The cost of finance and the cost of carbon: a case study of Britain's only PWR

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Keywords Regulatory Asset Base, carbon cost, nuclear power

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ABSTRACT

This paper argues that the cost of decarbonising depends critically on the Weighted Average Cost of Capital (WACC), illustrated with a case study of Sizewell B (SZB, the nuclear station commissioned in 1995). It calculates the cost per tonne of CO_2 abated with prices set as for transmission assets by the regulator under the Regulatory Asset Base model. The cost depends critically on the WACC set in comparable utility price controls. At a low WACC the cost is £$_{2019}$36.2/tonne CO_2 abated and £$_{2019}$43.3/t. CO_2 at the high WACC, compared with the roughly £40/t. CO_2 paid by GB generators in 2019. Moving from the social discount rate of 2.5% to a hurdle rate of 8% increases the cost from £15-20/t. to over £60/t. Had Britain continued building replicas of SZB the cost saving compared to the current programme might be £$_{2019}$9-19 billion.

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1. INTRODUCTION

The paper argues for the critical importance of the cost of finance for decarbonising the economy, and demonstrates this by calculating the cost of CO_2 abatement from Britain's only operational PWR nuclear station, Sizewell B. It computes this cost using a Regulatory Asset Base (RAB) model, whose efficacy in reducing the weighted average cost of capital (WACC) has been demonstrated in the financing of long-lived regulated utility assets like transmission and distribution networks. The resulting cost of decarbonisation is then compared with commercial financing (assuming, as is doubtful, that would be possible for nuclear power) and with keeping the station in public ownership at the social discount rate.

The advantage of studying Sizewell B is that we know its build and operating costs. A second objective is to show that its cost of abating CO_2 compares favourably with the social cost of carbon and the alternative ways of decarbonising electricity available. This incidentally sheds some light on the logic of the Central Electricity Generating Board's proposed nuclear power programme, derailed by privatization, and the consequential lost economies of replication – issues that are germane to the UK's current plans for future nuclear power stations.

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 looks at a particularly

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[3] I am indebted to very helpful comments from two referees and David Reiner, and to helpful advice from Alastair Davies, but take full responsibility for the interpretations advanced here.

expensive example and argue against that view, based on a tried and tested method of lowering the WACC used to set prices for regulated utilities. The evidence also allows us to speculate on a counterfactual in which decarbonisation had been taken more seriously in the early 1990s, when Britain's embryonic nuclear programme was abandoned under free market pressures.

2. THE COST OF FINANCE FOR DECARBONISATION

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 directly to green hydrogen by electrolysis, 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 and/or electrolysers 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 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 liberalised electricity markets. 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 and many are very long-lived, 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 matters both in exaggerating the true cost of meeting our climate targets, but also when choosing the best portfolio of techniques to deliver these targets. This paper will argue that the tendency to assume high hurdle rates is both damaging (in exaggerating the costs of decarbonisation), potentially dangerous (in the choice of techniques) and unnecessary, in that there are better methods of financing such investments that dramatically reduce the WACC.

3. THE WACC FOR SIZEWELL B

The central role of the WACC for the cost of nuclear power (and the cost of decarbonising) will be illustrated by considering three cases. The first is the social discount rate following the lead of the UK Government's *Appraisal Manual* (HMT, 2018), arguably appropriate if nuclear power is retained in the public sector. The other extreme is to follow the logic of the liberalized electricity market (as the Government did with Hinkley Point C, currently under construction - see NAO, 2017b) and assume a commercial hurdle rate. Finally, and the central case considered here, is to assume that SZB is treated as a regulated utility on a par with transmission and distribution companies. The three cases are set out below.

3.1. The Social Discount rate

The *Stern Report* (Stern, 2007) argues for a low social discount rate of 1.4% (real) for climate policy. 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 evaluate investments that reduce damaging CO_2 emissions. 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*. 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% and 2.57% for those lasting from 31-75 years (HMT, 2018, p104). That suggests a discount rate or WACC of 2.5% should not be too high and will be used as the WACC under public ownership.

3.2. The commercial hurdle rate

The hurdle rate is used by relevant Government Department (BEIS and previously DECC) to calculate the levelized cost of electricity from different technologies. BEIS (2020, p14) defines this "as the minimum financial return that a project developer would require over a project's lifetime on a pre-tax real basis." The hurdle rate for nuclear was left unchanged from BEIS (2016) at 8.2%, although other technology hurdle rates were reduced in line with falling rates of return elsewhere. NERA was commissioned by DECC to update its hurdle rates and for nuclear power gave a range of 9.5%-13.6% (NERA 2015, p vi), compared with DECC's earlier figure of 9.5% (all real). A WACC of 8% is probably the lowest relevant commercial WACC over the period we study.

3.3. The Regulatory Asset Model for the WACC

The argument of this paper is that lowering cost of finance is critical for decarbonisation, and that means reducing the risk. No nuclear power station has ever been constructed without some (and usually extensive) risk mitigation, either by public ownership or under regulatory guarantees (Newbery et al., 2019). The spirit of electricity liberalisation is consistent with regulating the return on investments that either have natural monopoly elements, or, more recently, deliver climate change objectives (now through auctioned long-term indexed contracts). The Thames Tideway Tunnel is a recent example where a company was set up to finance and construct a massive environmental project, subject to an agreed real rate of return set by the water regulator of 2.497% (NAO, 2017a, §3.8). It is a natural extension to update such contracts in a periodic regulatory review where the projects are both very long lived and face peculiar risks, like nuclear power.

Construction of SZB was started before the CEGB was privatized in 1989, and SZB remained in public ownership as part of the new company, Nuclear Electric, privatized as British Energy in 1996. The approach here is to assume that after commissioning in 1995, SZB is treated as a regulated asset like the similarly privatized transmission and distribution networks. In such cases the electricity regulator, Ofgem, determines the initial capital value, the Regulatory Asset Base (RAB). This is taken as the full construction cost including first of a kind costs, to be depreciated over 35 years. (If depreciated over its lifetime of 60 years, the annual costs would be lower, so this is a cautious assumption.) At the end of each year, the RAB is written down by depreciation, incremented by allowed investment in that year, and then uprated by the price index to give the RAB at the start of the next year.

The regulator resets the price control every 5 years. The return on the declining RAB at the regulated WACC, plus depreciation and the allowed operating costs (Opex) determine the strike price for the Contract-for Difference (CfD). CfDs specify a volume and strike price, with market prices below the strike price leading to payments from consumers to SZB, and prices above resulting in repayments to consumers. They are the mechanism for supporting renewables specified in the *Energy Act 2013* (House of Commons, 2013). Consumers are the counterparties to the CfD, underwritten by the Low Carbon Contracts Company Ltd.

Transmission and Distribution companies have been regulated by Ofgem under this model since 1990, so we can construct a time series of relevant WACCs from past regulatory decisions. These are shown in the right-hand two columns of Table 1, and are defined by Ofgem as "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 figures have been culled from a variety of sources.[4] 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 1 shows.

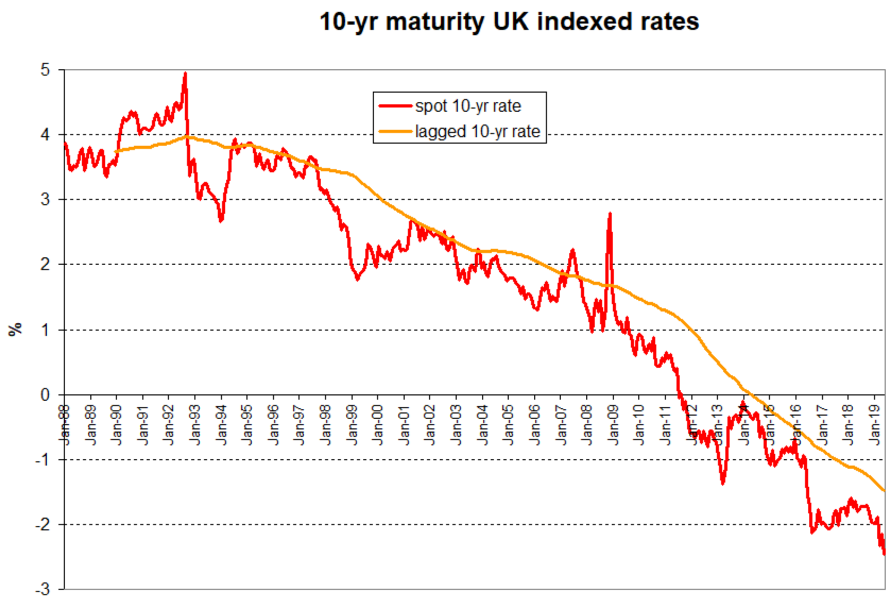

FIGURE 1

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

Source: Bank of England UK yield curve data

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

The WACC requires an estimate of the Equity Risk Premium (ERP, taken as 5-6%), the beta (correlation of the profits of the company with the market), the debt premium (1%, rising if the risk-free rate becomes negative), and the appropriate gearing (50% or 60%). The relevant risk-free rate is taken as the 10-yr Bank of England indexed interest rate as in Figure 1, averaged over the previous two years. The allowable debt, however, has to allow for the fact that the company will have issued past debt and will roll that over with a lag, so the relevant cost of debt is the 10-year past average of the risk-free rate, plus the debt premium, which is shown increasing as the real risk-free rate goes negative. The cost of equity (COE) is the ERP times the beta plus the risk-free rate. If we take beta as 1 (high) the COE is as shown in Table 1.

TABLE 1[5]

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

				ERP gearing	5% 60%	6% 50%	Regulated WACCs	
period starting	spot risk free rate	trailing risk free rate	debt premium	debt cost	low WACC	high WACC	DCPR	Other***
Jan-95	3.60%	3.79%	1.00%	4.79%	6.31%	7.20%	7.00%*	5.76%
Jan-00	3.32%	3.44%	1.00%	4.44%	6.00%	6.88%	5.15%	5.05%
Jan-05	2.36%	2.62%	1.00%	3.62%	5.12%	5.99%	5.50%	5.50%
Jan-10	1.94%	1.83%	1.25%	3.08%	4.63%	5.51%	4.70%	5.00%
Jan-15	1.24%	0.63%	1.50%	2.13%	3.78%	4.69%	3.76%	3.44%
Jan-20	-1.85%	-0.74%	1.50%	0.76%	1.72%	2.46%	2.47%**	2.92%**

* Pre-tax; normal WACC would be lower

** RIIO-2 Draft Determinations – Finance Annex (Ofgem, Sep 2020); *PR19 final determination*, Ofwat Dec 2019, both at CPI. At RPI the WACCs would be 1% higher. DCPR is Distribution Price Control Review

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

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 60% 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 CPI indexing (see data appendix), and the difference is about 1% (RPI higher). Our approach is to follow the Ofgem RPI methodology until 2016 and then switch to CPI indexing. As a sense check the final two columns give the WACC in contemporaneous regulatory price controls, recognising that these become more reliable as evidence accumulates and is tested. The low WACC seems to track the regulatory decisions from 2000 closely, the high WACC is above these except for the most recent settlement (which is in a period of unusually low real interest rates). With this financial machinery we can now turn to the case study of Sizewell B.

[5] The spreadsheets showing all calculations are posted with the working paper EPRG 2013 at https://www.eprg.group.cam.ac.uk/eprg-working-paper-2013/

4. 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 (SZB) model. In the opening words of the PIU[6] (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. 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."

SZB 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.

5. CALCULATING THE COST OF CO_2 SAVED

The cost of CO_2 saved is the excess of the contract revenue over sales revenue at market prices compared with the reduction in CO_2 emissions enabled. For that calculation we need to know the cost of the plant and the WACC to determine the contract price, the revenue from sales to the market *less* the cost of operation, and the CO_2 displaced compared to the counterfactual in which SZB had not been built. As we are looking back, costs and revenues are facts (even if some are confidential or somewhat problematic), displaced CO_2 can be estimated with some confidence, but the WACC is the most controversial and potentially the most important remaining variable.

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

[6] The Performance and Innovation Unit (PIU) was set up by the Government in 1998 "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)

kind costs (FOAK). Next, should the cost be uprated by the Retail Price Index (RPI) or the lower Consumer Price Index (CPI)? As we consider RAB financing, Ofgem's WACC used to be based on the RPI, but has been changed for the latest price controls to CPI, as discussed in the data appendix. Fortunately, the start date of the calculation is closer to the time of the cost estimates, reducing the potential index number discrepancies.

5.1 Capital costs, output and revenue

The cost, which should be an objective fact, on 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." Deflating this to its value in 1995, when it was commissioned, the cost would be approximately $£_{1995}$2,620/kW. This should include interest during construction and might include the cost of first fuelling, which should be excluded as it is treated here as a variable cost incurred when consumed.

Collier, who oversaw the construction of 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: "development of the design cost was of the order of £700 M" (Collier, 2015, p757). SZB delivers 1,198 MW to the grid, so at 1995 prices this is $£_{1995}$2,480/kW. This should include interest during construction as that should have been included in the budget, although if that had been overlooked, at a uniform construction rate and 6% real interest rate, the commissioning cost would be 20% higher. As it was then in public ownership a considerably lower rate would have been charged, increasing the commissioning cost by perhaps 10%. The figure assumed is the rounded simple average of the two original estimates, $£_{1995}$2,550/kW.

We have reliable figures for output supplied by EdF monthly from 1994 to end 2019. 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 wholesale price might be a reasonable proxy for the efficient value of electricity. Data sources are listed in the appendix.

Figure 2 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.

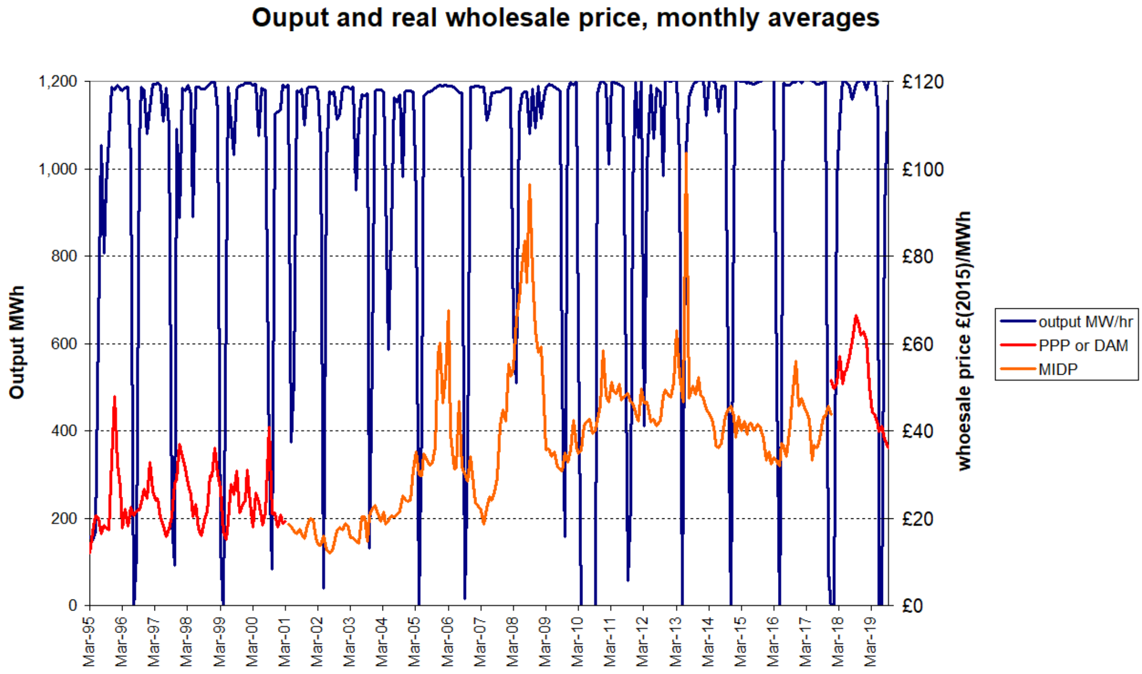

FIGURE 2

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

5.2 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. The data appendix pulls together estimates made for the UK Government and observed operating costs for US nuclear stations to give £$_{2019}$24/MWh.

6. 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 3 shows generation by fuel from well before privatization (and commissioning SZB). 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 regional 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 credit) and CCGT output.

[7] https://www.edfenergy.com/energy/power-station/daily-statuses

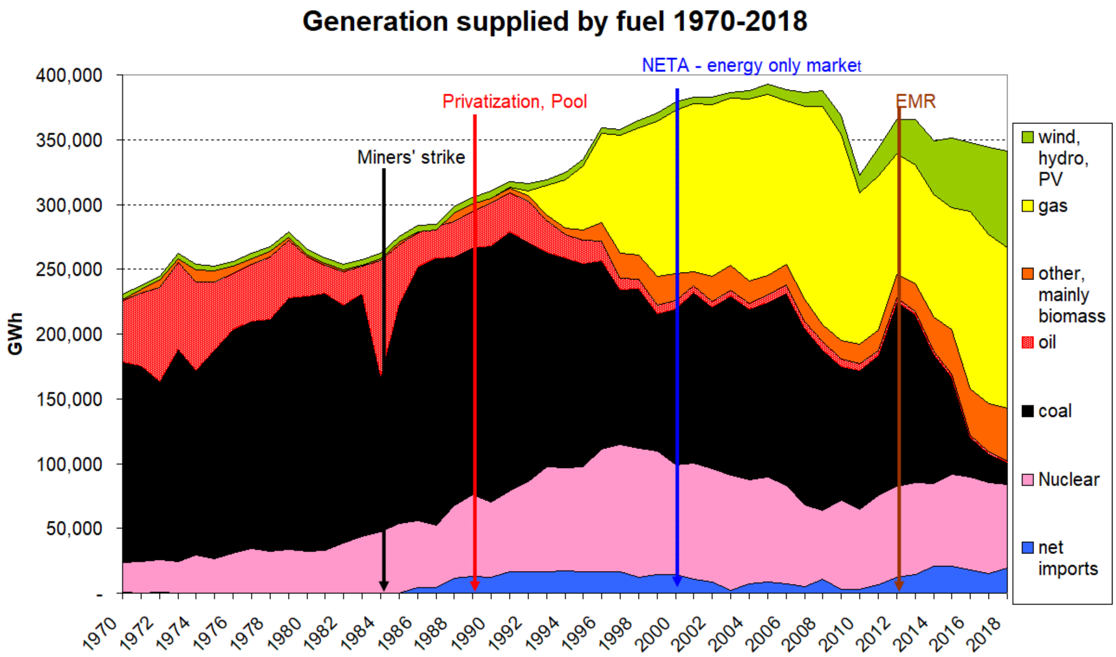

FIGURE 3

Generation by fuel, 1970-2018

Source: DUKES 5.1

The real fuel generation costs including GB carbon costs(CPI) are shown in figure 4, together with the day-ahead wholesale price (coal efficiency 35%, CCGT 48%).

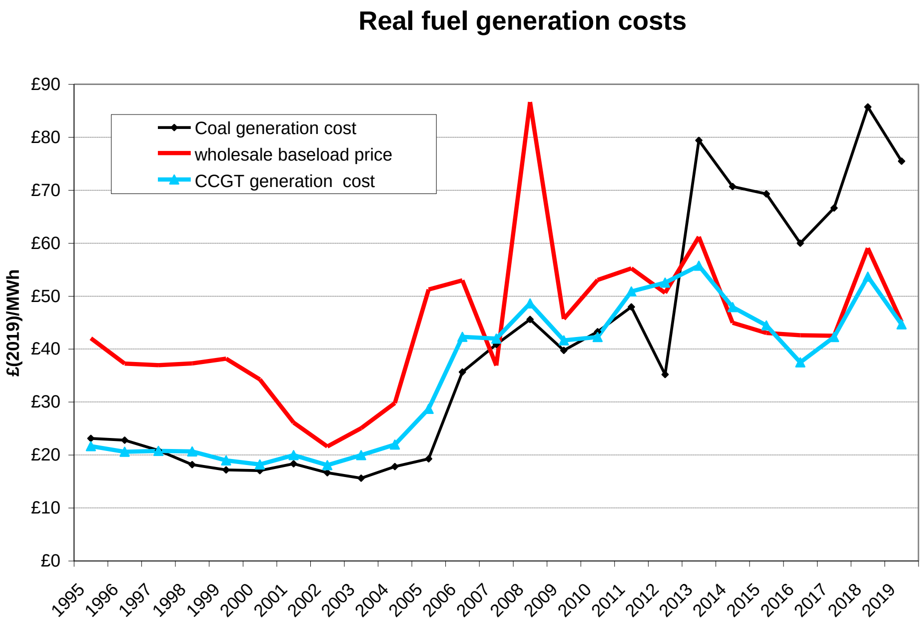

FIGURE 4

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

Source: Price data as fig.2, 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 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.)

7. 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 5.1 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 *R*	Deprec-iation *D*	end of yr. RAB *R-D*	Ofgem annual Inflator	WACC Low *r*	High *r*	capex £/MWh Low *K/h*	High *K/h*	opex £/MWh *o*	strike price £/MWh Low *K/h+o*	high *K/h+o*
1995	£2,550	£72.9	£2,477	1.021	6.31%	7.20%	£31.8	£34.9	£12.9	£44.7	£47.8
1996	£2,530	£74.4	£2,456	1.029	6.31%	7.20%	£31.9	£34.9	£13.2	£45.0	£48.1
1997	£2,528	£76.6	£2,451	1.037	6.31%	7.20%	£32.1	£35.2	£13.6	£45.7	£48.7
1998	£2,543	£79.5	£2,464	1.013	6.31%	7.20%	£32.7	£35.7	£14.1	£46.7	£49.8
1999	£2,497	£80.5	£2,416	1.033	6.31%	7.20%	£32.4	£35.4	£14.3	£46.7	£49.7
2000	£2,497	£83.2	£2,413	1.019	6.00%	6.88%	£31.7	£34.7	£14.7	£46.4	£49.4
2001	£2,460	£84.8	£2,375	1.010	6.00%	6.88%	£31.6	£34.6	£15.0	£46.6	£49.6
2002	£2,400	£85.7	£2,314	1.029	6.00%	6.88%	£31.2	£34.1	£15.2	£46.4	£49.3
2003	£2,381	£88.2	£2,293	1.030	6.00%	6.88%	£31.4	£34.3	£15.6	£47.0	£49.9
2004	£2,362	£90.9	£2,271	1.029	6.00%	6.88%	£31.6	£34.5	£16.1	£47.7	£50.6
2005	£2,337	£93.5	£2,243	1.033	5.12%	5.99%	£29.0	£31.8	£16.6	£45.5	£48.3
2006	£2,317	£96.5	£2,220	1.044	5.12%	5.99%	£29.3	£32.0	£17.1	£46.4	£49.1
2007	£2,319	£100.8	£2,218	1.046	5.12%	5.99%	£29.9	£32.6	£17.9	£47.7	£50.5
2008	£2,320	£105.4	£2,214	0.984	5.12%	5.99%	£30.5	£33.3	£18.7	£49.2	£51.9
2009	£2,180	£103.8	£2,076	1.050	5.12%	5.99%	£29.3	£31.9	£18.4	£47.7	£50.3
2010	£2,180	£109.0	£2,071	1.050	4.63%	5.51%	£28.5	£31.2	£19.3	£47.8	£50.5
2011	£2,173	£114.4	£2,059	1.032	4.63%	5.51%	£29.2	£31.9	£20.3	£49.5	£52.1
2012	£2,125	£118.0	£2,007	1.030	4.63%	5.51%	£29.4	£32.0	£20.9	£50.3	£52.9
2013	£2,068	£121.6	£1,946	1.024	4.63%	5.51%	£29.6	£32.1	£21.5	£51.1	£53.6
2014	£1,992	£124.5	£1,868	1.010	4.63%	5.51%	£29.5	£31.9	£22.0	£51.5	£53.9
2015	£1,886	£125.7	£1,760	1.010	3.78%	4.69%	£26.8	£29.1	£22.3	£49.1	£51.4
2016	£1,778	£127.0	£1,651	1.026	3.78%	4.69%	£26.4	£28.6	£22.5	£48.9	£51.1
2017	£1,693	£130.3	£1,563	1.023	3.78%	4.69%	£26.4	£28.5	£23.1	£49.5	£51.6
2018	£1,599	£133.3	£1,466	1.017	3.78%	4.69%	£24.1	£26.0	£23.6	£47.7	£49.6
2019	£1,491	£135.5	£1,355	1.006	3.78%	4.69%	£23.3	£25.1	£24.0	£47.3	£49.1
2020	£1,364	£136.4	£1,228		1.72%	2.46%	£21.0	£22.3	£24.2	£45.1	£46.5

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

Each year the RAB, *R*, is decreased by depreciation of 1/35 of the initial RAB, or *D* =£$_{1995}$72.9/kW. Table 2 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, *r,* is taken from Table 1 (the two columns headed "WACC"). Thus at the end of 1995 the RAB is £2,250 - £72.9 = £2,477 which is then uprated by RPI_{1996}/RPI_{1995} or 1.021 (shown in Table 2) to give the opening 1996 RAB of £2,530/kW.

The annual capex to be recovered from sales revenue depends on the MWh produced per kW capacity. The capacity factor of SZB 84%, taken as *h* =7.35 thousand hours, which Ofgem uses to specify the capex to be recovered via the strike price, in £/MWh. The annual capex, *K,* = *D*+*r***R* £/kWyr, so the allowable capex is *K/h* £/MWh, shown in the right hand columns in Table 2. Thus in 1995 the low capex = £72.9 (*D*) + 6.31% of £2,550 = £234/kWyr/7.35 = £31.8/MWh. The strike price is then set as the capex (a low and a high value for the low and high WACCs) plus the opex, *o,* calculated above as £$_{2019}$24/MWh = £$_{1995}$12.9 (using the relevant price indices) and shown in the right hand columns of Table 2.

The daily sales revenues at current market prices are aggregated to annual values and divided by annual output to give the nominal output-weighted sales price, shown in the Table 3, col 3.

TABLE 3

Annual real values of deficit and displaced CO_2

year	output/yr. GWh/yr.	nominal sales price £/MWh	displaced CO_2/MWh tonnes/MWh	displaced CO_2 Mt/yr.	CO_2 price £/tonne	deficit/yr. incl. CO_2 value £(2019) million Low	High
1995 H2	4,600	£26.22	0.82	3.78		£137.7	£160.5
1996	8,434	£23.63	0.82	6.94		£284.1	£324.4
1997	8,432	£24.20	0.82	6.94		£279.2	£318.6
1998	10,166	£24.73	0.82	8.36		£338.1	£385.0
1999	8,211	£25.60	0.82	6.75		£256.9	£293.4
2000	7,129	£23.22	0.82	5.86		£242.9	£274.5
2001	9,220	£18.09	0.63	5.80		£380.2	£419.7
2002	9,193	£15.19	0.62	5.72		£408.7	£446.7
2003	8,884	£17.85	0.62	5.53		£364.4	£400.3
2004	9,329	£21.48	0.63	5.84		£339.2	£376.1
2005	8,691	£37.57	0.63	5.50	£12.30	£186.1	£218.8
2006	8,908	£40.03	0.64	5.67	£11.58	£161.7	£194.2
2007	10,262	£28.51	0.63	6.49	£0.64	£260.5	£297.1
2008	9,273	£69.48	0.63	5.83	£22.53	-£71.4	-£39.4
2009	9,095	£37.26	0.63	5.71	£13.42	£210.3	£239.2
2010	4,724	£44.23	0.62	2.95	£12.91	£66.0	£80.9
2011	8,656	£47.92	0.62	5.40	£11.28	£86.0	£112.1
2012	9,375	£45.13	0.63	5.88	£5.98	£94.3	£121.2
2013	8,715	£55.69	0.63	5.45	£6.92	-£2.4	£21.4
2014	8,828	£41.60	0.63	5.53	£12.62	£170.3	£193.3
2015	10,507	£39.92	0.63	6.58	£21.43	£255.6	£282.1
2016	8,627	£40.03	0.63	5.44	£22.32	£211.2	£231.5
2017	8,834	£40.89	0.63	5.59	£23.13	£213.5	£232.8
2018	9,383	£58.26	0.64	6.02	£33.05	£101.1	£120.0
2019	8,481	£43.60	0.64	5.43	£39.42	£245.1	£260.7

Source: EdF and from Table 2

Annual CO_2 emissions are calculated from output times the emissions factors. The annual deficit is the strike price times output less sales revenue, which is then revalued (using the CPI) to 2019 prices. These revenue shortfalls are based on the actual wholesale price that has been increased since 2005 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 wholesale price falls by less than this carbon credit as the British carbon tax induces more imports that lowers the price (Chyong et al., 2020) so the deficit and CO_2 cost are overstated. However, by 2019 the total price of carbon had risen to its target level and arguably the attributable carbon savings should only continue to the end of 2018. Table 4 considers both end-date alternatives.

The levelized cost of carbon abated (deficit per tonne carbon abated) depends on the discount rate. As this changes every five years the annual WACCs need to be appropriately averaged to give 5.16% or 6.05%.[8] Levelizing the carbon price is then the ratio of the NPV of deficits divided by the NPV of emissions. As the study period ends before the end of the 35-year contract that determines depreciation, the costs need to be adjusted for the residual value of SZB, as discussed in section 8. The terminal RAB value at Jan 1 2020 of £1,364/kW (or Jan 1, 2019), multiplied by capacity of 1,198 MW to give £1,634 million, discounted back to 1995 and subtracted from the NPV of deficits gives values in the final two lines of Table 4.

TABLE 4

Levelized costs of CO_2 abated $£_{2019}$

	to end 2019			to end 2018		
WACC	NPV deficit £ M	NPV CO_2 Mt	CO_2 cost £/t	NPV deficit £ M	NPV CO_2 Mt	CO_2 cost £/t
5.2%	£3,446			£3,376		
6.1%	£3,657			£3,597		
Subtract residual RAB						
5.2%	£2,958	81.7	£36.2	£2,815.15	80.2	£35.1
6.1%	£3,258	75.1	£43.3	£3,134.53	73.9	£42.4

The cost of CO_2 abated is $£_{2019}$36.2/tonne CO_2 at the low WACC and strike price and $£_{2019}$43.3/t. CO_2 at the high WACC ending in 2019, and about £1/tonne lower if the period ends in 2018, suggesting that by the end of 2018 the GB carbon charge was about right. The deficit in each year is reflated to 2019 prices (using Ofgem's price index, RPI to 2015, CPI after) before finding the Net Present Value (in 1995) using the relevant WACC. 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). Over the whole life of SZB the cost of carbon abated would be considerably lower if the future gross profits selling at the market wholesale price were clawed back by the regulator. The cost of carbon abated is therefore less than the current carbon charge, which is presumably not thought to be excessive. SZB was therefore cost-effective by today's standards and certainly when compared to 1995 alternatives.

In order to examine the implications of discounting at other discount rates, the next section develops the formulae to explore the implications of a variety of WACCs.

8. A SHORT-CUT ESTIMATE

When, as is the case with regulatory accounting, the WACC changes every five years, it is necessary to rather laboriously work through the regulatory accounts annually. If, however, the WACC is held constant, then there is a short-cut way of calculating the cost per tonne CO_2 saved. Suppose the construction cost in 1995 is K (for the whole station) and the Net Present Value (NPV) of a stream of items, $\boldsymbol{x}$, = $(x_1, x_2, \dots x_T)$ at a discount rate r over the time horizon T, is $\varphi(r, \boldsymbol{x}, T)$. (All values are in $£_{2019}$.) If output in any year t is y_t MWh and revenue at the wholesale price is $s_t y_t$ (s_t is annual revenue divided by annual output) and the operating cost is m, the value of gross profits from selling on the wholesale market in each year is $(s_t - m)y_t$, and the NPV is $\varphi(r, (\boldsymbol{s}\text{-}m\boldsymbol{i}).\boldsymbol{y}, T)$, where $\boldsymbol{i}$ is a vector of 1's. If the value of

[8] i.e. the solution r from $(1+r)^n = \Pi(1+r_i)$

carbon abated (to be determined) is p_c, and the annual amount abated is c_t, then its present value is $p_c.\varphi(r, \boldsymbol{c}, T)$.

There are two more adjustments to make. The first is the carbon credit when there is a carbon price or charge, τ_t, (zero until 2005, thereafter the EUA price plus the CPS charge, shown in Table 3) with NPV $\varphi(r, \boldsymbol{\tau.c}, T)$. This is deducted from the value of the market revenue. Second, the capacity auction credit from 2017-2019 is κ_t /kWyr, and will need to be multiplied by the derated capacity of SZB, taken as 1,000 MW, so the station receipts are £ κ_t million/yr., with NPV to 1995 of $\theta\kappa$.

If we remain within the RAB framework then we need to deduct the final RAB, R_{2020}, discounted to 1995, V, from the station cost, K, where $V = e^{-rT}R_{2020}$, or, in discrete time, $\beta^T R_{2020}$ with $\beta = 1/(1+r)$, the discount factor. (Newbery, 1997, shows that the RAB at any moment is the discounted value of future regulated revenues, even with straight-line depreciation.) Otherwise we need to project future revenue in a follow-on period. That means distinguishing two time horizons, T, from 1995 to the end of 2019, the second from 2020 until either the end of the 35-year contract or even to decommissioning, length L years. Forecast electricity prices are given in BEIS (2018), which give high, medium and low (index j) values, p_{jt}. Assuming constant future average output, y, define gross profit per MWh as $\pi_{jt} = p_{jt} - m$, so the follow-on value in 2020, V_{2020}, is the NPV of future gross profits, $\Pi_{2020} = y\varphi(r, \boldsymbol{\pi_j}, L)$, or discounting back to 1995, $V = \beta^T \Pi_{2020}$. From 2020 assume that carbon is properly priced and so there is no additional value of carbon abated, then the value of carbon abated, p_c, until 2019 solves (for the appropriate V)

$$K = \varphi(r, \boldsymbol{s.y}, T) - m\varphi(r, \boldsymbol{y}, T) + p_c.\varphi(r, \boldsymbol{c}, T) - \varphi(r, \boldsymbol{\tau.c}, T) + \theta\kappa + V.$$

In the simple case of no capacity payments or carbon credits, and constant prices (or their levelized equivalent) and continuous time with $\varphi \equiv \int e^{-rt}dt$ between 0 and T,

$$p_c = (K - V)/(ey.\varphi) - (s - m)/e.$$

The first bracketed term is the levelized net capital cost and the remainder is net revenue per MWh, both divided by the emissions factor. Figure 5 shows the dramatic effect of the WACC on the cost of carbon abated.

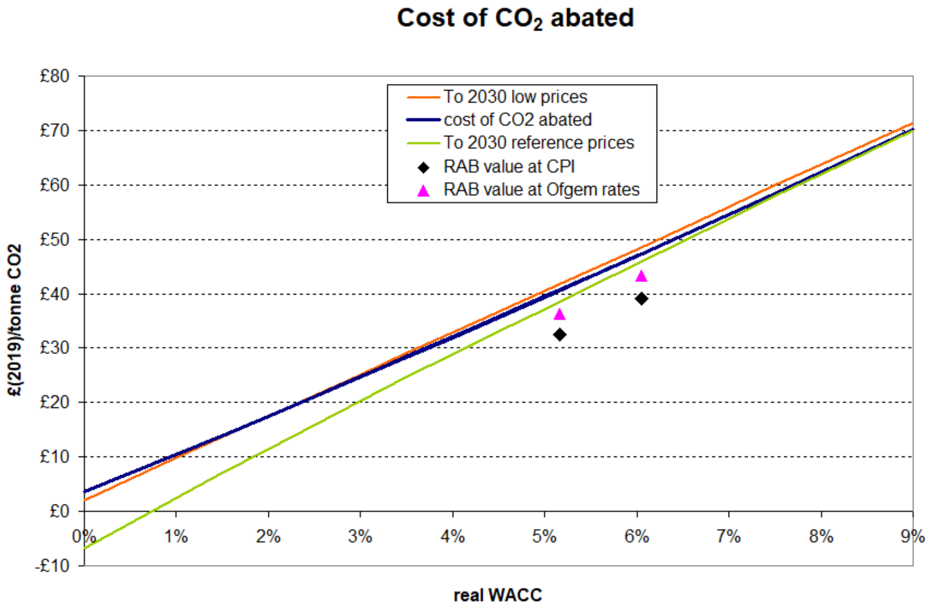

FIGURE 5

Cost of CO_2 abated £$_{2019}$/tonne CO_2

The graphs in Figure 5 are all shown reflating all values to £$_{2019}$ using the CPI, except for the triangle points that show the results from Table 4 (to end 2019). The central line takes the terminal value of the RAB to calculate the cost, while the two other lines calculate revenue to the contract end in 2030 (at which the RAB has been written down to zero) for two price projections, taken from BEIS (2018). Figure 5 shows that the cost of abating CO_2 by SZB is almost proportional to the WACC, so that moving from the social discount rate of 2.5% to a hurdle rate of 8% increases the cost from £15-20/t to over £60/t, more than trebling the cost, and underlining the core message of this paper that the cost of carbon depends critically on the cost of finance for long-lived low variable cost generation,

9. 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 £$_{2016}$20 billion (FOAK) to perhaps £$_{2019}$22 bn, or £$_{2019}$6,535/kW, as a result of "challenging ground conditions".[9] SZC was originally estimated to be 20% cheaper than the original budget, or £$_{2019}$5,340/kW for a second of a kind. BEIS (2016a) and NIC (2020b) estimate future nuclear capital costs at £$_{2016}$4,182/kW (£$_{2019}$4,464/kW).

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),

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

the cost in comparable terms would be £$_{2019}$3,100/kW (uprating by the CPI), £$_{2019}$3,690 (uprating by the RPI) or £$_{2019}$4,810 (uprating by the less reliable Construction Price Index). Taking the CPI figure, a follow-on series of 6.4 GW of SZB design might have cost £$_{2019}$19.8 bn compared to the predicted cost of HPC and SZC of around £$_{2019}$39 bn, a saving of about £$_{2019}$19 bn. Using the Construction Price Index, the saving would be about £$_{2019}$9 bn.

An alternative way of evaluating SZB is to compare the cost of carbon abated with the follow-on cost of £$_{2016}$3,100/kW over the same contract length of 35 years at the social discount rate of 2.5%. This would be £$_{2019}$4.4/tonne CO_2 at the reference price projections compared to SZB under the same assumptions of £15.9/tonne CO_2. At a WACC of 5% the carbon cost is £22.3/t CO_2 compared to £37.2/t CO_2 for SZB – a lower WACC would be more appropriate for a RAB model starting a few years later once Ofgem has improved its methodology and as discount rates fell.

When it comes to comparing nuclear and renewables cost, again the comparisons depend critically on both the WACC and the date of comparison, as renewables costs have fallen dramatically since 1995. BEIS (2016a) gives the latest construction costs for on and off-shore wind projecting forward to commissioning in 2025 (by when costs will have fallen compared to commissioning in 2018). At £$_{2019}$ prices, off-shore wind (medium estimate) would be £$_{2019}$2,880/kW. However, even at the impressive capacity factor of 48%, adjusting to a nuclear equivalent of 84%, the equivalent capital cost would be £5,040/kW, slightly cheaper than the forecast SZC. With a life of only 22 years rather than 60 years and higher opex of £26.7/MWh comparted to SZC at £24/MWh, the levelized cost of off-shore wind at 2.5% would be about £67/MWh (all in £$_{2019}$).

Cost data for on-shore wind from BEIS is less satisfactory, as the Government stopped supporting it in 2015, but IRENA (2018) has up-to-date data for the UK of £$_{2019}$1,560/kW (central estimate for 2018), with possibly a fall of 10-15% by 2025. At a capacity factor of 28% and the forecast cost fall, the 2025 equivalent baseload cost would be £$_{2019}$3,980/kW for a 20 year operating life and opex of £25/MWh. The levelized cost of on-shore wind at 2.5% would be about £60/MWh levelized. Compare that with SZB even over 35 years and first-of-a kind costs, the levelized cost at 2.5% would be about £49/MWh. While the relative advantage of nuclear over these renewables decreases as the WACC increases, it remains the cheapest even at a WACC of 8%.

10. 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[10] 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 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.

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

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.

This paper has argued that the particular characteristics of nuclear power (capital intensive, large scale, long construction time, very long life, and subject to the vagaries of changing political attitudes) makes it very unlikely that nuclear stations would be built in the private sector without government or regulatory guarantees. Either public ownership or the RAB model successfully applied to regulated utilities could bring down risk and the cost of finance to make the cost of abating CO_2 comparable to or below the current charge for CO_2 in the electricity industry. To demonstrate that, the paper 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. Just as other zero-carbon renewables required contractual support, SZB would have required a long-term contract at above market prices. The most appropriate contract would be a 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 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 review date there are a range of observed regulated WACCs set for electricity and other utilities, depending on their gearing and risk. At a low value of the WACC (comparable to that used for Transmission and Distribution utilities) the cost is $£_{2019}$36.2/tonne CO_2 abated and $£_{2019}$43.3/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. The key message, however, is that the cost of abating CO_2 by SZB is almost proportional to the WACC, so that moving from the social discount rate of 2.5% to a hurdle rate of 8% increases the cost from £15-20/t to over £60/t, more than trebling the cost.

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), the levelized costs of the original SZB in today's prices are below the project 2025 costs of both on and off-shore wind in Britain, even at higher WACCs (up to 8% real). Certainly in 1995, when renewables were much costlier than now, SZB was the cheapest way to abate CO_2 and even now the projected cost of SZC (the next PWR after Hinkley Point C) looks to be no more expensive in reducing CO_2 that renewables (Newbery et al., 2019). Had the original PWR programme continued in the 1990s, it would have been substantially cheaper. Lévêque (2015) documents the benefits of replicating existing designs in France.

The other striking observation is that the full cost of SZB (including FOAK costs) at $£_{2019}$4,290/kW is less than the $£_{2019}$5,340/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, this 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 Data appendix

Price indices

Until 2016, British regulators allowed for inflation using the Retail Price Index, RPI, but more recent price controls have been based on the Consumer Price Index, CPI, (actually CPIH). That was introduced as the Harmonised Index of Consumer Prices (HICP) in 1996 and later as the CPI. For updating prices, operating costs and the WACCs, the RPI is used until 2016, thereafter the CPI. The relevant series are available from the Office of National Statistic (ONS). Uprating construction costs is inherently more difficult, as it will depend on the type of construction and the mix of different materials and labour. The ONS only took control of the construction series in 2015 and has since revised the methodology.[11] As a measure of the problem of uprating construction costs, using the RPI from 1995 to 2019 the uprating factor is 1.94; using the CPI, it is 1.62; and using the even less reliable construction index and piecing together at least three series, it is 2.54. This wide range of uncertainty should be borne in mind when comparing more recent nuclear capital cost estimates with earlier values.

Electricity prices

The price received by SZB will depend on the kind of contracts it signs, for which we lack information, but contract prices are typically above the wholesale price, which we take as a better measure of the value of electricity compared to that supplied by fossil generation. From commissioning until 2001, the relevant price is the Pool Purchase Price, which includes a capacity payment in stress hours. From 2001 until 2014 the price is Market Index Price, and from 2015 it is the Day Ahead Market price published by ENTSO-E on its Transparency Platform. 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}$19.4/kWyr =$£_{2019}$21.8/kWyr. The second auction cleared at $£_{2014}$18/kWyr = $£_{2019}$17.3/kWyr. These are deducted from the annual value of capex in Table 2.

From 2006, fossil generation was subject to a carbon charge, initially just through the EU Emissions Trading System, and from 2014, the UK Government imposed an additional Carbon Price Support (CPS). The prices of the EU Allowances in €/tonne CO_2 are published by EEX. The CPS initially came in on 1 April 2013 at £4.94/tonne, raised in 2014 to £9.55/t and again in 2016 to £18./t. The sum of the two is shown in Table 3.

Operating costs

BEIS (2016b, Table 19) gives (all in $£_{2014}$) the fixed Operations and Maintenance (O&M) costs for a first of a kind PWR as £72,900/MWyr, insurance costs as £10,000/MWyr

[11] see https://www.ons.gov.uk/businessindustryandtrade/constructionindustry/articles/interimsolutionforconstructionoutputpriceindices/ukjantomar2017#toc

and connection and use of system as £500/MWyr. National Grid (later NGESO) publishes the annual Transmission Network Use of System (TNUoS) charges for the zone in which Sizewell B (SZB) is located, and the average for all zones. Taking the average over the period 2005-2019 the annual charge for SZB was $£_{2019}$1,710/MWyr compared to an average for all zones of $£_{2019}$7,740/MWyr, or $£_{2019}$6,030/MWyr cheaper, with recent and projected future years with negative charges for SZB (i.e. SZB is paid provided it delivers power in the peak periods). Arguably it is the relative connection cost that is required to compare generation costs at SZB with other stations, where SZB is considerably cheaper, meaning that SZB is better placed for delivering power than more distant generation. The least favourable assumption is to assume zero transmission charges for SZB.

Fuel and decommissioning costs are given as £7/MWh (BEIS, 2016a, Table 4) and the variable O&M as £5/MWh. 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 $£_{2014}$23/MWh. Uprated to 2019 prices gives $£_{2019}$24.8/MWh.

Table A2 gives US data or the average O&M and fuel costs at $£_{2019}$18.6/MWh. As these probably exclude decommissioning costs of $£_{2014}$2/MWh, at just below $£_{2019}$21/MWh they suggest rounding down the operating costs for this paper to $£_{2019}$24/MWh.

Table A2 US data on nuclear generation costs from existing utilities

Year	O&M	fuel	$/£	CPI Inflator to 2019	O&M	fuel	Total £(2019)
2009	$16.34	$5.35	1.56	1.23	£12.83	£4.20	£17.03
2010	$17.30	$6.68	1.54	1.20	£13.40	£5.18	£18.58
2011	$17.69	$7.01	1.60	1.15	£12.72	£5.04	£17.75
2012	$19.81	$7.61	1.58	1.12	£14.04	£5.39	£19.43
2013	$19.15	$8.14	1.56	1.10	£13.44	£5.71	£19.16
2014	$19.08	$7.71	1.65	1.08	£12.54	£5.07	£17.61
2015	$18.23	$7.48	1.53	1.08	£12.86	£5.28	£18.14
2016	$17.91	$7.45	1.35	1.07	£14.17	£5.89	£20.06
2017	$16.90	$7.47	1.29	1.04	£13.69	£6.05	£19.74
2018	$16.71	$7.15	1.33	1.02	£12.75	£5.46	£18.21
2019	$16.92	$6.81	1.28	1.00	£13.26	£5.34	£18.59
average	$17.82	$7.17			£13.25	£5.33	£18.57

https://www.eia.gov/electricity/annual/html/epa_08_04.html