nuclear power from 2012 to 2017[66]



It is partially for this reason that plans to build new nuclear reactors in the UK, both large and small, will initially focus on existing nuclear sites (though having existing grid infrastructure is also a major factor). A study by the UK's Energy Technologies Institute estimated that the maximum capacity of nuclear power that could be deployed on existing secure nuclear sites across England and Wales is 35 GW.[67] This is more than sufficient to enable the Government's ambition of 16 GW of new large reactors by 2030, and at least some of these sites could also be used for the rollout of small modular reactors in parallel.

In the longer term, however, if SMRs are to play a large role in decarbonising our whole energy system, consideration will need to be paid to whether and how reactors could be built on sites in places that do not have existing nuclear facilities. The Energy Technologies Institute in assessing the economics of small modular reactors have suggested that using them for combined heat and power, or perhaps even hydrogen production, will make them much more viable in the longer term. If using an SMR for district heating of homes, then they will need to be sited within a few miles of an urban centre, mostly on greenfield sites. Deployment of district heating systems in existing towns and cities is already a challenge due to the infrastructure changes that are required, but when the heat is derived from a nuclear power station then it may face public opposition. A recent poll by YouGov found that 62% of the public would not like to live within 5 miles of a small modular reactor.[69]

This is not a problem for deployment of nuclear power in the short term, but in the longer term it will increasingly become a consideration. Whether a majority of the general public can be convinced that living near a nuclear reactor is safe or not is an open question. The Government and companies interested in investing in small modular reactors should take a proactive approach.

65 Bisconti Research (2013) *Favorability Toward Nuclear Energy Stronger Among Plant Neighbors Than General Public*

66 Data source: https://www.gov.uk/government/statistics/energy-and-climate-change-public-attitudes-tracker-wave-22

67 ETI (2016) *The role for nuclear within a low carbon energy system*

68 Ibid

69 The Guardian (2017), *Most Britons 'dislike prospect of living near mini nuclear station'*

Policy recommendation: *The Government should commission polling of the populations closest to potential sites for small modular reactors. This can be used to inform future SMR siting studies and feed into the Government's existing energy and climate change public attitudes tracker.*

Key Takeaway Message

Cost reductions of solar and wind have been impressive and should not be downplayed. Biomass can play a role in reducing emissions from electricity generation and even more so in heat. Battery developments are welcome and much of our electricity system will become distributed and smart. These are promising and exciting developments.

But the limits of these technologies are such that all options should be kept on the table.

Carbon capture and storage will be a vital technology in the second half of the 21st century. The UK should lead in its deployment and begin with an industrial cluster in a suitable geographical location.

Development of large-scale storage would be welcome. There are many good ideas in this field and any additional large scale, low cost energy storage that can be added to our energy system should be welcomed.

The door should be also kept open to large nuclear, but vendors need to find ways to bring down cost, either through better project management, technological learning or innovative financing.

However, taken together, **the limitations of all the above technologies and the scale of the challenge we face mean that we may need more. The gap in our energy needs could be met by small modular reactors.**

The UK is seeking companies to lead on the design and build of new British small modular reactors. Given the ongoing problems of financing and constructing large reactors across the western world, this is a sensible strategy.

In the short-to-medium term, the most important aim should be to bring down the cost of nuclear power and add as much low cost, low carbon electricity to the grid as possible to meet our obligations under the Climate Change Act.

The Government should choose at least one Gen III+ design SMR to take forward through detailed design to demonstration. The metrics on which to judge the best SMR should be simplicity of design, potential for cost reductions and the speed of deployment.

The focus at this stage should be on simple designs that reduce costs through replication, while not compromising on safety.

The chosen project(s) should be assessed against measurable deliverables, most importantly if they can be built on time and to budget. Some extra expense should be allowed due to the fact that all of these projects will be first-of-a-kind, but on completion of the first SMR, the project leaders should be asked to produce plans for how they intend to reduce costs in the future. Any support for future projects should be based on the credibility of these plans.

An extra consideration is the potential for using the SMR for other services, including district heat, hydrogen production, or even in the manufacture of isotopes for medical imaging and treatment. In the future it is clear that nuclear power increasingly will not be able to continuously provide maximum power to the grid at all times of operation ('base-load' power). Periods of high wind and solar output will displace nuclear power from the grid and reduce revenues. As the marginal cost of nuclear power is so low, it makes little sense to load follow, however. The electricity produced at these times should be stored in some way in order to be sold later at times of higher demand. In order to maintain the financial viability of nuclear power in the future, reactor vendors should design SMRs with this in mind.

In parallel to this drive to bring down the cost of Gen III technologies, the Government should consult as widely as possible – including with the research councils and the nuclear industry – into what the priorities should be for research into Gen IV reactor designs. Developments in Gen IV technologies are welcome, but right now the factor holding back nuclear power is cost, and the more immediate focus should be on the deployment of Gen III reactors that have the potential to bring down costs through simplification and standardisation.

Policy Exchange

Recent cost reductions achieved in the solar and wind energy sectors have been impressive and should not be downplayed. Biomass can play a role in reducing emissions from electricity generation and even more so in heat. Battery storage improvements are welcome and as a result much of our electricity system will become distributed and smart. These are promising and exciting developments. But the limits of these technologies are such that that they cannot be the whole answer.

Powering the United Kingdom with 100% renewable energy would still be an incredibly difficult task. Even if achievable, the potentially high embedded life cycle greenhouse gas emissions associated with battery manufacture and biomass production may mean that pursuing a 100% renewable energy strategy would unsustainable and damaging to environment. All low carbon technologies should be on the table, including nuclear power.

However, nobody looking at the state of the nuclear industry in the Western world at the moment would say it is flourishing. The trend in recent decades of nuclear reactors becoming larger and more complicated has made financing and constructing them more challenging. The record of bringing nuclear power stations online within budget and on schedule has been poor.

Small modular reactors (SMRs) can be a solution. This report examines the role SMRs could play in the UK's energy system and makes recommendations as to how Government policy can lay the groundwork for their development and deployment.

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