Meeting the UK's 2050 De-carbonisation Targets for Electricity Generation: the Contribution of Nuclear Energy

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1. UK Energy Challenge

One of the key drivers of the decision, in 2008, for the UK to replace its older gas-cooled nuclear reactors, was a decarbonisation policy committed to cutting emissions by 80% (from 1990 levels) by 2050. Recently this goal has been stretched to 'Net Zero' carbon by 2050 [1]. The UK has made significant progress by: (i) a reduction in manufacturing; (ii) reducing the carbon intentsity of power generation by moving from coal to gas and by investing in large amounts of installed wind (20 GWe) and solar energy (13 GWe). In 2017 almost half of electricity was generated from low-carbon sources. More broadly across the economy, emissions have already fallen by 37% to 371 Mt CO_2 pa [2].

Current strategies to address the next phase of de-carbonsiation are common with many other countries: (i) improving energy efficiency; (ii) de-carbonisation of the electricity system; (iii) transfer of energy demand from fossil fuels to the de-carbonised electricity system such as by the introduction of electric cars and heat pump space heating. The key question for the UK and other developed nations is: How to de-carbonise the energy supply at the lowest cost, while ensuring the continuation of a highly reliable supply system?

In their seminal paper of 2004, Pacala & Sokolow [3] proposed global Climate Stabilisation Wedges, or major programmes, such as the wholesale switch from coal to gas in energy generation, or the replacement of oil with electricity for most of transport. Each Wedge is sized to provide savings of 1 Gt CO_2 pa by 2050. About twelve options were considered. They were all massive in scale and conventional, rather than novel, in technology. Eight of these programmes would save 8 Gt CO_2 pa, consisting of half the expected global emissions in 2050. This paper uses Wedge ideas, to identify the technologies and the scale of application to achieve UK emission targets by 2050. Climate Stabilisation Wedges are too large to apply to most economies. One tenth of a Wedge (deci-wedge (dw) = 100 Mt CO_2 pa) is more relevant for the UK. Here we will consider the major energy supply options together with the barriers and opportunities for nuclear to become a major part of the UK's Climate Change strategy providing at least one deci-wedge.

2. Low-Carbon Energy Options in the UK

The UK Climate Change Act 2008 is due to be amended to cut annual emissions of greenhouse gases (of which CO_2 is 80%) to Net Zero or <10 Mt CO_2 pa for energy. UK demand has fallen from 1802 TWh in 1990, to 1487 TWh in 2016 [2]. On current growth trends and with energy efficiency improvements, primary energy is expected to increase by a third, with a much larger share from electricity. Without change to the energy mix CO_2 emissions would rise. To meet the 2050 target, 488 Mt CO_2 pa savings are required - about half a Stabilisation Wedge: 4.9 dw.

Fifteen years after the Pacala & Sokolow paper, there is now both more information on what works and also less time to act, ruling out some of the less developed technologies. The main options for low-carbon electricity are now clearer. UK, with other developed countries [4], is looking to three main options: Renewables, CCS and Nuclear, together with hydrogen as an energy carrier.

Each of these options could supply at least one deci-wedge of Climate Stabilisation, as follows:

1. **Renewables**: 72 GWe offshore wind; 46 GWe solar (8 and 3.6 times current capacity respectively, based on current wind/solar share). Space is an issue for renewables in a populated country like the UK, but these issues may be able to be circumvented for wind located in deeper waters off-shore. The key issues for both wind and solar are their intermittency and how they affect the wider power network. This variable output means that stand-by generation or storage is required. It also affects the other suppliers within a grid system. Where generation prices are fixed by a market, this leads to huge variations in energy prices [5]. Low cost energy storage is required as renewable share grows. For periods longer than a few days, the volume of storage required becomes very large and the economics of storage equally unfavourable.
2. **Carbon Capture & Sequestration**: CCS capacity for one deci-wedge depends on the carbon intensity of its power cycle, but it could be in the range 57-80 GWe. For most CCS cycles only 90% of the carbon is captured. Additional energy is required to compress and transport the carbon dioxide. Published results for gas CCS carbon intensity are: 100-200 gCO2/kWh. These carbon intensities seem incompatible with a Net Zero target. Newer oxy-fuel cycles such as Allam could be capable of much lower levels of carbon intensity. Even though CCS has been a priority technology for more than 15 years, and some projects have been built linked to oil recovery, few purely CCS projects have been completed. CCS capital costs ($2,000/kWe) in the recent MIT study [4], are double those for CCGT, with LCOE value of $90/MWh, 40% higher than CCGT. Nevertheless, the cost of CCS generation and its infrastructure are yet to be demonstrated at scale.
3. **Nuclear Fission**: 29 GWe of capacity - seven times the committed UK nuclear capacity, post 2030. When UK nuclear energy policy changed in 2008 to support new nuclear generation, it was recognised that without investment, a large low-carbon energy source would be lost, as current reactors came to the end of their lives. Also, the planned exit from coal power generation removes another major source of stable and dispatchable power during the next decade.

Following the 2008 Nuclear White Paper, a major programme of new nuclear was planned, with about a dozen large reactors of several different designs to be built using private funding. Ten years on, only one project: Hinkley Point C, has been started. Several projects have stalled and others are still seeking funding. There are committed plans for only the two new nuclear reactors at Hinkley Point. It is likely that only 4.3 GWe of nuclear capacity will be operating beyond 2030.

UK experience over the last ten years has shown nuclear projects can be developed, but the large reactors being proposed are too large and too risky to be funded by the private sector. Also, the current approach to construction means that these reactors have too high capital costs (in part because of slow build) to be considered for a major role in Climate Change strategies. Furthermore, because they take too long to construct, they are not attractive to power utilities.

What are the feasible options for addressing these cost, funding and construction schedule problems? There are three possible strategies - each providing one deci-wedge and providing a build rate of about 1.5 GWe pa during the period 2030-50, well within the build rate achieved in France in 1980s: (i) Programme of standard large reactors – 20-30 reactors of a standard design built a 1-2 pa; (ii) Factory-made Small Modular Reactors using LWR technology 116*250 MWe units 6 pa; (iii) Advanced Modular Reactors using Gen IV technologies, ~100 reactors 10 pa from 2040.

3. Programmes of Standard Design Large Reactors

New information from the UK Energy Technology Institute on the Cost Drivers of Nuclear [6] shows that there are some different programme and construction strategies based on developing the particular ‘know-how’ of nuclear construction that could transform the economics of nuclear energy.

Based on the most recent 33 new nuclear projects, the ETI report identifies the programme strategies that reduce costs and it quantifies their different contributions. It shows how to cut capital costs by 50% from current levels - closer to those achieved by the French programme of 1980s. It was these French costs that were the basis of the UK’s Nuclear New Build decision in 2008. However, it was not the programme strategy the UK adopted.

Many of these new projects were from East Asia where capital costs, are low - one third of those in the West. Even discounting lower labour costs, East Asia’s more experienced teams deliver higher productivity. In many cases, productivity has been double the Western equivalent. Furthermore, it is significant that build schedules are half those of the West, even for the same design of reactor.

Many best practices can be adopted in the UK. These include (i) the adoption of a series of standard reactor designs; (ii) a fully completed design before start of construction; (iii) Construction by a consistent group of contractors and suppliers and (iv) Multiple units built on each site.

US reactors built in the 1980s provide the baseline, updated to 2017 economics. The model assumes experienced contractors, using an established design, managed in a conventional manner - one project at a time. Repeated construction of a single design delivers both lower costs and higher cost certainty. Three cases below show the scale of potential savings in both construction and energy costs.

Differences in cost between the cases is large. In the West, we need to re-learn nuclear construction. Costs are currently 54% above the benchmark. Adopting best practices could yield a 57% reduction. Energy costs would also be lower: \$81/MWh (£57/MWh at PPP rates). Regular delivery of projects would reduce the risk premium (7%), with energy costs 58% less than today: \$61/MWh (£44/MWh).

TABLE 1. LARGE REACTOR TOTAL COST OF CONSTRUCTION [7]

Case	Conditions	Specific Capital Cost $/kWe	Energy Cost $/MWh @ 9%
Benchmark	Single projects with proven reactors built conventionally by experienced staff	$6,826	$108
Start-up	Single projects built conventionally & where 'know how' is lost	$10,500 (+54%)	$148
Western Target	Programme of standard reactor builds. Best practices from East realised in the West –	$4,386 (-33%)	$81

At these cost levels, nuclear would be competitive with any other form of generation. Nuclear power's dependability would make it an attractive part of a low-carbon energy system.

None of the construction strategies being considered are not technically radical. They all depend on a consistent long term programme of build using the same design, with a commercial structure that incentivises the supply chain to: plan, design and deliver a continuously improving series of projects. One potential issue is the availability of coastal sites for these large units. But the key question is: Who would stand behind such a large programme of build of perhaps twenty large reactors, with an investment cost of more than $140bn (£100bn) over 20 years?

4. Small Modular Reactor Programme

SMRs are based on proven LWR technology. They seek to reduce both the cost of construction and the build schedule by adopting manufacturing methods. In some cases passive safety systems are used to simplify the design. Though smaller reactors have higher specific costs, SMRs are able to benefit from design for modular construction and assembly to a much greater degree than large reactor designs. These modular construction methods are routine in other sectors, such as Ship Building and Oil & Gas construction.

Manufacture of reactor modules in factories allows the better use of modern tooling and construction methods that substantially increase the productivity of both direct and indirect staff. Also, the greater volume of SMR modules promotes manufacturing learning that further reduces costs. Finally, modular construction removes many long duration processes from the construction critical path, enabling SMR build schedules to be radically reduced and with this, cut financing costs.

Preliminary studies [9, 10] show the potential of new construction practices applied to SMRs. More recent work at the University of Cambridge is showing that unit size is important to the degree of modularisation that is possible, which affects both cost and schedule. This work is showing that for the best case and a 250 MWe SMR, the combined effects of: Standardisation of design (16% lower scaled cost); Optimal Modularisation (-25%); Schedule reduction (-16%). Taken together these could cut the cost of construction of the 'first in a series' SMR, below that of an equivalent large reactor. Costs would fall further resulting from Production Learning (17%) across the larger number of units. Overall construction costs could be cut to below $4,000/kWe and LCOE is reduced to $70/MWh - a third less than the equivalent large reactor and half current nuclear energy costs.

The SMR concept depends on a large volume of units to offset the set-up costs for design, development and new production units. It is probable that the minimum sized programme would be about 10 GWe i.e. 40 * 250 MWe SMRs - which is well within the scope of an UK deci-wedge nuclear plan. UK studies [9] of nuclear sites show that using the current siting rules, there are many more sites for SMRs, because of their smaller space and lower cooling requirements. Though the investment cost for a programme of SMRs will be similar to Large Reactors, due to their much shorter build time, SMRs will require much less capital for the risky construction phase [11]. Also, their product-like characteristics allow project development risks to be radically reduced.

5. Advanced Modular Reactors

There is growing interest in US, Canada and UK in small reactors [10] that make use of Generation IV reactor technology, as well as modular design and manufacture (AMRs). These reactor designs seek to reduce cost by using higher coolant temperatures that enable higher efficiency power cycles and by their inherent safety features which simplify the design. The application of these features vary: (i) High Temperature Gas – Fuel that can withstand high temperatures and a core than can cool itself; (ii) Fast neutron reactors – Low pressure coolant, precluding a fast leak, with a large energy storage capacity for decay heat following an accident; (iii) Molten Salt – Low pressure, but high temperature coolant, precluding a fast leak and a large energy storage capacity for decay heat following an accident. Also, the fuel is already molten but contained in salt that retains most of the fission products.

Claims have been made that the cost of AMRs could be well below existing nuclear - with total capital costs in the range $3,700-5,000/kWe and LCOE between $50-80/MWh [6]. These cost etimates have been challenged in the recent MIT study [4], which puts AMR costs in the range $5,200-6,100/kWe, close to those for a large LWR reference plant, with LCOE values in the range $110-135/MWh. Until AMRs have been built, their costs will remain a matter of debate.

AMR technologies could have other benefits such as actinide burning, or fissile fuel breeding, depending on the configuration. On the other hand, they often require different fuel types, or higher fissile loadings that challenge current proliferation rules. Also, AMRs will need new fuel manufacturing and processing routes. There is some prototype experience of high temperature gas and fast neutron reactors, but there is very little experience of operating molten salt reactors.

These novel designs of AMR will require both a technology demonstration and a production prototype. The timescale of development proving and of the building and operating the prototypes means that deployment of AMRs in any volume within the next twenty years, looks problematic. These programme issues inhibit AMRs' potential to provide enough units to contribute a deci-wedge.

The development costs for AMR are large, as are their potential benefits. The scale of development funding and its uncertainty point to the need for international collaboration to make such programmes practicable on any accelerated timescale to make a significant contribution before 2050.

6. Conclusions

In the UK, as in other developed countries, there are three main options for low-carbon energy generation. None of these could be applied at the required scale without problems, or without development, which will require Government support in some form.

For reasons of cost and funding, nuclear power is not currently a preferred means of tackling Climate Change. There are at least two available approaches that would allow nuclear to become competitive with other low-carbon energy sources. If adopted quickly, they would allow nuclear energy to be a substantial contributor to Climate Change at scale - providing one or more deci-wedges towards UK strategy and when demonstrated, similarly in other developed countries.

A strategy of building 29 GWe of nuclear (for one deci-wedge) will be possible only with Government involvement to: a. Guarantee construction funding; b. Support collaborative design and development of Modular and Advanced reactors.

Future R&D for nuclear should focus two main task: Turning modern construction approaches for SMRs into practical solutions 2. Evaluating how AMRs can be developed and deployed before 2050.

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