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Keywords Cost of CO_2, Nuclear power, RAB, WACC, Cost Benefit Analysis

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24 March 2020

Abstract

This paper calculates the cost per tonne of CO_2 abated by Sizewell B (SZB, the nuclear power station commissioned in 1995). Other zero-carbon renewables received contractual support. A long-term Contract-for-Difference (CfD) is modelled with a strike price reset every 5 yrs. by the regulator under the Regulatory Asset Base model of electric utilities. The answer depends on the Weighted Average Cost of Capital (WACC), given the range of observed utility WACCs. At a low WACC the cost is £$_{2019}$34.1/tonne CO_2 abated and £$_{2019}$49.2/t. CO_2 at the high WACC, compared with the roughly £40/t. CO_2 paid by GB generators in 2019. Had the design for SZB been replicated for the 6.4 GW new nuclear the saving might have been £9-18 billion.

1. INTRODUCTION

The UK has now committed itself to Net Zero by 2050, and various bodies, such as the Commission on Climate Change and the National Infrastructure Commission are publishing pathways for the energy sector to meet that target (CCC, 2019a, b; NIC, 2020a). Considerable uncertainties are highlighted with important differences in possible pathways to net zero. Heating is recognised to be one, where the two extreme options are to decarbonise natural gas to hydrogen by Steam Methane Reforming (SMR) with Carbon Capture and Storage (CCS), or to electrify using heat pumps. The hydrogen pathway could use the existing gas pipeline system and (slightly modified) existing equipment in buildings, while electrification requires massive investment in heat pumps as well as a considerable expansion of the electricity system. The other major choice, or rather, the optimal balance, is between renewable electricity, nuclear power and/or CCS (including Bio-energy CCS, or BECCS, which can absorb CO_2 and thus offset unavoidable emissions).

Almost without exception, where these reports give costs, they do not draw attention to the cost of financing the investments (the Weighted Average Cost of Capital, WACC), and where they do the default assumption appears to be that these will be financed at the kinds of hurdle rates used by private companies investing in a liberalised electricity market. Thus the National Infrastructure Commission assumes almost all WACCS at around 9% real (NIC, 2020b). However, one characteristic shared by all zero and low-carbon energy technologies is that they are very capital intensive, so the cost of capital is a main determinant of their life-time costs. With the exception of CCS and SMR hydrogen, operating costs are low, further amplifying the role of the WACC in determining cost. This might not matter if the trajectory merely quantifies the annual rates of expenditure (investment and operating costs) as is common in the summary reports, but it can matter when choosing the best portfolio of techniques to deliver the target. This paper will argue that the tendency to assume high hurdle rates is both damaging (in exaggerating the costs of decarbonisation), potentially dangerous

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(in the choice of techniques) and unnecessary, in that there are better methods of financing such investments that dramatically reduce the WACC.

So what should the WACC be for investments to mitigate damaging climate change? The *Stern Report* (Stern, 2007) lays out the arguments for a low social discount rate of 1.4% (real). It logically follows that the social discount rate should be used not only to measure the damage caused by releasing CO_2 now, but should also be the rate used to discount the future benefits of zero-carbon generation investments that avoid damaging CO_2 emissions. (There are additional arguments relating to risk and distributional concerns that strengthen the case for a low rate discussed in Newbery et al., 2019.)

The UK Government's Appraisal Manual (*The Green Book*, HMT, 2018) follows the same utilitarian public economics theory that guided the estimates of the discount rate in the *Stern Report*. It sets out the principles of social cost-benefit analysis for appraising projects whose private returns are likely to understate their social benefits. That is pre-eminently the case with investments in zero-carbon technologies to mitigate climate change. The rate used for long-term discounting by the UK Government was reduced after the *Stern Report* from 2.5% for projects lasting 75+ years to 2.14% (HMT, 2018, p104). That suggests a discount rate or WACC of 3% should not be too high.

In an earlier project, the author and colleagues demonstrated the importance of the WACC in financing new nuclear power plants (Newbery et al., 2019). That was, however, a prospective analysis based on assumptions about future fuel, carbon and electricity prices. It therefore seems timely to conduct an *ex post* social cost-benefit analysis of a past nuclear power station (Sizewell B, on the east coast of Britain) to ask whether it was a cost-effective way of decarbonising. This is particularly important as the standard argument against nuclear power (other than dread of massive accidents, and its association with the bomb) is that it is too expensive compared to the now rapidly falling costs of renewables. This paper will look at a particularly expensive example ─ the first and only one of its kind in the UK ─ and argue against that view, based on a tried and tested method of lowering the WACC.

1. THE HISTORY OF BRITISH NUCLEAR AMBITIONS AND SIZEWELL B

Before privatization, the Central Electricity Generating Board (CEGB, the state-owned generation and transmission company for England and Wales) had an ambitious plan to build a fleet of nuclear power stations on the Sizewell B model. In the opening words of the PIU[2] (2002) study:

> "Nuclear power and the various forms of renewable energy are the two main virtually zero carbon electricity supply options. Even if UK energy efficiency is improved dramatically, new electricity supply options will be needed on a significant scale as older stations of all types are retired. In a world constrained to achieve major carbon emission reductions, nuclear power and renewables assume particular importance.

[2] The Performance and Innovation Unit (PIU) was set up by the Cabinet Secretary in 1998. "Senior officials and ministers, including the Prime Minister, believed that Government needed to rebuild its capacity to do long-term thinking and strategic policy work." (See https://publications.parliament.uk/pa/cm200102/cmselect/cmpubadm/262/2071103.htm)

The contribution that each could make to the UK energy mix is potentially large – but strictly limited if current market conditions alone determine investment choices. Renewables are mostly embryonic technologies with costs higher than gas-based alternatives, especially combined cycle gas-turbines (CCGTs). Nuclear power is a more mature technology, though also not currently competitive as a new investment option."

Sizewell B was the first, and so far the only Pressurised Water Reactor (PWR) commissioned in the UK, and its approval took one of the longest and costliest public inquiries to be held. Starting in 1982 under the chairman, Sir Frank Layfield, it finally reported in early 1987. The proposal was accepted by the Nuclear Installations Inspectorate, and the project was approved. Construction started by the CEGB in 1987, but the CEGB was unbundled and its fossil generation (and grid) were privatized in 1989. Sizewell B (and the other nuclear stations) remained in public ownership in Nuclear Electric until 1996, and the station was commissioned and first synchronised with the national grid on 14 Feb 1995.

2. CALCULATING THE COST OF CO_2 SAVED

The cost of CO_2 saved is the shortfall in revenue from the investment in the station compared with the reduction in CO_2 emissions enabled. For that calculation we need to know the cost of the plant, the required return (WACC), the revenue from sales less the cost of operation, and the CO_2 displaced compared to the counterfactual in which Sizewell B had not been built. Each step in the calculation requires assumptions, even if some of the elements are in principle known. Even the cost is problematic ─ should it include first of a kind costs (given that it was also the last of its kind)? In this paper we take the least favourable case of first of a kind costs (FOAK). Next, should the cost be uprated by the Retail Price Index (RPI) or the lower Consumer Price Index (CPI)? Here as we shall consider RAB financing by Ofgem, the normal estimate of the WACC used to be based on the RPI, but that measure of inflation is increasingly questioned and has been changed for the latest price controls to CPIH.[3] Fortunately, the start date of the calculation is closer to the time of the cost estimates, reducing the potential index number discrepancies.

To start first with the cost, for what should be an objective fact the available evidence is somewhat ambiguous. PIU (2002) stated that "In 2000 money, the construction cost was approximately £3000/kW including first of a kind costs, or around £2250/kW in their absence." As we are interested in its value in 1995, when it was commissioned, we need to estimate its value in 1995 money. At the time the PIU wrote its report, the standard price

[3] The Consumer Price Index, CPI, (actually CPIH) was introduced as the Harmonised Index of Consumer Prices (HICP) in 1996 and later as the CPI, but even now successive estimates of the CPI before 2000 are alarmingly variable. As a measure of the problem of uprating prices, using the RPI from 1995 to 2019 the uprating factor is 1.94; using the CPIH, it is 1.62; and using the even less reliable construction index and piecing together at least three series, it is 2.54. The Office on National Statistics only took control of the construction series in 2015 and has since revised the methodology – see https://www.ons.gov.uk/businessindustryandtrade/constructionindustry/articles/interimsolutionforconstructionoutputpriceindices/ukjantomar2017#toc

index was the Retail Price Index (RPI) and using that, the cost would be approximately £$_{1995}$2,620/kW.

Collier, who oversaw the construction of Sizewell B (SZB) as chairman of Nuclear Electric, reports that “the revised capital cost estimate in 1987 prices was £2030 million. The project was completed within this budget.” (Collier, 2015, p753). The follow-on plants would have cost less: “The development of the design cost was of the order of £700 M” (Collier, 2015, p757). SZB delivers 1,198 MW to the grid, so the budgeted figure was therefore £$_{1987}$1,695/kW (with some uncertainty as subsequent costs were probably revalued at the RPI but we do not know the time pattern of expenditure). In 1995 prices again using the RPI this is £$_{1995}$2,480/kW. A simple average of the two is £$_{1995}$2,550/kW.

Fortunately, we have reliable figures for output, kindly supplied by EdF. However, while the wholesale spot prices are observable, as a baseload inflexible plant with predictable refuelling cycles, its output would be sold on contract and for that we have no published data. However, in a cost-benefit study we are less interested in the financial transactions and instead need to know the cost of the electricity displaced. If markets were competitive (a major qualification before about 2000) the spot price might be a reasonable proxy for the marginal cost of electricity (although it ignores the contribution to capacity adequacy). We have daily spot price data (the Pool Purchasing Price from 1990-2001, thereafter the Market Index Price (MIDP) until ENTSO-E started publishing Day-Ahead Market (DAM) data on its Transparency website).

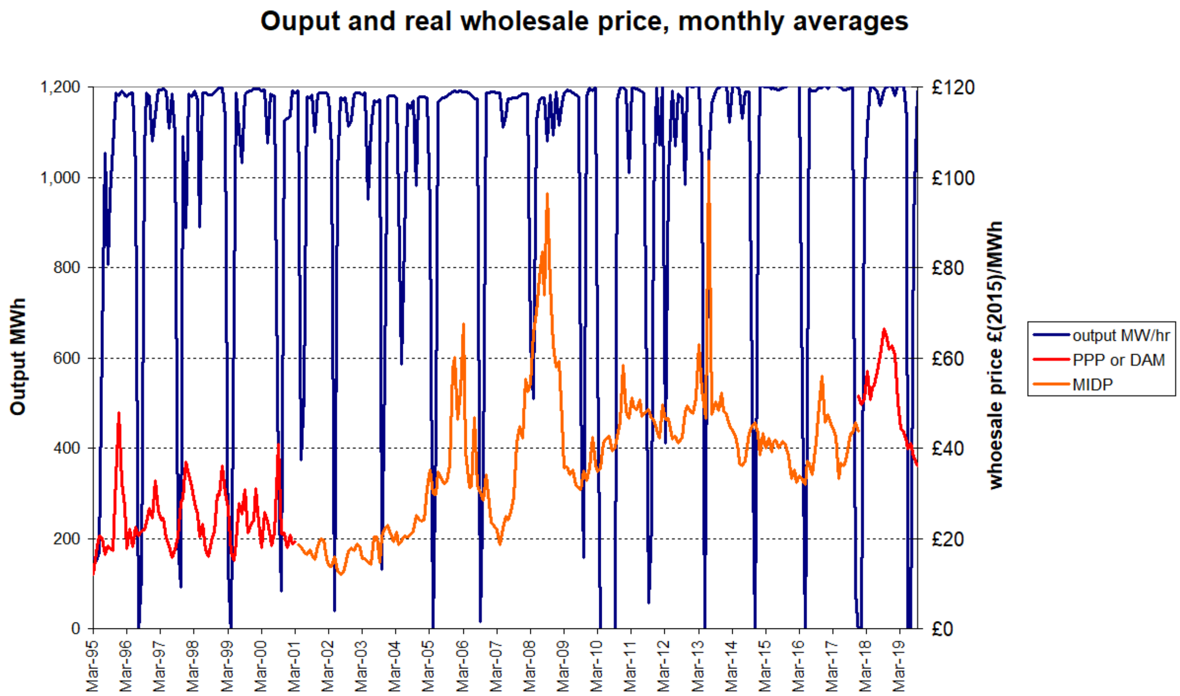

FIGURE 1

Hourly output and real (£2015) wholesale prices, monthly averages

Source: Output from EdF, prices pre-2001: PPP from the Pool, post 2001: MIDP, later ENTSO-E

Figure 1 shows the monthly averages of output and the relevant wholesale prices since Mar 1 1995 (shortly after first synchronising to the grid on 14 Feb 1995). The cumulative average capacity factor was 84% from Oct 1995 to Dec 2019. The output shows periodic outages for refuelling every 18 months and a major repair outage in 2010 after an incident due to problems with the pressuriser.[4] Additional specialised staff were needed during such outages, as reported by Balfour Beatty for the 2012 statutory outage.[5] For example, "The nuclear power station stopped generating electricity at the end of May 2019 as 1,200 specialist workers joined the 800 workers on site for the £60 million outage project. The station is brought offline every 18 months where a third of the fuel is replaced in the reactor and thousands of maintenance jobs are completed during this work period."[6]

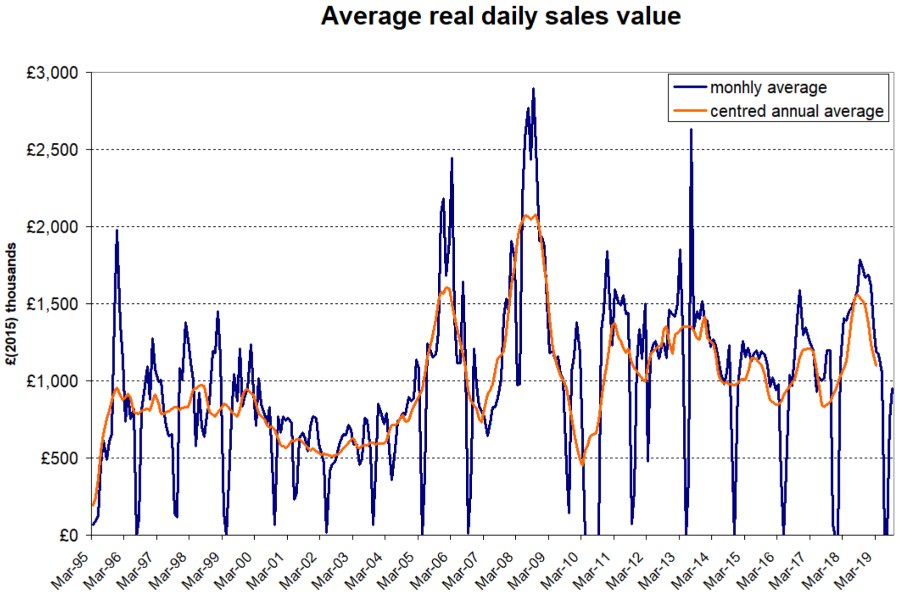

Figure 2 Average daily real sales value of output from Sizewell B (deflated by CPI)
Source: as fig 1

Figure 2 shows the daily sales value at the spot price (uprated by the CPI to 2015 prices) from March 1995.

2.1 Operating costs

To compute the cost of CO_2 saved we need to estimate the gross profit of running the plant and that requires estimating operating costs. These include the cost of running the station (personnel, which according to EdF includes "approximately 520 full time EDF Energy employees plus over 250 full time contract partners",[7] the fuel and other material costs, the cost of eventual decommissioning, the cost of repairs and maintenance, and the cost of the grid connection. As noted, the 2019 refuelling and maintenance cost £60 million. If such expenses occur every 18 months the average fixed cost of the workforce (at £50,000/employee-yr) and maintenance alone would be £64,000/MWyr, but this excludes materials and other overheads.

[4] "Sizewell B outage will extend into summer". Nuclear Engineering International. 11 June 2010.
[5] https://nrl.co.uk/beyond-recruitment/sizewell-b-statutory-outage-2012/
[6] https://www.eadt.co.uk/news/sizewell-b-refuelling-edf-energy-outage-1-6199326
[7] https://www.edfenergy.com/energy/power-station/daily-statuses

BEIS (2016a, Table 19) gives the fixed Operations and Maintenance (O&M) costs for a FOAK PWR as £72,900/MWyr, the variable O&M as £5/MWh, insurance costs as £10,000/MWyr and connection and use of system as £500/MWyr. Appendix A suggests that compared to the average baseload power station, SZB has annual Transmission Network Use of System TNUoS) costs in $£_{2015}$-4,000/MWyr (i.e. negative, the station is paid to generate in system peak hours), although from 1995 the cost has gradually decreased from $£_{2015}$+1,000/MWyr to $£_{2015}$-10,000/MWyr. The least favourable assumption would be to ignore this TNUoS benefit and set it to zero. Fuel and decommissioning costs are given as £6/MWh (BEIS, 2016a, Table 4). At SZB's capacity factor of 7,350 hrs/yr. the fixed costs would average to £11/MWh, so total operating costs (including fuel) would be $£_{2015}$22/MWh.

MIT (2018, table A5, p151, shown below in Appendix B) gives fixed O&M costs as $95,000 (£71,000)/MW, variable as $6.89 (£5.14)/MWh and fuel as $1.02(£0.76)/MWh. Averaging over 7,350 hours/yr. this gives £16/MWh. This is consistent with (and probably taken from), US EIA[8] data. The average total cost is $£_{2015}$16.4/MWh, but this probably does not include decommissioning costs that might add £1-2/MWh. It thus seems reasonable to take an average operating cost as $£_{2015}$22/MWh.

2.2 Financing Sizewell B

Construction was started before the CEGB was privatized in 1989, and SZB remained in public ownership as part of the new company, Nuclear Electric, until it was privatized as British Energy in 1996. The approach here is to assume that after commissioning in 1995 (just before its public sale) SZB is treated as a regulated asset like the similarly privatized transmission and distribution networks, and as has been proposed for a future Sizewell C under the Regulatory Asset Base (RAB) model (Newbery et al., 2019). This requires an initial valuation of the RAB in 1995, taken as the full construction cost including first of a kind costs, to be depreciated over 35 years. (If, as might also be reasonable, it is depreciated over its lifetime of 60 years, the costs would of course be lower, so this is a cautious assumption.)

If we assume that the Office of Electricity Regulation, Offer, later Ofgem, sets the price control every 5 years (coincidentally at the same time as the Distribution Price Controls) then we need to specify a suitable WACC. The return on the declining RAB at this WACC, with depreciation and allowed operating costs (Opex) determine the strike price for the Contract-for Difference (CfD). Consumers would then pay for the excess of the strike price over the market price: effectively they would be the counterparties to the CfD.

Transmission and Distribution companies have been regulated by Ofgem under this model since 1990, and so we can construct a time series of relevant data from past regulatory decisions. These are shown where available in the right-hand two columns of Table 2. Note these are normally the vanilla rate, which Ofgem defines as "is the weighted average of the expected cost of debt (pre-tax) and the expected cost of equity (post tax) and is used in our modelling to determine allowed revenues." The methodology for calculating the WACC and the treatment of tax has changed over the years, as has the assumed gearing, and in some cases the earlier price controls have been re-opened (mainly to address cost issues

[8] At https://www.eia.gov/electricity/annual/html/epa_08_04.html

unconnected with the WACC). The figures have been culled from a variety of sources,[9] some from consultation proposals that give a range, in which case the numbers have been averaged. The 1995 WACC and/or the RAB for the Distribution Companies were considered excessive and resulted in a merger wave and some resetting of the price control.

The main change over the past 30 years has been in the real risk-free rate, as figure 3 shows.

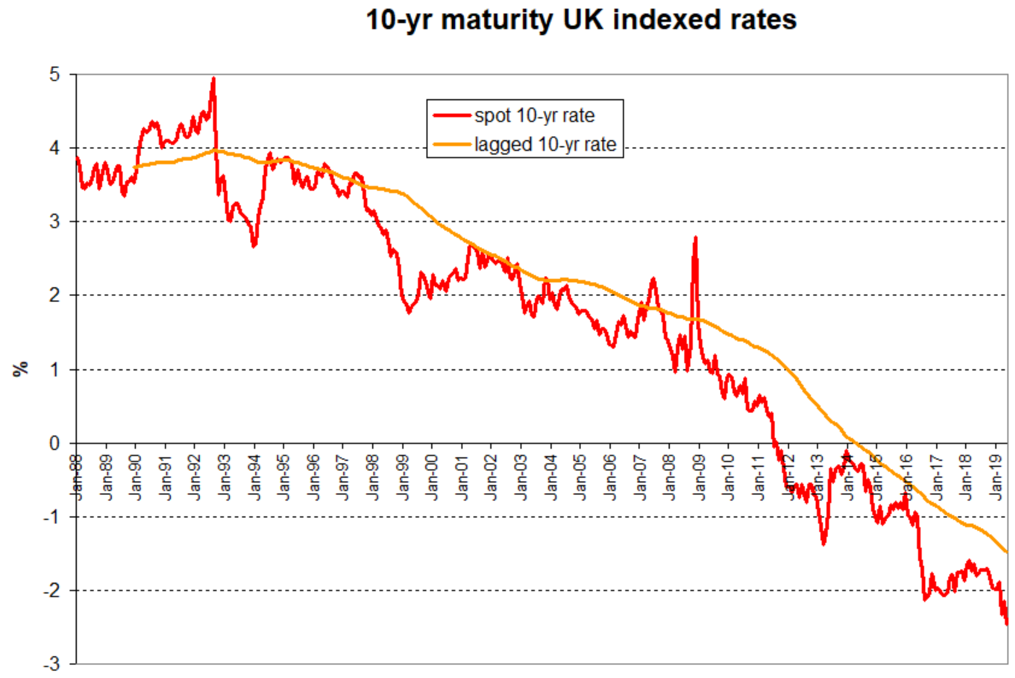

FIGURE 3

Risk-free real interest rate (5 and 10-yr maturity)

Source: Bank of England UK yield curve data

Note: The figure ends before the dramatic further declines caused by Covid-19

An alternative approach would be to assume a constant Equity Risk Premium (ERP) of 4-6%, a debt premium of 1% (rising if the risk-free rate becomes negative), and a gearing of 55% or 65%. If take as the risk-free rate the average of the previous 5 years of the 10-yr Bank of England indexed interest rate as in Figure 3, then Table 1 shows how to estimate the WACC at 5 year intervals from 1995. The choice of gearing is clearly a key determinant of the WACC and 65% may be considered high for a nuclear power station (Drax, a mixed coal and bio-mass station, has a gearing of 55%) but the nature of the RAB model is to de-risk returns allowing higher gearing. Note also that Ofgem have recently switched from RPI indexing to CPIH indexing, and the difference is about 1% (RPI higher). Our approach is to follow the Ofgem RPI methodology until 2020, and then switch to CPIH indexing.

[9] I am indebted to CEPA for their useful time series of regulatory decisions

TABLE 1

Estimated real WACCs for Sizewell B's RAB model (RPI based unless noted)

				ERP 4%		ERP 6%		Energy vanilla WACCs	
				gearing 65%		gearing 55%			
period starting	risk free rate	debt premium	debt cost	CoE	WACC	CoE	WACC	DCPR	Other***
Jan-95	3.84%	1.00%	4.84%	7.84%	5.89%	9.84%	7.09%	7.00%*	5.76%
Jan-00	3.05%	1.00%	4.05%	7.05%	5.10%	9.05%	6.30%	5.15%	5.05%
Jan-05	2.18%	1.00%	3.18%	6.18%	4.23%	8.18%	5.43%	5.50%	5.50%
Jan-10	1.47%	1.25%	2.72%	5.47%	3.69%	7.47%	4.86%	4.70%	5.00%
Jan-15	-0.23%	1.50%	1.27%	3.77%	2.14%	5.77%	3.29%	3.76%	3.44%
Jan-20	-1.47%	1.50%	0.03%	2.53%	0.90%	4.53%	2.05%	1.81%**	1.96%**

* Pre-tax; vanilla would be lower

** Working assumptions for RIIO-GD2 and T2 WACCs based on CPIH (Ofgem, May 2019)

*** Utilities such as water, transmission, gas, to the nearest starting date

3. CARBON SAVED

In the counterfactual in which SZB is not built, other forms of generation would be needed to replace its output, with its associated emissions. Figure 4 shows generation by fuel from well before privatization (and commissioning SZB).

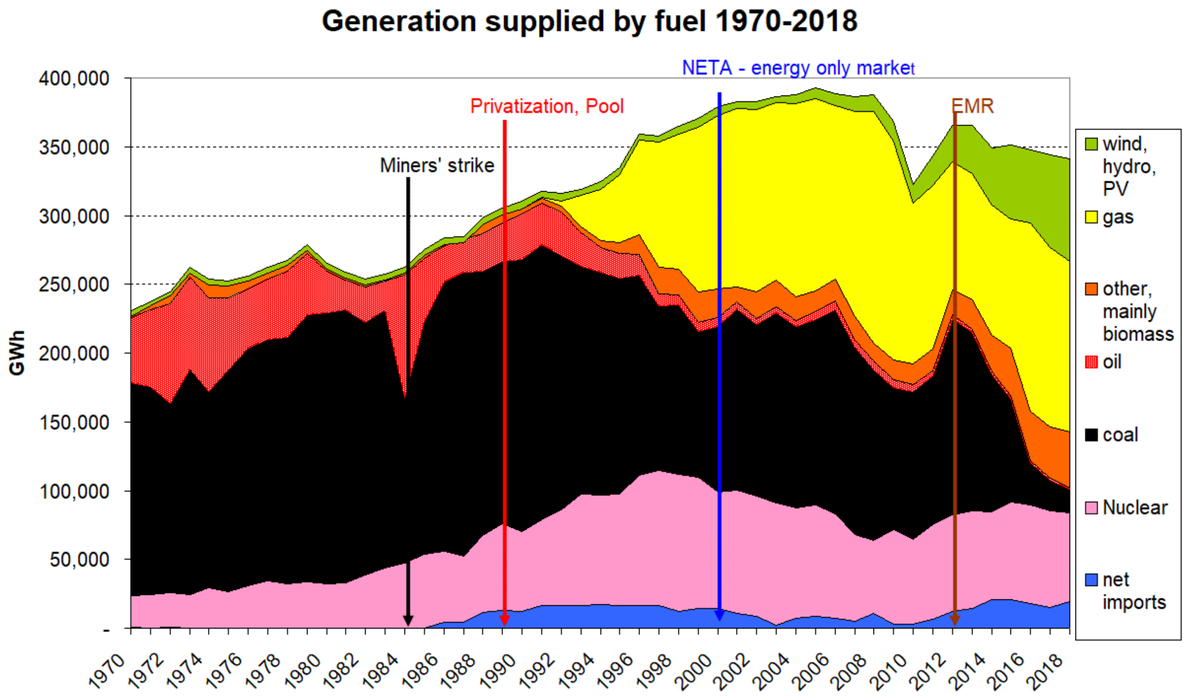

FIGURE 3

Generation by fuel, 1970-2018

Source: DUKES 5.1

Starting in 1995, gas-fired CCGTs started to enter, mostly on the back of favourable long-term contracts with the newly privatized Public Electricity Suppliers (PESs, the successors to the Area Boards). It seems likely that the CCGTs would have entered at least as quickly without SZB, in response to the need for new capacity and the very favourable contracts they were able to sign with the PESs, so the counterfactual would likely have had more coal generation, which was clearly declining in response to increased nuclear output, higher imports (enjoying a non-fossil fuel benefit) and CCGT output.

The relative variable costs (variable O&M plus fuel costs)[10] are shown in figure 5 with and without any GB carbon costs, together with the day-ahead wholesale price.

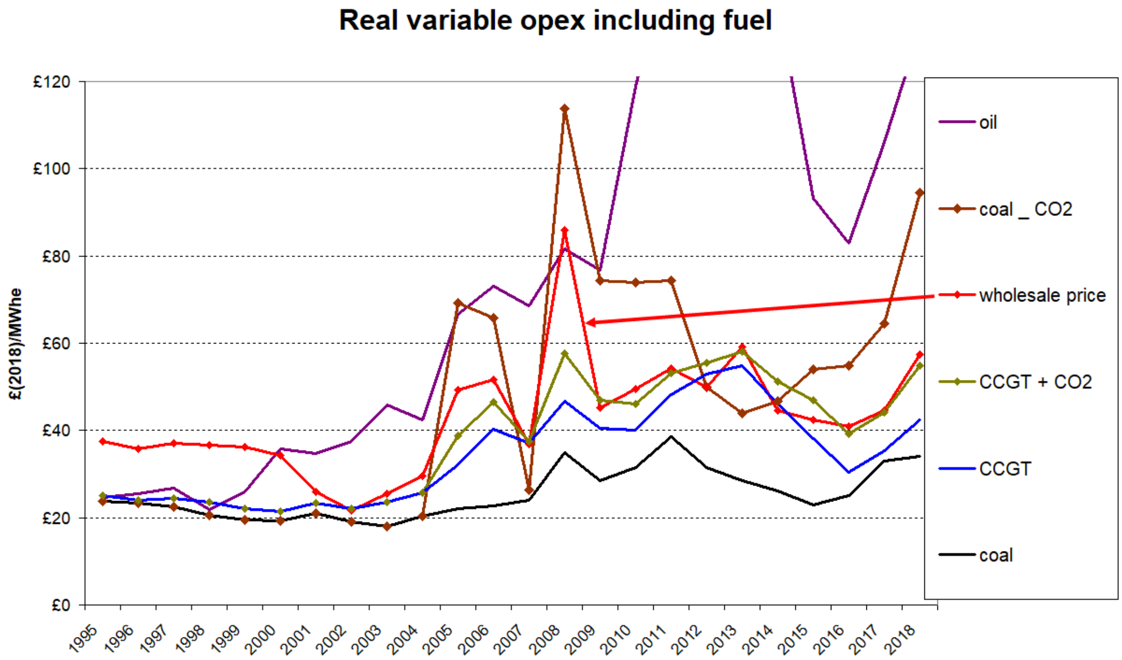

FIGURE 5

Avoidable costs of coal and CCGTs and wholesale price, 1995-2018

Source: Price data as fig.1, fuel costs: BEIS *Quarterly Energy Prices* Table 3.2.1

In the period before retail prices were liberalised (1998-2000) the avoidable gas cost was slightly above the avoidable coal cost, but the contract position with the PESs probably meant they were dispatched before coal. Oil prices were consistently above coal prices and so oil is primarily used for peaking plant, and would likely continue in that role until displaced by gas. Thus from 1995 to 2000 each MWh generated by SZB would displace the carbon content of 1 MWh of coal generation, which gradually rose from 0.82t CO_2/MWh to 0.87t CO_2/MWh.

Between 2000 and 2005, during which period competition was intensifying with plant divestment from the two major generators (National Power and PowerGen) and the move to an energy-only market (NETA), coal costs were below gas costs, favouring running coal on base load. The decline in coal burn seems to have ceased during this period although CCGT production increased.

Figure 6 shows the plant load factors (running hours as a percent of annual hours) for coal, CCGT and nuclear. CCGT load factors are falling from 1999 to 2006 while coal is rising, partly because of the retirement of inefficient coal plant and hence lower coal capacity.

[10] Costs are calculated from the price of fuels into major generators (DUKES, table 5.1) and the efficiencies of coal and CCGTs (from DUKES 5.10).

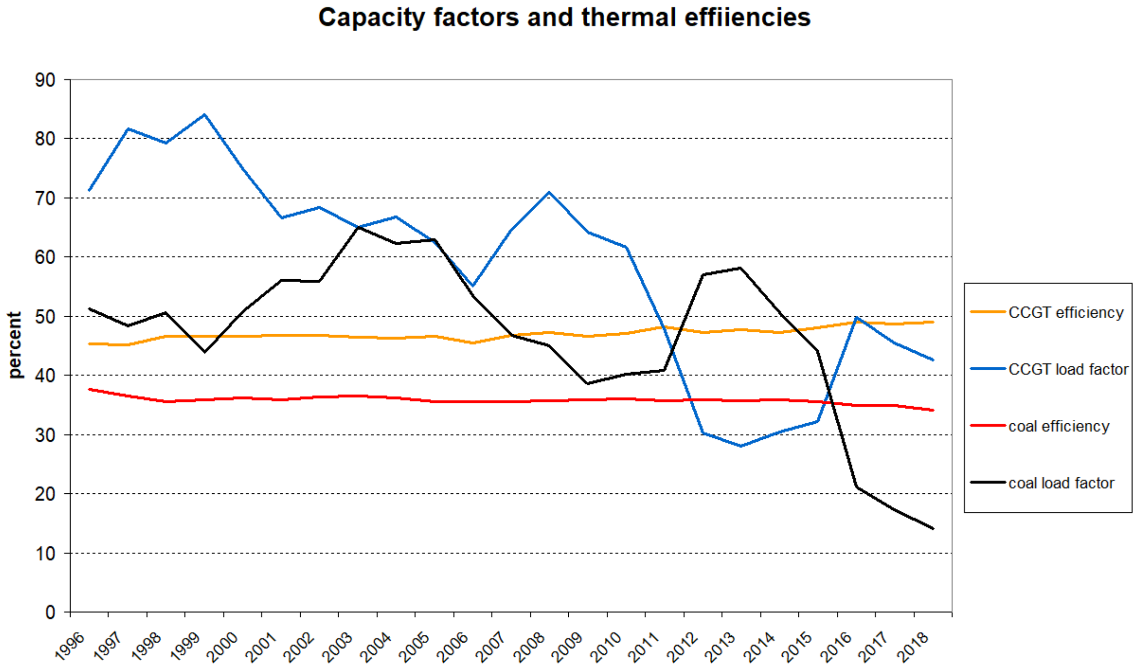

FIGURE 6
UK Plant load factors and thermal efficiencies, 1996-2018
Source: DUKES, Table 5.10

After 1999 CCGT had a less secure place with the PES's, with the end of the domestic franchise and with it their guaranteed market, and coal would likely run on baseload while CCGTs moved to mid-merit and peaking. Nevertheless, the pressure to retire coal plant might have been lower had SZB not been commissioned, so while some of the time SZB replaced gas, it may also have displaced some baseload coal. We assume that the generation displaced is 50:50 coal and gas.

From 2006 with the introduction of first the EU Emissions Trading System (for CO_2) ETS and later the GB Carbon Price Support (an additional carbon tax on generation fuels), the carbon-inclusive cost of coal was almost always above that of gas, making coal the marginal fuel unless constrained by its capacity (often the case for hours of higher demand). If these occur half the time, then again the generation displaced is 50:50 coal and gas. Thus from 2006 to 2019 the displacement is roughly 0.63 tonnes CO_2/MWh (the falling efficiency of coal generation is almost exactly offset by the rising efficiency of gas). (Chyong et al. 2019, sets out a more sophisticated method used for measuring the displacement factor of wind but that would require calibrating a counterfactual plant mix back to 1996.)

4. MODELLING THE COST OF CARBON SAVED

We assume the starting value of the Regulatory Asset Base (RAB) in 1995 is the final construction cost at 1995 prices. Section 3 gave that as £$_{1995}$2,550/kW. In the event, SZB did not produce a positive daily supply to the grid until 1 June 1995 and this will be taken as the start date for revenue recovery. For the previous six months the cost of electricity taken was £2.1 million (or £2/kW), which is small enough to ignore, so we take the opening RAB as £2,550 for the rest of the first year, as shown in Table 2.

TABLE 2

Building blocks for the capex to be recovered each year in prices of that year

year	start RAB	£/kW Deprec	end of year RAB	WACC Low	High	capex £/MWh Low	High	opex £/MWh	strike price £/MWh Low	high
1995	£2,550	£75.7	£2,474	5.89%	7.09%	£30.7	£34.9	£12.7	£43.5	£47.6
1996	£2,527	£77.9	£2,521	5.89%	7.09%	£30.9	£35.0	£13.1	£44.0	£48.1
1997	£2,521	£80.8	£2,532	5.89%	7.09%	£31.2	£35.3	£13.6	£44.8	£48.9
1998	£2,532	£81.9	£2,483	5.89%	7.09%	£31.4	£35.6	£13.8	£45.2	£49.4
1999	£2,483	£84.7	£2,478	5.89%	7.09%	£31.4	£35.5	£14.3	£45.7	£49.7
2000	£2,478	£86.3	£2,438	5.10%	6.30%	£28.9	£33.0	£14.5	£43.5	£47.5
2001	£2,438	£87.2	£2,375	5.10%	6.30%	£28.8	£32.8	£14.7	£43.5	£47.4
2002	£2,375	£89.7	£2,351	5.10%	6.30%	£28.7	£32.6	£15.1	£43.8	£47.7
2003	£2,351	£92.4	£2,327	5.10%	6.30%	£28.9	£32.7	£15.6	£44.5	£48.3
2004	£2,327	£95.1	£2,297	5.10%	6.30%	£29.1	£32.9	£16.0	£45.1	£48.9
2005	£2,297	£98.2	£2,271	4.23%	5.43%	£26.6	£30.3	£16.5	£43.1	£46.9
2006	£2,271	£102.6	£2,264	4.23%	5.43%	£27.0	£30.7	£17.3	£44.3	£48.0
2007	£2,264	£107.3	£2,256	4.23%	5.43%	£27.6	£31.3	£18.1	£45.7	£49.4
2008	£2,256	£105.6	£2,116	4.23%	5.43%	£27.3	£31.0	£17.8	£45.1	£48.8
2009	£2,116	£110.9	£2,106	4.23%	5.43%	£27.3	£30.7	£18.7	£45.9	£49.4
2010	£2,106	£116.4	£2,088	3.69%	4.86%	£26.4	£29.8	£19.6	£46.0	£49.4
2011	£2,088	£120.1	£2,031	3.69%	4.86%	£26.8	£30.1	£20.2	£47.0	£50.4
2012	£2,031	£123.7	£1,965	3.69%	4.86%	£27.0	£30.3	£20.8	£47.9	£51.1
2013	£1,965	£126.7	£1,882	3.69%	4.86%	£27.1	£30.2	£21.3	£48.4	£51.6
2014	£1,882	£127.9	£1,771	3.69%	4.86%	£26.9	£29.8	£21.8	£48.6	£51.6
2015	£1,771	£130.2	£1,670	2.14%	3.29%	£22.9	£25.6	£22.0	£44.9	£47.6
2016	£1,670	£131.1	£1,550	2.14%	3.29%	£22.7	£25.3	£22.2	£44.9	£47.5
2017	£1,550	£134.6	£1,453	2.14%	3.29%	£22.8	£25.3	£22.7	£45.6	£48.0
2018	£1,453	£137.9	£1,347	2.14%	3.29%	£20.7	£23.0	£23.3	£44.0	£46.3
2019	£1,347	£139.8	£1,225	2.14%	3.29%	£20.1	£22.2	£23.6	£43.7	£45.8
2020	£1,225			0.90%	2.05%					

Note: values are uprated each year by the appropriate price index inflator (RPI until 2016, thereafter CPIH)

One further modification is needed to take account of the capacity auctions held from 2014. The capacity payments compensated plant for availability in stress periods, and SZB received payments for electricity years 2018/19 and 2019/20, effectively reducing the cost to be recovered from the RAB. The wholesale price fell, increasing the costs of the CfD, and so it is logical to reduce the RAB by the annual capacity payments. The first auction cleared at $£_{2012}$19.4/kWyr =$£_{2018}$22.5/kWyr. The second auction cleared at $£_{2014}$18/kWyr = $£_{2019}$20.3/kWyr. These are deducted from the annual value of capex in Table 2.

Each year the RAB is decreased by depreciation of 1/35 of the initial RAB, or $£_{1995}$75/kW, and the costs to be recovered from the sales contract is $WACC_t$ x RAB_t uprated each year by the RPI (until 2016, after which the uprating is by the CPIH). Table 2 below shows the capex building blocks set at the quinquennial price controls, which are rolled forward each year with the relevant price inflator. A low and high value for the WACC is taken from Table 1 (the two columns headed “WACC”). The next step is to determine the de-rating factor for SZB, which has a capacity factor of 84%. This is equivalent to full 7,358 hrs, taken as 7,350, over which the capex needs to be recovered. If *K* is the capex in £/kWyr, then the allowable capex is *K*/7.35 /MWh, shown in the right hand columns in Table 2. The de-rating implies that SZB, which has a nominal rated capacity of 1,198 MW is 1,006 MW, but taken here as 1,000 MW (83.5% capacity factor). The strike price is then set as the capex (a low and a high value for the low and high WACCs) plus the opex calculated above as $£_{2015}$22/MWh and shown in the right hand columns of Table 2.

TABLE 3

Annual real values of deficit and displaced CO_2

year	Output/yr GWh/yr	mart price £/MWh	displaced CO_2/MWh tonnes/MWh	displaced CO_2 Mt/yr	deficit/yr including CO_2 value £(2019) million Low	High
1995	5,307	£23.2	0.82	4.16	£146	£179
1996	8,434	£23.2	0.82	6.94	£269	£323
1997	8,432	£24.5	0.82	6.94	£271	£324
1998	10,166	£24.7	0.82	8.36	£317	£381
1999	8,211	£24.6	0.82	6.75	£245	£294
2000	7,129	£23.5	0.82	5.86	£213	£256
2001	9,220	£19.6	0.63	5.81	£343	£397
2002	9,193	£15.2	0.62	5.72	£381	£433
2003	8,884	£18.2	0.62	5.53	£338	£387
2004	9,329	£21.4	0.63	5.82	£306	£356
2005	8,691	£36.4	0.63	5.50	£160	£205
2006	8,908	£39.0	0.64	5.67	£143	£188
2007	10,262	£28.4	0.63	6.49	£239	£289
2008	9,273	£68.8	0.63	5.83	-£118	-£75
2009	9,095	£37.0	0.63	5.71	£193	£232
2010	4,724	£41.7	0.62	2.95	£55	£74
2011	8,656	£47.8	0.62	5.40	£64	£97
2012	9,375	£45.2	0.63	5.88	£69	£103
2013	8,715	£54.9	0.63	5.45	-£29	£1
2014	8,828	£42.1	0.63	5.53	£141	£170
2015	10,507	£40.0	0.63	6.58	£208	£240
2016	8,627	£38.9	0.63	5.44	£176	£200
2017	8,834	£51.7	0.63	5.59	£177	£199
2018	9,383	£57.4	0.64	6.02	£73	£95
2019	5,828	£43.9	0.64	3.73	£138	£150
Total £2019	214,009			144	£4,517	£5,499
per tonne CO_2	undiscounted				£31.4	£38.3
	at WACC				£34.1	£49.2
	at 3%				£33.3	£40.4

Source: From Table 2

The consumer payment is the excess (possibly negative) of the strike price over the wholesale price, for each of SZB's actual operating hours. Annual CO_2 emissions can similarly be calculated for each of SZB's actual operating hours. These revenue shortfall estimates are based on the actual wholesale price that has been inflated by the carbon price, so the price already includes some carbon benefit. The simplest way to recognise this is to multiply the CO_2 displaced by the total carbon price and add this back to the shortfall in revenue. The costs to consumers per tonne saved can now be calculated in £(2019) and are shown in Table 3.

The undiscounted cost is $£_{2019}$31.4/tonne CO_2 at the low strike price and $£_{2019}$38.3/t. CO_2 at the high strike price. Accumulating the costs and CO_2 savings forward at the relevant WACCs (as with the method of levelizing costs) gives $£_{2019}$34.1/t. CO_2 at the low strike price and $£_{2019}$49.2/t. CO_2 at the high WACC. Levelizing at a constant discount rate of 3% gives slightly lower values as more recent costs have been falling as the RAB is depreciated and the WACC falls. The 2019 carbon charges on GB electricity are about £40/t. CO_2, made up of the EUA price and the Carbon Price Support (of £18/t CO_2). If we were to roll forward the contract to 2030 after which SZB could sell on the wholesale market the required future subsidy would likely be negative (relative to the actual wholesale price), further reducing the lifetime cost of abating CO_2 from the original investment, and demonstrating that, compared to presumably what is now thought to be a not excessive carbon tax, SZB was cost-effective.

5. A COUNTERFACTUAL FOLLOW-ON NUCLEAR FLEET

Britain abandoned its nuclear aspirations with privatization, but it is interesting to speculate what might have happened if that ambition had been at least partially realised. Since then EdF has started constructing the 3.2 GW Hinkley Point C (HPC) station and is pressing for approval for another identical station at Sizewell C (SZC). The latest cost estimate for HPC has risen from its earlier investment decision budget of about £20 billion or $£_{2016}$6,250 (FOAK) to perhaps $£_{2019}$22 bn, or $£_{2016}$6,535/kW, as a result of "challenging ground conditions".[11] SZC was originally estimated to be 20% cheaper than the original budget, or $£_{2016}$5,000/kW for a second of a kind. BEIS (2016a) and NIC (2020b) estimate future nuclear capital costs at $£_{2016}$4,182/kW.[12]

If instead we had built follow-on copies of the original SZB, at a discount of 25% (based on PIU and Collier's follow-on costs) of the FOAK of $£_{1995}$2,550/kW (i.e. $£_{1995}$1,912), the cost in comparable terms would be $£_{2016}$2,900/kW (uprating by the CPI) or $£_{2016}$4,370 (uprating by the less reliable Construction Price Index). Taking the lower figure, a follow-on series of 6.4 GW of SZB design might have cost $£_{2016}$18.6 bn compared to the predicted cost of HPC and SZC of around $£_{2016}$37 bn, a saving of about £18 bn. At the higher rolled forward cost of SZB the follow-on cost would be about $£_{2016}$28 bn and the cost saving still £9 bn.

An alternative way of evaluating SZB is to compare its levelized follow-on cost of $£_{2016}$2,900/kW over an assumed 60-year life at a WACC of 3% real (reflecting more recent interest rates) of £36.7/MWh with the cost of an efficient CCGT over its 25-year life at the same 3% WACC and a carbon price of £40/tonne. Depending on the estimated range of 2020 capital costs from BEIS (2016b) and future gas prices ranging from a low of £15/MWh_{th} to £35/MWh_{th} the levelized costs would range from £50-70/MWh.

[11] https://www.bloomberg.com/news/articles/2019-09-25/edf-raises-cost-of-flagship-u-k-nuclear-project-warns-of-delay

[12] Figures are in £2016 to allow comparison with those in BEIS (2016) and NIC (2020b).

6. A SHORT-CUT ESTIMATE

Rather than laboriously working through the daily outputs, prices and emissions abated, it is useful to ask if there is a short-cut way of calculating the cost per tonne CO_2 saved. Given the capital cost, *k*, of per kW in £$_{2019}$ (uprating first by the RPI to 2016 and then by the CPIH to 2019, as with the Ofgem inflator) it is simple to compute the annual capex at a WACC of *r*, as $rk/(1-(1+r)^{-35}) = \theta k$ in £/kWyr. This can be expressed in £/MWh if the capacity factor is *f* by setting $h = 8.76f$ to give capex as $\theta k/h$. If the total cost (fuel + fixed and variable O&M) is *v*/MWh, the CO_2 displaced in t/MWh is *e*, and the average wholesale price is *p* (all in £2019) then the average cost per tonne CO_2 saved is $(v + \theta(r)k/h - p)/e$. For SZB, $v =$ £$_{2019}$23.72, $k =$ £$_{2019}$5,170/kW, $p =$ £$_{2019}$43.47 (historic average), and $h = 7.35$.

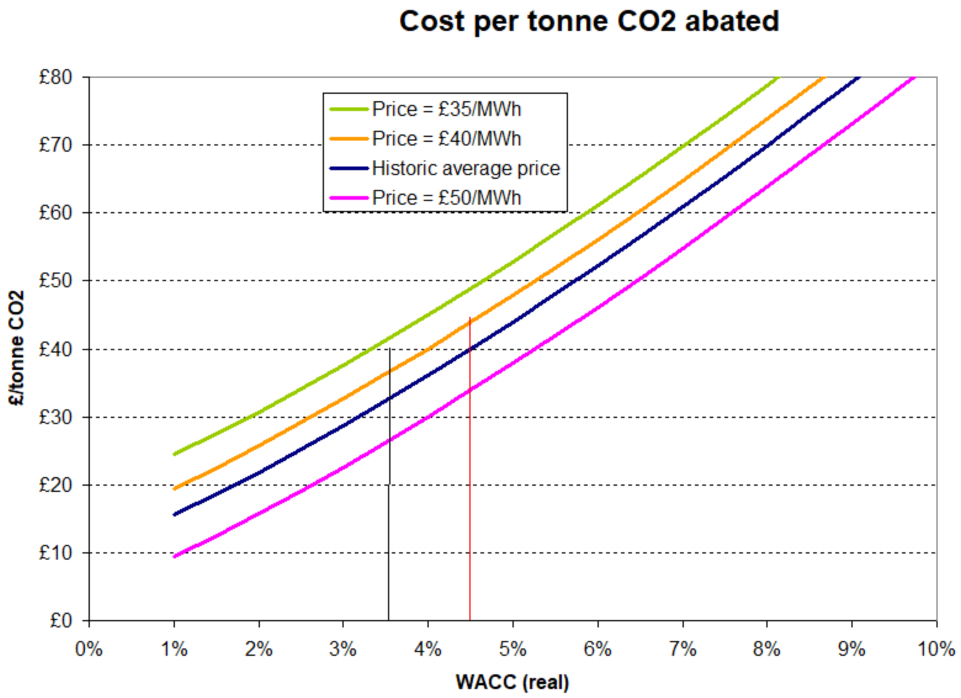

FIGURE 7

Relationship between cost of CO_2 abated and WACC allowed

Figure 7 shows the results for the historic average wholesale price (in £2019), and for various constant real wholesale prices, together with the two average values of the WACCs (vertical lines) used in the calculations. The results at the Low Ofgem WACC is £37.7/tonne and at the Ofgem High WACC is £47.2/t, close to the correctly computed values.

7. CONCLUSIONS

Britain originally planned a nuclear power programme, partly in response to Prime Minister Margaret Thatcher's concern over the environment and global warming (HMSO, 1990). This became very clear when on November 8, 1989[13] she told the UN: "What we are now doing to the world, by degrading the land surfaces, by polluting the waters and by adding greenhouse gases to the air at an unprecedented rate - all this is new in the experience of the earth. It is

[13] Reported on the BBC at https://www.bbc.co.uk/news/science-environment-22069768

mankind and his activities that are changing the environment of our planet in damaging and dangerous ways." Perhaps her more pressing reason was to reduce the UK's dependence on coal-fired generation and in turn its dependence on the coal miners' union. That same year the Thatcher Government announced a programme of ten new PWR reactors (Taylor, 2016, p22), of which Sizewell B is to date the only one commissioned, a programme certainly brought to an end with the privatization of the CEGB and the realisation that the nuclear power plants were at that time unsaleable to the private sector (at least without the kind of long-term contract examined here).

This paper has asked whether Sizewell B (SZB) was a cost-effective way of abating CO_2, and specifically, what it cost per tonne of CO_2 abated by displacing fossil generation. The assumption on which this calculation is based is that without an adequate carbon price, new nuclear power was not commercially viable. Just as other zero-carbon renewables required contractual support, SZB would have required a long-term contract at above market prices. The simplest such contract would be a long-term Contract-for-Difference (CfD) with the terms periodically revisited in quinquennial price controls under the Regulatory Asset Base model of the privatised utilities. With some further assumptions about the carbon saved per MWh of SZB generation it is then possible to estimate the amount of implicit subsidy required to abate this displaced CO_2. The answer depends on the Weighted Average Cost of Capital (WACC) used by the regulator (now Ofgem) in setting the strike price in the CfDs. At each date there are a range of observed WACCs set for different utilities, depending on their gearing and risk.

At a low value of the WACC the cost is $£_{2019}$34.1/tonne CO_2 abated and $£_{2019}$49.2/t. CO_2 at the high WACC, compared to the roughly £40/t. CO_2 paid by GB generators in 2019, which is presumably now thought to be a not excessive carbon price. While it is difficult to estimate the cost of carbon saved by renewables, as a large part of the required subsidy was to pay for learning spill-overs (Newbery, 2018), it seems likely that nuclear power was a cheaper form of carbon abatement, at least until very recently (when some renewables proposals claim to be subsidy-free). It is certainly cheaper than the levelized cost of the cheapest unabated fossil alternative, CCGTs paying the £40/t. CO_2 cost.

The other striking observation is that the full cost of SZB (including FOAK costs) at $£_{2019}$4,290/kW is less than the £5,000/kW estimated for the proposed second EPR planned for Sizewell C (itself 20% less than the FOAK budget for Hinkley Point C). As SZC has not yet been built, the £5,000/kW remains an estimate, and indeed one that the National Infrastructure Commission (2019) considered with some scepticism. If (and it is a big if, given the difficulty of retaining the construction and engineering expertise until needed) instead Britain had built both Hinkley Point C and Sizewell C at the cost of a N^{th}-of-a-kind PWR, the saving would have been $£_{2016}$9-18 billion.

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Appendix A TNUOS Generation tariffs

Table A1 shows the annual grid transmission charges for the zone in which Sizewell B (SZB) is located, and the average for all zones. Arguably it is the relative connection cost that is required to compare generation costs at SZB with other stations, and this is normally negative, meaning that SZB is better placed for delivering power than more distant generation, notably in Scotland, but generally north of North Wales and Yorkshire. Over time the zonal boundaries and the methodology have changed several times.

Table A1 £/kWyr £$_{2015}$/kWyr

Year starting 1 April	SZB	Average	SZB-Av	CPI	SZB real	SZB-Av
1994	£1.056	£1.133	-£0.077	65.4	£1.62	-£0.12
1995	£1.352	£0.672	£0.680	67.2	£2.01	£1.01
1996	£1.637	£0.837	£0.800	68.8	£2.38	£1.16
2005	£1.323	£7.106	-£5.783	78.1	£1.69	-£7.40
2006	£1.219	£6.614	-£5.395	79.9	£1.53	-£6.75
2007	£1.974	£6.526	-£4.552	81.8	£2.41	-£5.57
2008	£2.317	£7.712	-£5.395	84.7	£2.74	-£6.37
2009	£2.111	£7.444	-£5.334	86.6	£2.44	-£6.16
2010	£1.936	£0.758	£1.178	89.4	£2.17	£1.32
2011	£1.564	£7.638	-£6.074	93.4	£1.67	-£6.50
2012	£2.393	£7.543	-£5.150	96.1	£2.49	-£5.36
2013	£2.443	£10.078	-£7.635	98.5	£2.48	-£7.75
2014	£3.548	£11.463	-£7.915	100.0	£3.55	-£7.92
2015	£2.089	£10.116	-£8.027	100.0	£2.09	-£8.03
2016	£2.346	£5.734	-£3.388	100.7	£2.33	-£3.36
2017	-£0.150	£8.573	-£8.723	103.6	-£0.14	-£8.42
2018	-£2.561	£6.107	-£8.668	105.9	-£2.42	-£8.19
2019	-£2.600	£8.981	-£11.581	107.8	-£2.41	-£10.74
2020	-£3.200	£8.544	-£11.744	110.0	-£2.91	-£10.68
2021	-£4.320	£8.318	-£12.638	112.2	-£3.85	-£11.27
2022	-£6.930	£7.224	-£14.154	114.4	-£6.06	-£12.37
2023	-£8.850	£5.657	-£14.507	116.7	-£7.58	-£12.43
average 1994-2019	£1.336	£5.174	-£3.838		£1.69	-£4.07

Source: National Grid, then NGESO

Appendix B

Table B1 US data on nuclear generation costs from existing utilities

Year	$/£	CPI UK inflator	O&M £$_{2018}$/MWh	fuel	total
2007	2.00	1.27	£9.73	£3.17	£12.90
2008	1.85	1.23	£10.67	£3.51	£14.18
2009	1.57	1.20	£12.57	£4.11	£16.68
2010	1.55	1.18	£13.15	£5.08	£18.23
2011	1.60	1.13	£12.49	£4.95	£17.43
2012	1.59	1.10	£13.79	£5.30	£19.08
2013	1.56	1.08	£13.20	£5.61	£18.81
2014	1.65	1.06	£12.31	£4.98	£17.29
2015	1.53	1.06	£12.63	£5.18	£17.81
2016	1.35	1.05	£13.96	£5.81	£19.76
2017	1.29	1.02	£13.44	£5.94	£19.38
		average	£12.54	£4.88	£17.41

US EIA data at https://www.eia.gov/electricity/annual/html/epa_08_04.html