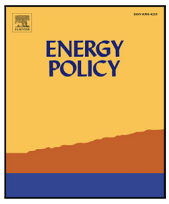
Energy Policy 205 (2025) 114653



Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol



Research article



A Robust Decision-Making approach to evaluating state support for nuclear programmes under uncertainty: A UK case study

J. Mangin [a,e,*], M. Bluck [b,**], G. Darch [c], D. Roberts [d], S. Brown [d], M. Workman [a,**]

[a] Energy Futures Lab., Imperial College London, South Kensington Campus, London SW7 2AZ, United Kingdom
[b] Centre for Nuclear Engineering, Imperial College London, South Kensington Campus, London SW7 2AZ, United Kingdom
[c] Anglian Water, Thorpe Wood House, Thorpe Wood, Peterborough PE3 6WT, United Kingdom
[d] University of Sheffield, Western Bank, Sheffield S10 2TN, United Kingdom
[e] École polytechnique, Route de Saclay, 91128 Palaiseau Cedex, France

ARTICLE INFO

Keywords:
Robust decision-making
Nuclear finance
Regulated asset base
Decision under uncertainty

ABSTRACT

Several western countries have announced ambitious nuclear energy programmes to boost energy security and support decarbonisation targets following the 2022 energy crisis. However, persistent delays, cost overruns, and volatile financial conditions hinder orthodox strategic planning and deter investment in a sector that has stagnated for two decades.

To accommodate for the deep uncertainty, this study employs a Robust-Decision Making (RDM) approach to develop financing policy recommendations to meet the United Kingdom (UK) government's nuclear ambitions for 2050. Different revenue, financing, and government support schemes are tested via the RDM framework across wide-ranging plausible future conditions. Three deployment scenarios that meet the government's target build upon current UK construction and planned initiatives, incorporating GenIII+ light-water technologies with varying amounts of large-scale reactors (LR) and Small Modular Reactors (SMR). Findings indicate that the financial and revenue structure of nuclear programmes, particularly the adoption of regulated models over market-aligned ones, helps manage financial risks by addressing uncertainties inherent in nuclear power deployment. This could in turn facilitate investment in the sector and restrict the risk costs falling on consumers. Direct government backing is discussed, and the fiscal cost of state majority investment is estimated and set against broader public energy funding.

1. Introduction

Western economies are relaunching nuclear programmes after a two-decade industry slowdown with ambitious post-2022 announcements in nations like the United States (US), the United Kingdom (UK), France, Poland and Czech Republic (The White House, 2024; Department for Energy Security and Net Zero (DESNZ), 2024b; Macron, 2022; Polityka Insight Baker McKenzie, 2023; Government of the Czech Republic, 2024). Following the 2022 energy crisis in Europe caused by surging gas prices, the UK launched its own nuclear initiative to reduce its gas dependency, bolster energy security, and support decarbonisation targets. The programme aims at reaching 24 GW of available nuclear capacity by 2050, projected to supply approximately 25% of national electricity demand by that time. New infrastructure will necessitate substantial investments, with construction costs potentially reaching £100–250 billion over the next 25 years (Fig. 5), a substantial portion of which is expected to come from public funding.

In 2024, the UK released a civil nuclear roadmap to establish foundational planning for its proposed nuclear programme (Department for Energy Security and Net Zero (DESNZ), 2024b). However, detailed scenarios outlining timely deployment to meet the defined objectives have yet to be laid out. Much remains undecided, including the types of technology that will predominate by 2050, deployment timelines, projected costs, key investors, and the revenue and financing frameworks under which reactors will operate. The call for clearer direction has emerged from a number of fronts: the industry seeks signals to enable upfront supply chain investments, independent bodies warn of risks to decarbonisation target timelines, and concerns are raised over taxpayer liabilities and state budget burdens of non-quantified objectives (Environmental Audit Committee (EAC) Chair, 2024). In practice, providing definitive answers is complicated by large uncertainties in nuclear project performance, both in terms of cost and timeline, as well as by

* Corresponding author at: Energy Futures Lab., Imperial College London, South Kensington Campus, London SW7 2AZ, United Kingdom.
** Corresponding authors.
E-mail addresses: jeremy.mangin@polytechnique.org (J. Mangin), m.bluck@imperial.ac.uk (M. Bluck), mark.workman07@imperial.ac.uk (M. Workman).

https://doi.org/10.1016/j.enpol.2025.114653
Received 29 December 2024; Received in revised form 15 April 2025; Accepted 16 April 2025
Available online 21 May 2025
0301-4215/© 2025 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

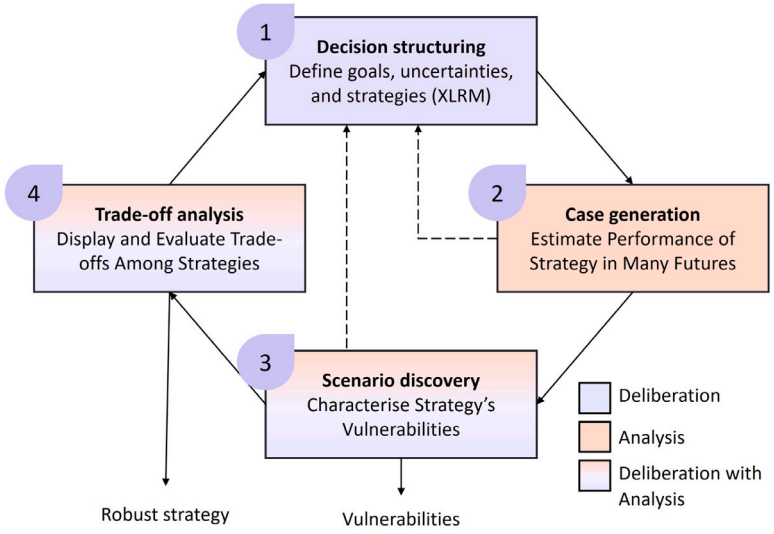


Fig. 1. Iterative, participatory steps which characterise robust decision making analysis (RAND Corporation, 2013).

the complex financial and regulatory landscape. Conventional large-scale nuclear projects in the US and Europe, including the UK, have suffered over the past two decades critical budget overruns and delays though benefiting from established supply chains. Advanced reactor designs, not yet licensed, also face significant uncertainties, especially in cost projections, scaling capabilities, and supply chain development, and can be biased by early-stage appraisal optimism. Furthermore, the single largest expense for privately-financed, capital-intensive nuclear projects lies in financing costs, heavily influenced by volatile interest rates driven by crises, pandemics, and wars, as well as perceived investor risk, and anticipated government intervention in the coming years which prove difficult to anticipate. Based on the characterisation above, the circumstances around nuclear deployment in the UK and more generally, is likely to therefore to be considered to be one which is steeped in deep uncertainty i.e., "where analysts do not know, or the parties to a decision cannot agree on, (1) the appropriate conceptual models that describe the relationships among the key driving forces that will shape the long-term future, (2) the probability distributions used to represent uncertainty about key variables and parameters in the mathematical representations of these conceptual models, and/or (3) how to value the desirability of alternative outcomes. In particular, the long-term future may be dominated by factors that are very different from the current drivers and hard to imagine based on today's experiences" (Lempert et al., 2003).

This study therefore seeks to undertake a first of a kind assessment of the application of deep uncertainty approaches to nuclear programme deployment. It does this by exploring the deployment of light-water Gen III+ nuclear reactor designs, including a conventional Large-scale Reactor (LR) and a Small Modular Reactors (SMR), to evaluate three options for achieving the UK's electricity sector nuclear deployment target by 2050. The evaluation of these options under different revenue and funding structures via a deep uncertainty approach is anticipated to provide clearer insight across wide-ranging future scenarios as to how a financial framework of a nuclear programme can effect a paradigm shift in its market perception, attractiveness to investors, and consumer costs. It is observed that improved risk management schemes that address specific project uncertainties inherent in new nuclear power deployment enhance the stability and certainty of desired policy outcomes. This could in turn restrict the cost of risk falling on consumers and facilitate the large, long-term investments required in the sector. Finally, achieving robust programme performance in volatile economic conditions could also translate into greater resilience to increasingly frequent shocks and disruptions. The analysis incorporates UK-specific revenue frameworks and economic conditions, drawing on country-specific data.

Section 2 details the application of the Robust Decision-Making (RDM) approach to the problem prescribed above. Nuclear sector uncertainties are mapped within the framework so as to apply the method to this study. Section 3 unpacks the insights provided via the RDM as to the application of a regulated or a market-based financing and revenue structure, at both project and programme scales. Government direct backing is considered in Section 4, which evaluates a subset of fiscal costs associated with direct public investment in the nuclear programme and comparing it to broader public energy funding. Finally, the discussion and conclusion in Section 5 expands on the ability of robust evaluations to address the additional insights sought for better-informed policy design, and explores practical implications of the considered financial policy decisions.

2. Mapping nuclear cost uncertainties

With the financial shortfalls of the latest Western nuclear power plant constructions, the emergence of advanced reactor projects, and the expected relaunch of larger programmes, the question of nuclear costs and the associated uncertainties is a prolific topic in the literature; and various studies have characterised uncertainty sources surrounding new nuclear construction project costs (Newbery et al., 2019; Agar et al., 2018; Stewart and Shirvan, 2022; Mignacca and Locatelli, 2020). How these are applied to an RDM analysis is laid out in subsequent sections, below.

2.1. The application of Robust Decision-Making (RDM) to nuclear financing

In line with the characteristics as to deep uncertainty – as described respectively above – (1) there are limitations in accurately predicting nuclear power costs and global economic conditions; (2) there is no consensus on the probability distributions of key economic parameters and related risks, including the impact of delays, innovation, supply chain dynamics, and scalability as driving forces; and (3) a portfolio of nuclear technologies and varying types of policy support exist, each with unique characteristics that could influence investment in the sector and affect consumers and taxpayers differently. In a climate of deep uncertainty, the RDM approach carries the probability risk analysis "backward", starting from policy actions and exploring their ability to reduce risks over assumption configurations. It is done in practice by visualising how a policy performs across wide-ranging plausible

Table 1
Overview of uncertainty vectors and problem parameters for contemplated futures under high-end (pale grey), mean (grey), and low-end (dark grey) assumptions.

Technological uncertainties		
	Large-scale nuclear reactor (LR) *2 × 1.6* GWe	*Small Modular Reactor (SMR)* *470* MWe
Overnight capital costs (OCC - £$_{2024}$/kWe) (Buongiorno et al., 2018; Agar et al., 2018)	5000 £$_{2024}$/kWe	6500 £$_{2024}$/kWe
	10 yrs (on schedule)	FOAK: 4 yrs - NOAK: 2.5 yrs
	7000 £$_{2024}$/kWe	7500 £$_{2024}$/kWe
Construction time (yrs) (Buongiorno et al., 2018; Expert Finance Working Group on Small Reactors, 2018)	14 yrs (4 years delayed)	FOAK: 6 yrs - NOAK: 3 yrs
	9000 £$_{2024}$/kWe	9750 £$_{2024}$/kWe
	18 yrs (8 years delayed)	FOAK: 7 yrs - NOAK: 4 yrs
Load factor (%) (National Energy System Operator (NESO), 2023)	88%	93%
		80%
		55%
Fuel costs (Bles et al., 2011; Mignacca and Locatelli, 2020)	4.5 £$_{2024}$/MWh	4 £$_{2024}$/MWh
O&M - Fixed costs (Bles et al., 2011; Mignacca and Locatelli, 2020)	80 £$_{2024}$/kW/yr	105 £$_{2024}$/kW/yr
O&M - Variable costs (Bles et al., 2011; Mignacca and Locatelli, 2020)	13.5 £$_{2024}$/MWh	17.5 £$_{2024}$/MWh

Financial uncertainties	
Risk-free rate (%) (UK Debt Management Office (UKDMO), 2025)	1% 2016–2021
	3% 2009–2015
	5% 1995–2008, 2023-
Asset beta (Nuclear Energy Agency (NEA), 2022)	0
	0.5
	1
Systemic risk (%) (Rachel and Summers, 2019)	5%
Credit spread (%) (Rachel and Summers, 2019)	2%
Social discount Rate (%) (Stern, 2007)	1.4%

Learning-by-doing (Stewart and Shirvan, 2022)					
	Project cost structure		Fast	Slow	Plateau
	LR	*SMR*			
Factory	44%	51%	16%	8%	–
Labour	42%	33%	13%	6%	5th unit
Material	14%	16%	7%	3%	5th unit
LR delay reduction rate			20% (Hinkley Point C., 2022)	8%	–

futures, which requires to test models over hundreds to thousands different sets of parameters. RDM can therefore determine the conditions under which a policy is likely to succeed or fail, and identify clusters of scenarios that reveal potential vulnerabilities, trade-offs, threshold effects, and exposure to external shocks (RAND Corporation, 2013). RDM shifts the policy-design focus from optimisation under most-likely future forecasts to exploring resilience against diverse and uncertain conditions, thereby reducing policy appraisal's reliance on the accuracy of future predictions. A robust strategy is not necessarily optimal in any given future but performs well across a wide range of possibilities. RDM has already seen applications in deeply complex sectors with high social, environmental and economic stakes such as water management and Net Zero policies (Workman et al., 2024).

The RDM process relies on the XLRM framework, which structures the decision space by identifying the following : (1) key uncertainties (X), such as nuclear cost drivers and economic conditions; (2) available policy levers (L); (3) relationships (R) between these factors, and (4) performance metrics (M) relevant to stakeholders such as consumers, investors or government (RAND Corporation, 2024). A matrix framing the XLRM process that underpinned the analysis is provided with the economic model in Appendix A. The iterative and participative steps that characterise RDM are presented in Fig. 1. This study proposes a first iteration of this approach, applied to financing policies relative to the UK's nuclear objectives for 2050, based on criteria of cost to the consumer, risk to the investor and weight on the public purse. The subsequent sections focus on problem parameters and nuclear cost uncertainties (X), summarised in Table 1, providing a better context to characterise them as deep. Additionally, a data appendix in Appendix B summarises data sources and provides further details and justifications on parameter values. These sections explore, through a review of the literature, three driving uncertainty domains: (1) nuclear technology costs and schedule; (2) financing conditions; and (3) integration into the existing energy mix. The uncertainties within these domains are categorised into five independent exogenous variables, each assigned two or three levels (e.g., high, low, and occasionally medium). This results in a dataset of approximately 500 scenarios, built through a systematic exploration of the uncertainty space (Cartesian product of uncertainty vectors). This dataset is used to generate test cases for the considered policy levers (L), compare financing and revenue schemes in Section 3, and estimate the impact on public finance of direct government investment in Section 4. The identified policy vulnerabilities and trade-offs are discussed as the test cases shed light on strategy performance under uncertainty.

2.2. The overnight cost and schedule of nuclear new builds

The Overnight Capital Cost (OCC) of nuclear power facilities refers to the projected expenses for engineering, materials, and construction, excluding interest accrued during the project's duration. This metric provides a cost estimate as if the plant were built 'overnight', reflecting the value of the infrastructure independent of financing considerations. Significant uncertainty surrounds the OCC of nuclear plant projects, with large gaps observed between vendor-provided estimates and actual expenses in 21st-century Western projects. The risk of overrun is especially pronounced in first-of-a-kind (FOAK) projects, as new designs and sector re-emergence necessitate new processes and restructuring of the industrial base. As nth-of-a-kind (NOAK) units are deployed, project OCCs are anticipated to decrease and gain in certainty, with project replication benefiting from significant cumulative learning.

This study considers the deployment of Gen III+ light-water Nuclear Power Plants (NPP) in the form of conventional gigawatt-scale reactor units or more innovative Small Modular Reactors (SMRs), whose more recent commercial development envisions series of smaller reactors (ranging from tens to hundreds of MWe), line-produced in a factory setting. While large-scale reactors benefit from greater economies of scale, they are highly complex construction mega-projects prone to delays and cost overruns, as seen in high-profile projects like Plant Vogtle, Okiluoto, Flamanville, and Hinkley Point C (HPC) in the United States and Europe. Although SMRs offer fewer economies of scale per unit, their smaller project scope lowers the risk of overruns on more

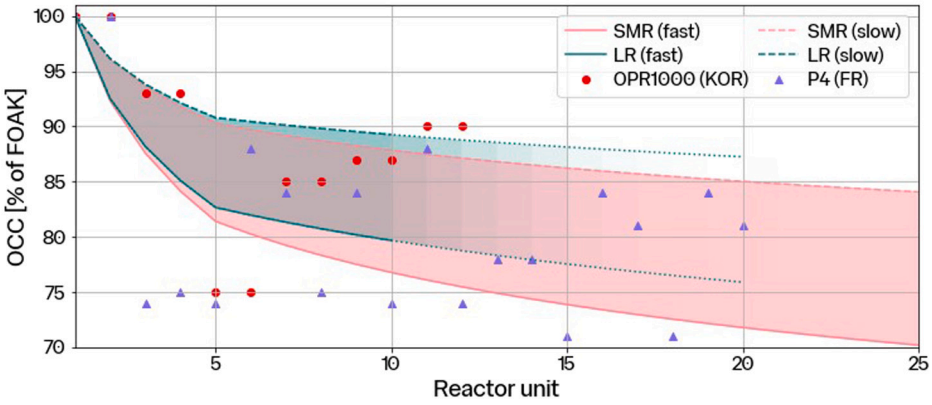


Fig. 2. Assumed OCC reduction range from learning-by-doing in comparison with historic learning from Korean and French reactor series.
Source: Adapted from Stewart and Shirvan (2022).

modest financial outlays, and swifter cost reductions are anticipated through the higher cadence of industrial replication and streamlined processes. Most SMR designs are however still in the development phase, meaning that cost estimations are still preliminary, and likely understated, as the design usually gains in complexity throughout the licensing process (Buongiorno et al., 2018).

OCC and schedule estimates for the large-scale reactor design, specifically the European Pressurised Reactor (EPR), recently deployed in China, Finland and France, and under construction in the UK, assumes cost overruns rise linearly with delays. These estimates are based on historical experiences in Western nuclear projects, including industry claims of on-schedule outcomes and worst-case scenarios with delays of up to eight years (Newbery et al., 2019; Buongiorno et al., 2018). The OCC range for the SMR, modelled on the Rolls-Royce 470 MWe design, reflects the 5th, 50th, and 95th percentiles of a Rolls-Royce study's OCC probability distribution, calculated through a bottom-up, component-level cost analysis and Monte Carlo simulation (Agar et al., 2018). The resulting range aligns with recent estimates from a US Department of Energy (DOE) study (US Department of Energy (DOE), 2023) and the −15%/+30% cost accuracy range is consistent with the Association for the Advancement of Cost Engineering (AACE) standards for Class 3 projects, of maturity levels below 40%. SMR construction time ranges, informed by a UK Government expert report on SMR market entry and finance (Expert Finance Working Group on Small Reactors, 2018), are considered to correlate with costs as design or manufacturing complexity increases.

Capital cost reduction from learning-by-doing is modelled using a multi-factor learning curve adapted from Stewart and Shirvan, who developed a bottom-up tool to forecast costs for new US reactors (Stewart and Shirvan, 2022). The model assigns different learning rates to factory, material, and labour-related expenses to reflect varying cost structures across projects. Material and labour learning plateaus after 5 units, and new factory learning is conservatively limited by accounting for previously acquired learning from the existing industrial base and know-how (see model in Appendix A). Drawing on Stewart and Shirvan's work, the cost structure for large reactors is based on historical data from US reactor series, while the SMR cost structure is adjusted for modularisation impacts as outlined in a McKinsey report (Bertram et al., 2019). Fast and slow-end learning rates are designed to match historical learning in French and Korean reactor series deployments, illustrated in Fig. 2. For SMRs, NOAK units are assumed to have an additional 10% OCC reduction due to cost savings from co-siting multiple units. This conservative, low-end estimate is based on a literature review by Mignacca and Locatelli (Mignacca and Locatelli, 2020). Large LR construction lead times are also expected to decrease with the deployment of additional units in the context of industrial recovery and stable regulation. Electricité de France (EDF) reports observed acceleration between the construction of the first and second HPC units, ranging from 25% to 45% (Hinkley Point C., 2022). While significant timescale accelerations are expected compared to FOAK projects, which were severely delayed, industry claims should be approached with caution. Therefore, an acceleration rate of 20% is applied to delays (excluding scheduled construction time) in a fast learning scenario. In a slow learning scenario, a more conservative rate of 8% is used, more in line with historical experience (Stewart and Shirvan, 2022). There are indeed concerns about slow learning rates on decade-long construction sites, due to labour constraints and regulatory changes, which is driving the development of modular reactors in more industrial settings. Learning rates also rely on a stable regulatory landscape and long-term societal commitments on infrastructure that looks ahead a century, factors which lacked in the past two decades.

2.3. The weight of financing new nuclear utilities

In addition to capital costs, the financial structuring, borrowing rates and payback terms of a NPP project have a major impact on its performance, likely doubling total costs over the project lifetime. Unlike a gas-fired plant, a NPP has comparatively low operating costs, but requires large volumes of capital to be raised to finance its construction, necessitating heavy borrowing on which interest accumulates exponentially over relatively long construction times. The competitiveness of the most capital-intensive energy technologies, such as dams and nuclear power stations, therefore primarily relies on the cost of capital, which derives from interest rates on the project. Built at low cost of capital, conventional LRs are the cheapest source of energy production, but quickly become uncompetitive as interest rates rise (Nuclear Energy Agency (NEA), 2022). Increasingly volatile financial conditions, driven by more frequent crises, are raising uncertainties about the ability to commit to funding a substantial, long-term nuclear programme and the ability to meet the deployment targets set by governments.

The cost of capital for a project is measured using the Weighted Average Cost of Capital (WACC), denoted as r, the main factors of which are set out in the formula below. Both the cost of capital and cash flows are considered in real terms in the analysis, meaning that the value flows over the years, represented in $£_{2024}$, are not adjusted for inflation.

$$r = \alpha[\overbrace{(R_f + \delta_c)}^{\text{cost of debt}} - \tau] + (1-\alpha)\overbrace{(R_f + \beta \times R_s + \sum R_{ext})}^{\text{cost of equity}} \quad (1)$$

With α the debt:equity ratio, R_f the risk-free rate, δ_c the credit spread, τ the tax rate, β the "asset beta" referring to the correlation between the project and market risk, R_s the systemic market risk, and R_{ext} the idiosyncratic risks, or project-specific risks for which shareholders demand compensation—such as construction risks or illiquidity premiums for nuclear investments. WACC is primarily a measure of project risk,

and a function of risk management and risk allocation. The riskier the project, the higher the returns required on the capital lent or invested. Risk can also be directly measured through the debt:equity ratio α: The safer the project, the more debt it tends to contract, as debt is generally less costly than equity. The cost of capital is typically around 10% real for a private project, and around 4%–6% real for public investment, as governments have access to the lowest borrowing rates in the economy and accept lower returns on investments considered strategic.

The deep uncertainties weighing on the WACC justify the use of an exploratory approach to examine multiple plausible futures and the need to identify strategies that remain robust under diverse WACC scenarios. They are mainly due to the volatility of government bond rates (or "risk-free" rate), and the market-related perceived risks of nuclear assets, which affect their attractiveness to investors. The risk-free rate reflects unpredictable macroeconomic and geopolitical changes: While weak growth and growing confidence in governments led to zero or even negative borrowing rates in developed countries between 2016 and 2021, rates soared in 2022 in response to inflationary pressure following the Covid pandemic and the Ukraine invasion, and have since shown unusual volatility (Office for Budget Responsibility (OBR), 2024). With regard to market-related risk, the correlation of the risk or asset beta is typically more important than the systemic risk itself, and is shaped by broader shifts in policy, market dynamics, and public perceptions. A recent report by the Nuclear Energy Agency (NEA) on the prospects for financing new nuclear power highlights that the economic risks of nuclear power generation are effectively independent of broader market risks, a valuable attribute reflecting a high degree of risk insulation and analytically referred to as a zero asset beta (Nuclear Energy Agency (NEA), 2022). Indeed, the production of low-carbon energy tends to thrive when fossil fuels stumble, and fossil fuel production remains, to date, closely correlated with the overall performance of the economy. The report also highlights that stricter carbon emission constraints gradually make decarbonised means of production appear increasingly derisked in the global market. Investing in nuclear assets therefore emerges as an attractive strategy for diversifying the risk profile of a private portfolio, and investors should be willing to accept lower returns on a derisked investment. In practice, the zero asset beta hypothesis is not currently illustrated in the cost of capital of recent projects and, more generally, by investor appeal to nuclear projects. The delay to work on the HPC site caused by the Covid-19 pandemic, leading to construction cost estimates doubling from £18 to £35 billion (2015 prices), also highlighted the non-hermetic nature of NPP projects in relation to market risks. The study therefore considers the possibility of an asset beta varying between zero and a more standard unit value, which could be influenced over the decades by global economic conditions and enforced environmental policies. The systemic risks and the credit spread for investment-grade assets (BBB or Baa and above) are assumed constant in this study, as an evaluation of equity and credit spreads in the United States from 1970 to 2015 proved that they are in the long term found to remain close to historical averages (Rachel and Summers, 2019).

2.4. The integration in the energy mix

While large uncertainties surround NPP construction, nuclear production from light-water reactors is acknowledged to have reached record and resilient operating levels over the last decades. Reaching load factors of up to 90%, NPP typically serves as a baseload, with more flexible means of operation such as gas-fired power plants adapting their production according to electricity demand. Nevertheless, higher renewable and low-carbon penetration in the energy mix can impact plant operating levels. In countries with largely decarbonised grids like France, NPP load factors are for example reduced to 70%–80%. SMRs, marketed for their flexibility and ability to load-follow to meet peak and intermediate demand, could be primarily affected by reduced operational levels. Indeed, large-scale units benefit from economies of scale, achieving lower marginal/operational costs when operating continuously at full capacity, securing their position as priority baseload in the Merit Order. In the UK, simulations carried out by the National Energy System Operator (NESO) show that SMR units could reach load factors as low as 50%–55% with higher renewable penetration, economically preventing their deployment after 2040 (National Energy System Operator (NESO), 2023). Technical solutions are under consideration to maintain higher load factors, such as producing hydrogen or running direct air capture during periods of low demand, but there are currently no planned rollouts of such projects in the UK. This study evaluates the impact of potential exogenous limitations from the grid that reduce SMR asset utilisation, either within an energy system that allows units to run at full potential capacity (93%), or when facing load-following limitations similar to those in the French grid (80%), or as captured in NESO integrated energy system simulations for a more intermittent 2050 energy mix (55%). Operational impacts on LRs are not considered here, as the scenarios studied assume substantial fleet deployment of both LRs and SMRs, although they may eventually be affected in low-flexibility, renewables-heavy grids. The flexibility value of SMR and LR units, which is dependent on the rest of the energy mix, is not accounted for in this study. This presents a significant avenue for future work that would integrate the entire energy system, particularly as LRs are found to play an increasingly important role in the French capacity market as the contribution of renewables rises, representing half of the certified reserve in 2025 (Réseau de transport d'électricité (RTE), 2025).

3. Comparing regulated and contractual market models

Revenue Support Mechanisms (RSMs) have been introduced in the UK to support the development of low-carbon technologies. Notably, the introduction of Contract for Differences (CfD), guaranteeing electricity sale prices, is unanimously recognised for having supported the rapid expansion of renewable generation. More recently, the Nuclear Energy (Financing) Act of 2022 has introduced a new financing and revenue framework called Regulated Asset Base (RAB) for NPP projects (UK Parliament, 2022). To date, and despite the fact that other funding models have been adopted overseas, the UK government has no plans to introduce new financing frameworks beyond the CfD and RAB (Department for Energy Security and Net Zero (DESNZ), 2024a.). This study simulates and compares the overall performance of CfD-backed project finance and RAB frameworks, at the scale of a NPP project and the UK nuclear programme, in the light of the technical and economic uncertainties presented previously mentioned. It highlights the more resilient nature of regulated frameworks to real-life uncertainties, bringing common benefits to both consumers and investors.

3.1. Presentation of revenue mechanisms

A CfD artificially provides a power plant with a guaranteed electricity price, known as the strike price. The supplier sells electricity on the market at the wholesale market price, and if the market price is lower than the strike price, government undertakes to pay the difference. Reciprocally, the supplier commits to paying back its surplus to government if market price stands above the strike price. CfDs are praised for having allowed a rapid growth of renewable generation in the UK by providing greater return certainty to industry facing market price risks. Competitive call for tenders have also driven strike prices down, making them typically comparable to customary wholesale electricity prices, and notably lower during periods of market tension (Department for Energy Security and Net Zero (DESNZ), 2024c). Since the mechanism support is only provided after commissioning, the developer has to resort to traditional project and corporate financing to carry the project to this point, taking on all construction, regulatory, and licensing risks. In 2017, a 35-year CfD was awarded to HPC's NPP project, financed

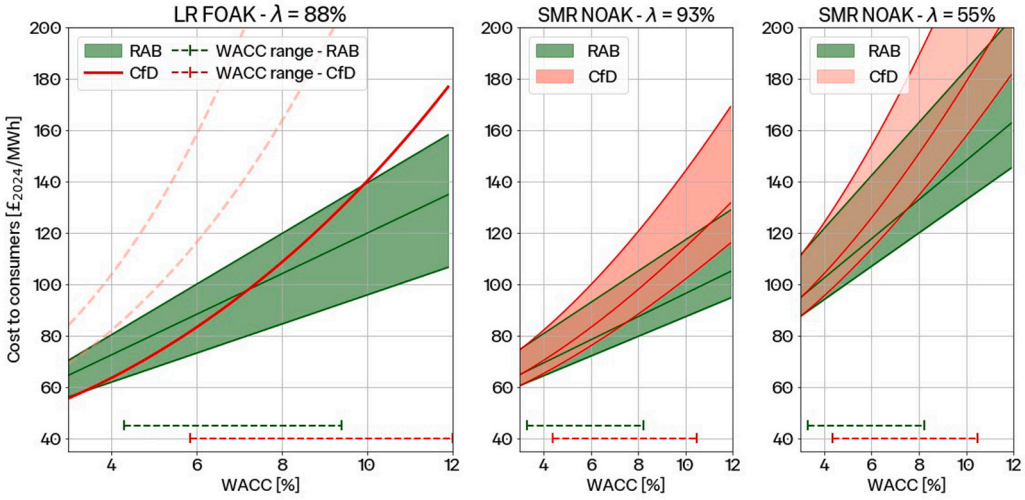


Fig. 3. Levelised cost to consumers of NPP projects related to the cost of capital and load factor λ, for CfD and RAB revenue mechanisms.

by private investors at a post-tax nominal WACC of 9.2% at time of investment decision, resulting in a strike price above market prices of £92.5/MWh in 2012 prices, or £129/MWh in 2024 prices (National Audit Office (NAO), 2017; Nuclear Sector Deal, 2020).

The RAB model is a financing approach used for infrastructure projects where the asset value is used to determine an allowable revenues to investors from the construction phase to decommissioning, thus providing them with a revenue stream before the project becomes operational. This revenue is set by a regulatory body throughout the project's lifetime to cover operating costs, asset depreciation, and a predetermined rate of return on investment through ex-ante price control. Although the model used here ideally assumes that the revenue derives directly from the present asset value, assuming straight-line depreciation, RAB works in practice similarly to a CfD when the plant operates, with the strike price readjusted every five years to reflect the predetermined return on investment. Prior to commissioning, the tariff charged to consumers through a premium on electricity bills pays the interest on the contracted loans and equity funding continuously, stabilising the debt to the principal amount only, which would otherwise grow exponentially as a result of years of compound interest. The framework also allows construction risk to be partially shared with consumers by aggregating a share of cost overruns into the asset value, thereby reflecting them in long-term electricity prices. By spreading construction risks across all consumers, RAB reduces the economic cost of that risk. Two contractual parameters characterise the terms of risk sharing: (1) the co-sharing ratio, which specifies the fraction of cost overruns passed on to consumers through increased long-term electricity prices—unshared overruns result in a net loss to investors, and (2) a potential funding cap, defined as a limit beyond which investors are no longer liable for cost overruns, and government steps in by providing backstop equity funding. In the same way that the risks of delays are shared, potential underspend relative to expectations is inversely shared with the consumer. The greater certainty of returns provided by RAB helps capture low-interest investments, reflected in a lower cost of capital for heavily capital-intensive infrastructure. The RAB model has been in practice in the UK since the 1990s to regulate newly liberalised essential utilities such as water and gas, to control consumer prices and prevent companies from extracting monopoly profits. More recently, it has been used in 2016 to finance the Thames Tideway Tunnel, a major London sewer infrastructure project, at a real WACC as low as 2.5%, and was selected to be employed for the forthcoming replica of the HPC NPP project, Sizewell C (SZC).

3.2. Project-scale comparison

For a given NPP project under uncertainty, Fig. 3 compares CfD-backed project finance and RAB performance in terms of levelised cost of electricity (LCOE) to the consumer, and its reliance on the cost of capital. The RAB co-sharing ratio is by default set at 50%, and the funding cap at 150% of contractual cost expectations. RAB calculations are based on the assumption that, in an optimistic and competitive market, cost expectations for SMRs are priced at a low level, with any excess costs treated as overruns. The LCOE over the plant lifetime corresponds to the strike price under CfD, and under RAB is calculated by a discounted aggregation of prior and post-commissioning charges, accounting for cost-overrun sharing and government-injected equity beyond the funding cap, which is assumed to be fully passed down to taxpayers. Cost and schedule characteristics for a LR and a SMR NOAK (5th Unit) are derived from Table 1 and run through an economic model detailed in Appendix A. The impact on consumer costs of potential cost overruns for LRs and capital cost uncertainties for SMRs are represented by uncertainty bands in Fig. 3. The deterministic LCOE curve for a LR operating under a CfD framework reflects that all overrun risks are fully absorbed by the developer in absence of risk-sharing mechanism. The subsequent dotted curves indicate what would be the cost penalty to the consumer if investors were to be compensated for cost overrun investments. The abscissa intervals indicate the estimated range of the project's WACC to be secured under each contract, for fully privately funded projects, calculated from Eq. (1) and under the economic conditions and uncertainties outlined in Table 1. The WACC valuation assumes a standard 70:30 debt:equity ratio, and includes compensation for project-specific risks, such as foreseeable construction delays and challenges related to investment illiquidity. The illiquidity premium is set at 0.01% and 0.03% per month of planned construction for lenders and equity investors, respectively. The construction risk premium is conservatively estimated as the net loss in investor rate of return (IRR) under the most adverse scenario of delay considered for each project.

The comparison of LCOE under CfD and RAB for NPP projects highlights CfD-backed project finance's vulnerability to rising interest rates. Under CfD, the cost to the consumer grows exponentially with the cost of capital due to the accumulation of compound interest during construction. The more capital-intensive a project, the more susceptible it also is to increasing costs of capital, as demonstrated by comparing large-scale projects with SMRs. Conversely, RAB, by paying interest continuously, proves more resilient to unfavourable economic conditions and crises, with the LCOE increasing only linearly with the cost of capital.

When examining the WACC valuation range under both frameworks, it is also observed that the cost of capital can be significantly reduced under regulated conditions. A regulated income and risk-sharing mechanisms provide greater return certainty to investors, reducing construction risk premiums from 3%–4% of additional real WACC under CfD to less than 2% real WACC premium under RAB. In a traditional project finance scheme, a 3% increase in real WACC to compensate investors for the risk they are taking – from 7% to 10% – results in an electricity price increase of around 50% to consumers, which is greater than the cost of partially supporting large cost overruns with a real WACC below 9% under RAB. Put simply, the cost to consumers of inflated interest to compensate investors for the construction risks they undertake under project finance is greater than the cost of partially sharing these risks in a regulated scheme.

Overall, if government backing enables the financing of a LR project at low cost of capital (<4%) through direct investments or loan guarantees, CfD would provide better value to consumers, notwithstanding the potential additional impact of government support on taxpayers. This is because the impact of compound interest at a low WACC is less than the potential costs associated with sharing construction risks. However, this scenario would not be feasible for privately financed projects, which inherently have a higher WACC to reflect the risks borne by investors in CfD-backed financing. RAB, meanwhile, allows privately funded projects to be financed at lower cost. It also quickly becomes more cost-effective as interest rates rise in the economy, with the LCOE under CfD at a WACC of 10% equivalent to which of an 8-year delayed project under RAB.

When comparing a series of SMRs with a LR operating at similar levels, SMRs benefit from a lower cost of capital due to their inherently swifter payback period and shorter investment cycle, whereas large projects have the advantage of greater economies of scale, provided the project is kept under reasonable delay. Overall, given the uncertainties involved, the costs of the technologies are comparable and it comes down to the leveraging of a sufficient level of learning of one and the project management of the other to determine which is more competitive. It should be noted, however, that since economies of scale are best manifested at low cost of capital, the introduction of a regulated scheme to finance large capital-intensive projects at favourable rates renews the economic attractiveness of LRs. While often portrayed as less competitive in a private financing context that extols the virtues of more flexible SMR investments, large reactors possess notable advantages, including established supply chains and reduced operational risks due to their prioritised position in the Merit Order. At the same time, lower SMR load factors logically decrease plant competitiveness, with this effect amplified under higher costs of capital. When comparing the economic performance of an SMR operating at full capacity versus half-load, a low-operating asset proves more vulnerable to rising interest rates. This relationship reflects the principle that higher costs of capital increase the importance of asset utilisation. Regulated frameworks, therefore, appear similarly beneficial to SMRs, as lower WACC and regulated income can support more flexible operations.

3.3. Programme-scale comparison

To investigate how a revenue mechanism manages cost uncertainties on a larger scale, where significant learning is anticipated for both SMR and LR deployment, financial simulations are used to compare the performance of the UK's 2050 nuclear programme under RAB and CfD models. Fig. 4 illustrates three programme deployment scenarios assuming on-time delivery. These scenarios align with the UK's 2050 nuclear energy target, achieving 24 GW of operational nuclear capacity by 2050, while accommodating the potential considered delay ranges. Scenarios account for the decommissioning of nearly all currently operational nuclear capacity by 2028 in the UK and build upon construction and planned initiatives including: the ongoing construction of the HPC power plant, which began in 2018, its SZC replica with pre-construction

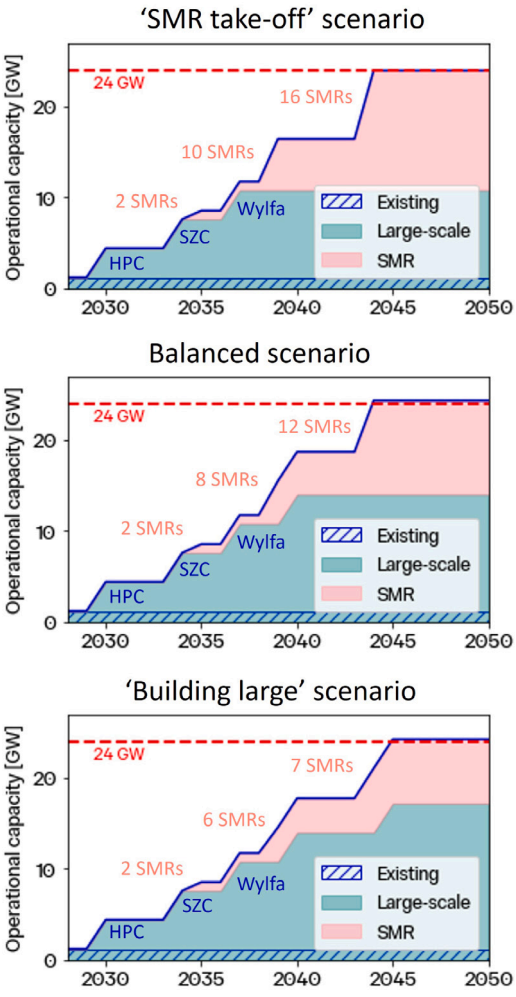


Fig. 4. Nuclear power deployment strategies for meeting the UK's 2050 target: 'SMR take-off', 'balanced', and 'building large' scenarios, represented assuming on-time delivery. Scenarios include UK projects under construction (HPC power plant), programmed (SZC power plant, UK SMR race end contenders), and future construction forecasts.

work underway and a pending final investment decision, a subsequent LR project at the Wylfa site, and UK SMR race end contenders which construction is expected to start in 2029. Future forecasts reflect, as far as is realistic, intermediate contractual targets of 3–7 GW every five years between 2025 and 2045. LRs are typically built in pairs and contracted periodically from 2025 onwards, while SMR FOAK projects start construction in 2029, with industrial capacity progressively scaling up after 2035 and into the 2040s. They differ in their relative share of technology deployment, adopting LR:SMR ratios of 11:13 GW, 14:10 GW, and 17:7 GW, respectively. The 'SMR take-off' strategy limits LR construction to currently considered government plants, with three EPR pairs (HPC, SZC, Wylfa) adding 11 GW of LR capacity by 2040. The SMR sector expands significantly with 28 reactors deployed by 2044, totalling 13 GW. While this scenario aligns with government announcements, it misses the interim deployment target between 2030 and 2034 and raises concerns about Europe's industrial capacity for rapidly scaling up to 26 small reactors over 15 years from 2035 to 2050. The 'balanced expansion' scenario equally divides future construction between large and small reactors, each contributing around 10 GW, with the construction of 4 LR pairs and 22 SMRs over the next 20 years. Finally, the 'building large' strategy focuses on proven large-reactor technology, leveraging established LR supply chains and replicating the HPC project at multiple sites to add 17 GW of new capacity, while maintaining steady SMR growth with 15 reactors over 20 years.

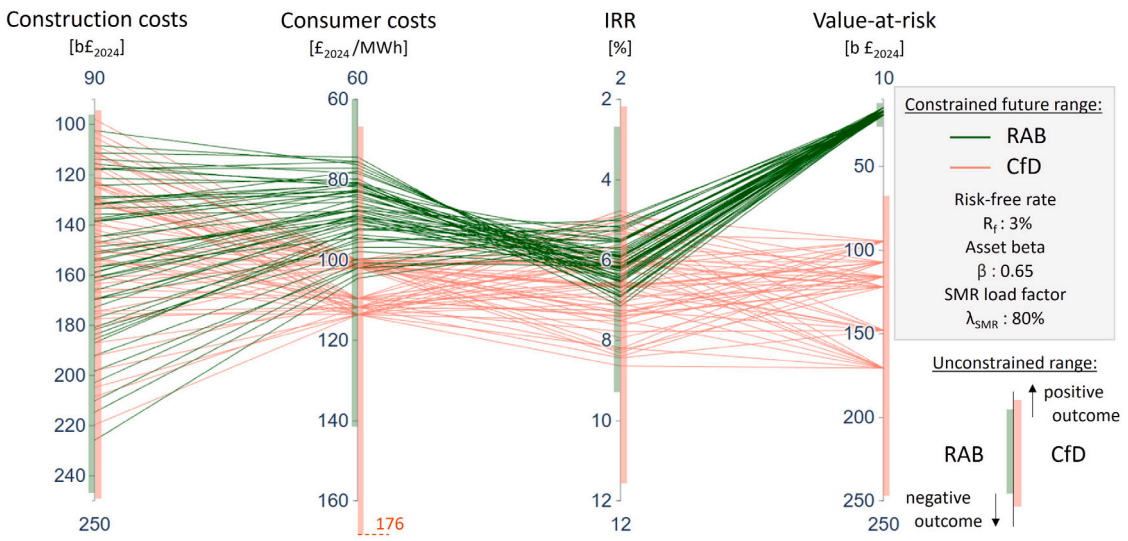


Fig. 5. Comparison of CfD and RAB revenue mechanisms for UK nuclear programme deployment scenarios (SZC and subsequent projects) under a constrained standard economic future, alongside an unconstrained performance range for the futures listed in Table 1.

Fig. 5 compares the performance of deployment strategies under CfD and RAB by evaluating the project costs of projects for which investment decisions are yet to be made (SZC and subsequent projects), considering the uncertainties outlined in Table 1. The performance of the programme is assessed using indicators reflecting the interests of various stakeholders, quantifying construction costs, consumer costs or LCOE, Investor Rate of Return (IRR), and Value-at-risk (VaR) measuring financial contingencies. In the vulnerability plot, each line represents the performance of a given strategy under a specific future. To manage the large multidimensionality and enhance readability, the performance of revenue models is highlighted under median economic conditions and a mid-range 80% SMR load factor, while unconstrained result ranges are also displayed on the plot. An outcome pictured as positive is orientated towards the top of the graph, meaning that a strategy outperforms another when lines are above another. Crossing lines suggest a situation of trade-off between strategies and line spacing indicates the level of uncertainty related to a given strategy. Construction costs include OCC, interest during construction (IDC) and charges to consumer prior to commissioning under RAB, aggregated over all projects. LCOE is calculated similarly to Section 3.2 and averaged by plant energy production. IRR reflects averaged investor returns in the nuclear programme weighted by power plant capacity. It equals the project WACC if the project is delivered according to expectations. Low returns relative to expectations indicates additional costs and delays, and a requirement for high returns typically reflects high project risks for which investors expect to be compensated. The UK government typically sets returns for public infrastructure projects, including water utilities, at approximately 6%. Finally, the VaR quantifies the investment risk of a deployment strategy, serving as a measure of potential economic loss to investors in a worst-case scenario. In practice, for a given project, it is calculated based on its net present value (NPV) under the most unfavourable conditions outlined in Table 1, or equivalently, within the worst 95% uncertainty margins.

It may be observed in Fig. 5 that RAB overall outperforms CfD-backed project finance under the examined conditions. Construction costs remain comparable under the two schemes, though they are slightly higher under RAB in expected scenarios with reasonable economic conditions and moderate delays, due to the additional tariff charged to consumers prior to commissioning to pay returns to shareholders. However, under CfD, delays inflate IDC exponentially, and construction costs can end up similar or greater than under RAB, particularly in high interest rate conditions. The most striking comparison between the two schemes is the financial risk to investors measured by the VaR, which is divided tenfold under RAB under the influence of more stable, guaranteed revenues to investors, and construction risk-sharing mechanisms. Bearing lower risks, investors impose smaller construction risk premiums, and lower accepted returns to investors result in smaller cost to consumers through a lower cost of capital. Risk-sharing is also made evident on the graph, with cost uncertainties completely borne by investors under CfD being partially transferred to consumers under RAB. Consumer costs are thus admittedly more uncertain in a guaranteed return scheme, but significantly lower than under a competitive revenue one, so that the worst-case scenario under RAB still benefits the consumer. Greater price certainty to consumers under CfD comes indeed at a cost greater than risk-sharing under RAB, as investors demand higher returns to offset their additional risks. Construction risk-sharing mechanisms are therefore shown to deliver mutual benefits under standard economic conditions, providing value for money to consumers and greater return certainty for investors, and reflecting the principle that sharing a risk reduces the economic cost of that risk. This gap is expected to be narrowed or reversed under more clement economic conditions, where CfD compound interest effects are mitigated, and exaggerated under unfavourable and volatile economic environments.

4. Estimating the fiscal impact to government as a majority investor

Governments have a large role to play in supporting the deployment of a nuclear programme, including through direct financial support. Government financial backing can indeed enable access to lower-cost capital for nuclear capital-intensive projects and is strategic for supporting the gradual relaunch of the industrial sector, particularly as investor confidence is built while FOAK projects are proven and supply chains are established. Governments are also among the few investors in the economy capable of securing financing and endorsing the financial risks associated with large-scale nuclear plant projects without jeopardising their economic survival.

The fiscal impact of the announced nuclear power programme on the UK government has not yet been forecasted nor included in fiscal outlooks (Office for Budget Responsibility (OBR), 2024), raising concerns among public committees (Environmental Audit Committee (EAC) Chair, 2024). Government financial backing can take various forms and at different costs, notably through government-issued loan guarantees or direct government investment. Loan guarantees provide access to low-interest loans and are effective in reducing the cost

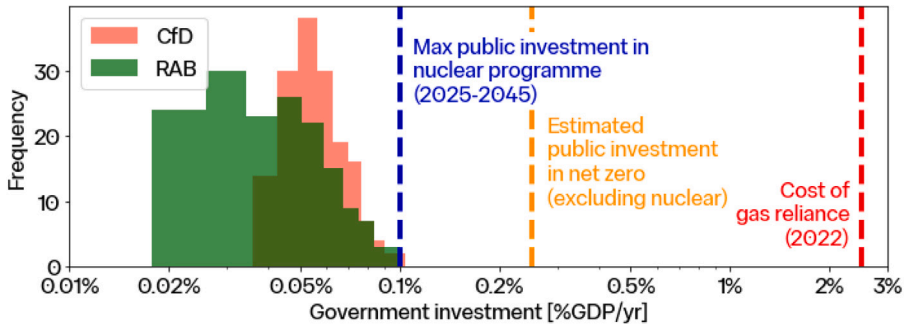


Fig. 6. The fiscal impact of investment and partial cost overrun socialisation to the government as a majority investor in the UK nuclear programme, set against broader public energy spending.

of capital for large infrastructure projects, which typically rely on substantial debt. These guarantees are perceived as relatively low-cost for the government due to the low likelihood of being called upon, especially for projects led by large, resourceful companies with government backing. In the US, the DOE's Loan Programs Office is committed to providing hundreds of billions in low-interest loans for new nuclear projects, supporting the Biden administration's target of deploying 200 GW of new nuclear capacity by 2050. However, contingent liabilities are highly visible in a country's financial statements and can ultimately impact government borrowing costs. In practice, the UK Parliament approves a cap on guarantees granted each fiscal year, and departments must demonstrate the ability to manage worst-case scenarios, meaning the government's capacity to issue these guarantees is proportionate to its reserves.

Direct government investment in nuclear projects is another way the government can support new deployments. A preliminary estimation of the fiscal impact of government direct investments as a majority investor in the UK nuclear programme, and the provision of partial cost overrun coverage, is evaluated relative to UK GDP in Fig. 6. This estimation assumes that the government remains the owner of the projects throughout their lifetime, without considering potential refinancing agreements upon successful demonstration or options such as selling the project, equity, or debt, which could release funds for subsequent investments. By not considering such optionality, the evaluated fiscal impacts represent a subset of potential outcomes, which are dependant on the programme's evolution. Nevertheless, it provides a useful approximation of what could be the cost to the government based on initial contractual agreements, without accounting for future arrangements that would alter today's cost assessment. This evaluation considers the deployment strategies in Section 3.3 and the uncertainties in Table 1, under both RAB and CfD revenue frameworks. In the assessed strategy, the government holds significant stakes in LR projects (80%) and SMR projects (70% for FOAK, 50% for NOAK), with a low project overrun cap (130% of contractual cost expectations), beyond which it covers the full investment cost. Given the lack of government involvement in the HPC project and the current 76.1% stake in the SZC project (Électricité de France (EDF), 2024), the modelled levels of involvement represent an upper-bound estimate of potential fiscal impacts. Government investment is measured as a discounted valuation of direct equity funding, including overruns. This also accounts for potential RAB equity injections beyond caps and return on investment to the investor state during the construction phase, set at 1.4% above the risk-free rate. This rate is lower than the more standard 3.5% and reflects the social discount rate recommended by the Stern report for climate change mitigation investments (Stern, 2007). UK GDP is assumed to grow at a real rate of 0.7% annually to 2045, consistent with 2023 and 2024 rates and conservatively overlooking the expected economic acceleration anticipated by 2026 (Office for Budget Responsibility (OBR), 2024).

Government direct investment and partial cost overrun coverage, with majority ownership in the nuclear programme (50%–80%), is assessed as carrying an uncertainty-adjusted cost of £10 to £60 billion (2024 prices), corresponding to £0.5 to £3 billion annually, or less than 0.1% of GDP per year over the next 20 years, potentially aggregating to 2% of GDP by 2045, not including return on investment to the investor state. In the most adverse scenario, 0.1% of GDP represents 0.25% of annual UK public spending, and aligns with low-carbon energy investments in other developed economies, which increased by 0.1% of GDP in France in 2022, 0.2% in Germany, and 0.2% in Italy, while it decreased by 0.2% in the UK (Office for Budget Responsibility (OBR), 2023). Annual public investment of 0.1% of GDP would total approximately 2% of GDP by 2045, to about a third of the 6% of GDP required to complete the net zero transition, as estimated by the Office of Budget Responsibility (OBR) (Office for Budget Responsibility (OBR), 2023). Public spending however remains under significant pressure due to rising debt levels across Europe. For example, UK government debt had tripled since the start of the century, hovering around 100% of GDP in 2024, the highest level in over 60 years. Policy-related fiscal risks are also growing as governmental aspirations outpace current resources. Nevertheless, future investments in low-carbon energy remain justifiable, as they are likely to be less costly than continued reliance on gas imports in a business-as-usual scenario. Nuclear deployment would enhance the UK's resilience to energy shocks, whose fiscal response to protect households and businesses cost government 2%–3% of GDP during the 2022 crisis alone. The OBR's latest fiscal risk report warns that gas volatility, under a business-as-usual scenario, could deepen public debt by an additional 13% of GDP by 2050 (Office for Budget Responsibility (OBR), 2024), underscoring the public interest in state investment to reduce dependence on gas imports and the need to integrate the potential impact of disruptions into policy appraisal methodologies.

It should finally be noted that conditions of large government investment levels differ under CfD and RAB. Under CfD, equity investments carry a higher opportunity cost in high-interest-rate environments, whereas under RAB, the state investor is entitled to higher returns under similar conditions. Consequently, RAB naturally eases the government's investment burden when the risk-free rate is high, though at the expense of greater consumer charges, and maximises investment when the cost of raising capital is low.

5. Discussion and conclusion

5.1. Novel insights generated by the RDM approach

Driven by the energy security and decarbonisation concerns surrounding the shift away from fossil fuels, Western economies are turning back to nuclear power, announcing ambitious energy targets for the coming decades. The launch of new civil nuclear programmes raises major financial questions about the ability to secure the volumes of capital needed for their construction, especially at a time when state finances are strained, and volatile economic conditions hinder long-term

commitments. Faced with technological and economic uncertainties, this RDM study shows that regulated financing models incorporating risk-sharing clauses perform more robustly than traditional private finance supported by a CfD, by offering better cost control and a more balanced distribution of risks, which in turn provides greater certainty in performance and stronger assurance for both public and private investments. Specifically, RAB is shown to reduce the impact of delays and rising interest rates on a project's economic performance and to lower investor risk tenfold, allowing to hope for private pools of capital to engage with new nuclear construction at a lower cost of capital. RAB also delivers value for money to consumers, as the benefits of securing a lower cost of capital outweigh the drawbacks of partial construction risk-sharing in a vast majority of scenarios. In terms of direct financial support, governments can employ mechanisms such as loan guarantees or equity stakes. By quantifying, under uncertainty, the fiscal cost to the UK government as a majority investor in its stated objectives, it is found that while the substantial investments must be evaluated against public debt levels, they remain consistent with the investment levels projected for the net-zero transition and are likely to be lower than the cost of continued gas dependency in the event of future energy shocks. Ultimately, the cost of capital remains the key determinant of the cost of nuclear power, underlining that the design of revenue mechanisms and the extent of government support will be critical to the success of forthcoming nuclear programmes.

From a broader perspective, there is a need for more robust and detailed planning for nuclear targets to come forth, including a more comprehensive risk assessment. The lack of structured methodologies for managing uncertainties and appropriate modelling prevents clear directional guidance and holds back mid-term decisions necessary to achieve the stated objectives. RDM, in contrast to traditional uncertainty assessment approaches, provides a systematic framework to address the profound uncertainties surrounding nuclear projects. By accounting for widely varying conditions, it enables a clearer mapping of risks, their consequences, and the most resilient decisions to effectively mitigate them. While significant uncertainties will inevitably remain, they must be acknowledged and integrated into robust, adaptive strategies that can remain flexible to technological advancements and macroeconomic shifts. Such approaches will not only improve the resilience of nuclear programmes but also enhance investor confidence and public trust, ultimately supporting the broader goals of achieving net-zero emissions and long-term energy security.

5.2. Model limitation and future evolution of RDM in nuclear policy analysis

As stated above, RDM allows for a broader exploration of possibilities by considering a more diverse range of plausible futures. It, however, holds limitations as to the following : (1) Exploratory methods require computing power and appropriate models to handle wide-ranging future conditions. For instance, testing 10 uncertain variables across n levels yields 10^n possible outcomes all of which need to be visualised and processed to inform decision-making. (2) The long-term future may be dominated by factors that are very different from the current drivers and hard to imagine based on today's experiences. In this case, unaccounted factors could for example emerge from net developments in the LR industry in a context of recovery, disruptive innovations from advanced reactor technologies, or unforeseen economic or regulatory shocks.

Notably, the study assumes large reactor projects are delivered on time at best, with an initial schedule spanning a decade and delays potentially doubling costs and construction times. While conservative, these figures align with the outcomes of Western nuclear projects over the past 20 years, during a period of industry stagnation. However, such performance levels are not universal. Countries like China and South Korea, which have continuously deployed reactors since the 1960s, achieve more consistent deliveries with shorter construction times (World Nuclear Industry Status Report, 2024). Western nations themselves historically demonstrated robust capabilities, as seen in the French nuclear programme of the 1980s, which connected 3–4 GW per year to the grid, often ahead of schedule and under budget. Recent developments, such as EDF's accelerated construction of the second HPC reactor and its pledge to build EPR2 reactors in France within six years, offer grounds for cautious optimism (Hinkley Point C., 2022; Électricité de France (EDF), 2024). Improved LR project delivery, particularly reductions in construction times, could significantly lower interest servicing costs and reshape industry dynamics. As for advanced nuclear technologies, disruptive innovation or the promise of modularity and serial production could lead to similarly surprising outcomes, much like the unexpected price trends of renewable energy over the past decade. As it remains challenging to determine which developments are most likely, decision-making under deep uncertainty approaches, such as RDM, can effectively guide governments in providing tailored and renewed support, thereby steering the industry towards achieving desired policy outcomes.

5.3. Policy implication 1 - Practical considerations in implementing regulated revenue models

In the UK, the RAB model is already widely recognised as more suitable for NPP projects than CfDs, notably under the influence of Newbery et al.'s work (Newbery et al., 2019), and is to be implemented in the forthcoming SZC project. The operational protection provided by a CfD for intermittent energy sources was indeed not designed in accordance to more nuclear specific risks related to financing and construction. Nevertheless, practical concerns remain regarding the implementation of a regulated revenue model. These include a lack of clarity on risk-sharing modalities, insufficient risk assessment, and limited definitions of extreme cases, which are critical to avoiding systematic socialisation of extra costs while maintaining incentives to minimise costs and delays. Additional concerns include the administrative costs of a RAB, which would likely be passed on to consumers (Expert Finance Working Group on Small Reactors, 2018), and potential distortive effect arising from RAB subsidies. Indeed, since cash flows under RAB depend on the value of the asset, the successful implementation of a RAB depends on the regulator's ability to accurately assess and monitor this value. Errors in the valuation of public utilities have historically been an issue in the UK, particularly during the privatisation processes of the 1990s, when infrastructure assets were often undervalued (Newbery, 1997; Whittington, 1994). A regulated framework with a predetermined rate of return also entails disconnecting an asset from market dynamics. For instance, while CfDs provide a guaranteed electricity price, they still reward production, meaning that a plant producing less as renewable penetration increases earns less over the years. In contrast, RAB could mitigate this effect if the strike price were readjusted every 5 years to reflect the same return on the initial investment. RAB could thus allow more flexible operational levels in a more decarbonised mix, but would ultimately risk that the cost of running a plant could be the same as the cost of not running it, with low asset utilisation suggesting a suboptimal energy system. Market integration of revenue mechanisms, including with increasingly important capacity markets, will more generally be key in the energy transition towards a more flexible energy mix. Addressing each of these considerations will require the introduction and standardisation of administrative processes and contractual clarifications.

5.4. Policy implication 2 - The question of raising the necessary capital

The most significant challenge in achieving a swift low-carbon transition lies in securing the substantial capital required to finance long-term, capital-intensive technologies. This challenge extends beyond the energy production system to include thermal refurbishment of buildings, electrification, and the decarbonisation of transport. If a

fraction of this capital is to be provided by the public purse, there is significant value, especially as governments approach the limits of their resources, to incentivise private pools of capital to contribute to the effort.

The limiting factor in the construction of new nuclear power plants over the past 25 years has been the inability of private investors to face up to the colossal financial risks involved. To put this in perspective, EDF, the largest European energy supplier and operator of over 60 GW of nuclear capacity, was renationalised by the French government in 2022 due to overwhelming financial pressures from the construction of three LRs totalling 5 GW at HPC and Flamanville, projects that represent the renewal of only 8% of its nuclear fleet. It appears therefore evident that owning nuclear assets under current conditions does not provide the financial backing to renew them. Consequently, the UK's ambitions to not only renew but also expand its historic nuclear capacity cannot be realised without strong government support to shoulder the financial risks faced by private investors. Potential investors have expressed interest, including fossil fuel companies aiming to secure their future in a decarbonised world, though many remain cautious due to perceived risks. Meanwhile, Big Tech companies, driven by rising data centre demands, are actively betting on advanced nuclear and the refurbishment of existing units (Penn and Plumer, 2024). Governments are also looking towards pension funds, whose direct infrastructure investments represented only 1.1% of their assets in 2018 according to the OECD annual survey (Organisation for Economic Co-operation and Development (OECD), 2018), yet they remain cautious about returns, particularly as their liabilities are tied to inflation-indexed salaries.

Raising capital for large nuclear projects backed by a CfD alone has proved challenging in the UK, as demonstrated by Hitachi's withdrawal from the Wylfa Newydd project in 2020, and motivated the introduction of RAB for nuclear (Department for Business, Energy & Industrial Strategy (DBEIS), 2019). Despite smaller risks related to SMR construction, experts also expressed concerns to secure private investment for FOAK projects through CfDs (Expert Finance Working Group on Small Reactors, 2018). Under RAB, lower risks and greater certainty and stability of project cash flows ease the challenge of raising the necessary capital. Loan guarantees, equity participation and tighter carbon constraints are some of the other ways that the government can hope to attract more private investment. Be that as it may, achieving the UK's nuclear ambitions will require coordinated action on all fronts, both public and private.

5.5. Policy implication 3 - The false choice of large versus small reactors

In the last decade, the debate in the nuclear sector has centred on whether SMR series hold greater economic potential than LRs (Mignacca and Locatelli, 2020; Locatelli et al., 2014; Carelli et al., 2008). Rather than demonstrating an absolute economic advantage at this date, LRs and SMRs possess distinct characteristics that perform well under different conditions. Historically, LRs have been developed within state-supported programmes with access to low cost of capital under which large projects leveraging significant economies of scale perform well. However, as the sector became privatised, smaller, less risky investments with quicker financial turnover became more appealing to private investors, driving the development of SMRs. When asking the question of what technology should be prioritised in coming years to achieve a swift energy transition, a suitable answer is that technology diversity adds both economic and operational value to the grid, and that the real question lays in what financial and revenue models for LRs and SMRs respectively could allow the grid to perform the best. In a privatised energy sector, SMRs naturally have the upper hand due to LR vulnerability to higher interest rates. Nonetheless, regulated models or approaches like the Finnish Mankala and French Exceltium models, where financial risks are distributed among multiple shareholders (Expert Finance Working Group on Small Reactors, 2018), can provide LRs with access to lower cost of capital and recreate the conditions under which it constitutes an attractive investment.

When however comparing technologies from a decarbonisation perspective, deployment strategies relying more heavily on advanced nuclear technologies results in steeper and further deployment timelines, reducing their ability to contribute to energy security and decarbonisation objectives in the short term. Regulated revenue models and government interventionism could steer deployment in favour of LRs, at the potential cost of involving greater public resources.

CRediT authorship contribution statement

J. Mangin: Writing – review & editing, Writing – original draft, Visualization, Software, Investigation, Formal analysis, Conceptualization. **M. Bluck:** Validation, Supervision. **G. Darch:** Writing – review & editing, Validation, Methodology. **D. Roberts:** Writing – review & editing, Validation, Methodology. **S. Brown:** Writing – review & editing. **M. Workman:** Writing – review & editing, Validation, Supervision, Project administration, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. The economic model in a nutshell

This appendix provides an overview of the economic model used to evaluate financial frameworks and policy impacts for the UK nuclear programme under diverse future conditions. CfD and RAB cashflow projections are adapted from Newbery et al. (2019). Learning-by-doing is modelled after the MIT TIMCAT framework by Stewart and Shirvan (2022), and the standard capital asset pricing model (CAPM) is used to estimate the weighted average cost of capital (WACC), with more details available in the NEA perspectives on financing nuclear new builds (Nuclear Energy Agency (NEA), 2022). Consumer costs are calculated over the project's lifetime using a time-dependent social time preference rate (STPR), denoted by ρ (%) in the model, which measures the time value of money. The specific time-dependent values of the STPR, sourced from the Green Book (H.M. Treasury, 2022), are presented in Table 3. A comprehensive list of symbols used in the analysis is provided in Table 2. The variables underlying the model are reorganised within the Robust Decision-Making (RDM) framework through the XLRM matrix in Table 4. This matrix structures the analysis around uncertainties (X), policy levers (L), relationships (R), and performance metrics (M), highlighting the study's aim to evaluate how strategies perform across diverse futures and identify robust, adaptive policies.

A.1. Learning rates

The model utilises multi-factor learning curves accounting for different reduction in the overnight capital costs (OCC) related to factory activities, labour and material in the project. Large-scale reactor projects are considered to have a cost structure of $C_f = 44\%$ factory, $C_l = 42\%$ labour, and $C_m = 14\%$ material, based on the cost breakdown of historic median experience PWR12 projects (Stewart and Shirvan, 2022). This structure is adjusted for highly modularised SMRs to $C_f = 51\%$ factory, $C_l = 33\%$ labour, and $C_m = 16\%$ based on an analysis of the median impact of modularisation on project costs, according to McKinsey & company (Bertram et al., 2019).

The evolution of the OCC of a n*th*-of-a-kind (NOAK) reactor K_n relatively to the first-of-a-kind (FOAK) unit K_1, as a function of the

Table 2
List of symbols of the economic model.

Symbol	Definition	Symbol	Definition
P	Reactor power (MW)	λ	Load factor (%)
K	Planned overnight capital cost (£$_{2024}$)	k	Overnight capital cost (£$_{2024}$/MW)
K^*	Overnight capital cost - delayed (£$_{2024}$)	k^*	Cost overrun (£$_{2024}$/MW/yr)
T/T^*	Construction time (yrs) scheduled/with delay	M	Plant lifetime (yrs)
c_0	Operation and maintenance - Fixed costs (£/MW/yr)	c_1	Fuel and operation and maintenance - Variable costs (£/MWh)
T	Scheduled construction time (yrs)	T^*	Construction time, with delays (yrs)
R_f	Risk-free rate (%)	β	Asset beta
R_s	Systemic risk (%)	R_{ext}	Idiosyncratic risk (%)
δ_{cs}	Credit spread (%)	δ_{ilp}	Illiquidity premium (%/mo)
R_{cons}	Construction risk premium (%)	R_{ilp}	Illiquidity premium (%)
R_d	Cost of debt (%)	R_e	Cost of equity (%)
α	Debt:equity ratio (%)	τ	Tax rate (%)
r	Weighted average cost of capital (%)	θ_T	Learning rate - Delay mitigation (%)
C_f	Cost structure share - Factory (%)	θ_f	Learning rate - Factory (%)
C_l	Cost structure share - Labour (%)	θ_l	Learning rate - Labour (%)
C_m	Cost structure share - Material (%)	θ_m	Learning rate - Material (%)
SDR	Social discount rate (%)	R_g	Cost of government equity (%)
α_g	Shares held by the state (%)	X	CfD strike price (£/MWh)
σ	RAB co-sharing ratio (%)	γ	RAB funding cap (%)
$\bar{T}$	Construction time to funding cap (yrs)	CC	Construction costs (b£)
$LCOE$	Levelised cost to consumers (£/MWh)	IRR	Investor rate of return (%)
VaR	Value-at-risk (b£)	GC	Government investment (b£)

Table 3
Time-dependent social time preference rate (STPR) (H.M. Treasury, 2022).

Year	0–30	31–75	76–125
ρ	3.5%	3.0%	2.5%

learning rates over factory-related, labour-related and material-related costs θ_f, θ_l and θ_m, respectively,is expressed as follows:

$$\frac{K_n}{K_1} = C_f \times (\frac{n}{N_0})^{log_2(1-\theta_f)} + C_l \times n^{log_2(1-\theta_l)} + C_m \times n^{log_2(1-\theta_m)} \quad (2)$$

With N_0 representing a reduction in the industrial learning potential of reactor factories, due to the non-novelty of many components already produced industrially, and for which significant learning has already been achieved. For a large-scale reactor, $N_0 = 10$, whereas $N_0 = 5$ for an SMR, modelling the potential of an SMR to modularise new reactor components, which until now had only produced on site.

Learning is also accounted in reduction of delays when replicating a large-scale reactor. The reduction of construction delays to commissioning for a NOAK project relatively to a FOAK is expressed as a function of the learning rate on construction delays θ_T:

$$\frac{T_n^* - T}{T_1^* - T} = n^{log_2(1-\theta_T)} \quad (3)$$

A.2. Cost of capital

The cost of equity R_e is calculated as follows:

$$R_e = R_f + \beta \times R_s + \delta^e_{ilp} \times 12T \quad (4)$$

With R_f the risk-free rate, β the "asset beta" representing the correlation between the project risks and the systemic market risk, R_s the systemic market risk, i.e. the market risk for a perfectly diversified portfolio, and $R^e_{ilp} = \delta^e_{ilp} \times 12T$ the illiquidity risk premium imposed by equity owners, and valued at $\delta^e_{ilp} = 0.03\%/mo$. In this study, the systemic risk is assumed at his long-term historical average $R_s = 5\%$ (Rachel and Summers, 2019). Various asset beta values are considered in the study, but a value of 0.65 is assumed in a median economic scenario, corresponding to the asset beta attributed to all of EDF's commercial activities in 2018 (Performance Review Body of the Single European Sky (PRB), 2019), which owns a majority of nuclear generation assets, including all currently operating nuclear plants in the UK.

The cost of debt R_d is then determined in the following equation:

$$R_d = R_f + \delta_c + \delta^d_{ilp} \times 12T \quad (5)$$

With δ_{cs} the credit spread, and $R^d_{ild} = \delta^d_{ilp} \times 12T$ the illiquidity risk premium imposed by creditors, and valued at $\delta_{ilp} = 0.01\%/mo$. In this study, the credit spread for investment-grade assets (BBB or higher) is assumed at his long-term historical average $\delta_c = 2\%$ (Rachel and Summers, 2019). The cost and share of debt could also be reduced by government-issued loan guarantees, which would effectively clear a large share of the credit spread on a portion of the debt.

Thirdly, the cost of government equity R_g can be expressed in terms of the risk-free rate R_f and the social discount rate SDR:

$$R_g = R_f + SDR \quad (6)$$

The social discount rate is set at $SDR = 1.4\%$, lower than the standard government investment rate of 3.5%, as recommended by the Stern Review for projects focused on mitigating climate change (Stern, 2007).

The WACC r is ultimately determined in Eq. (7) as a function of the debt-to-equity ratio α, the share of government-owned equity α_g, the tax rate $\tau = 25\%$, the costs of equity R_e, debt R_d, and government equity R_g, as well as the construction risk premium R_{cons}.

$$r = \alpha \times (1-\tau) \times R_d + (1-\alpha) \times [\alpha_g \times R_g + (1-\alpha_g) \times R_e] + R_{cons} \quad (7)$$

In the model, the construction risk premium is calculated by the potential investor rate of return (IRR) loss between a nominal on-schedule scenario and the most adverse cost and delay uncertainty scenario outlined in Table 1, corresponding to the worst 95% uncertainty margin. It is obtained by carrying out preliminary simulations of CfD or RAB models under the constraint $R_{cons} = 0$.

$$R_{cons} = |IRR^{nominal}_{R_{cons}=0} - IRR^{adverse}_{R_{cons}=0}| \quad (8)$$

A.3. Contract for Difference (CfD)

Considering a CfD project with a strike price X, the net present value (NPV) of the plant calculated at time of commissioning under construction uncertainty is:

$$NPV = \overbrace{-e^{r(T^*-T)} \int_0^T kPe^{rt}dt - \int_T^{T^*} k^* Pe^{rt}dt}^{\text{Construction costs}} + \overbrace{\int_0^M P[8760\lambda(X-c_1)-c_0]e^{-rt}dt}^{\text{Future cash flows}} \quad (9)$$

Table 4
XLRM matrix.

(X) Uncertainties ~5 independent uncertainties • LR Construction delay $T^* - T$ • SMR Overnight Capital Costs (OCC) K • SMR load factors λ • UK risk-free rate R_f • Market risk correlation factor ("asset beta") β	**(L) Policy Levers/Strategies** • Number of final investment decisions (FID) of large-scale nuclear or SMRs in years spans 2030–2034, 2035–2049 and 2040–2044 • Revenue support mechanism (RSM) : Project finance backed up by a contract for difference (CfD) or regulated asset base (RAB) • Under RAB, the level of risk sharing through the co-sharing ratio σ and the overrun cap γ • Direct government investment
(R) Models/Relationships • The regulated asset base (RAB) model, with an overrun cap (Newbery et al., 2019) • Project finance backed up by a contract for difference (CfD) (Newbery et al., 2019; Expert Finance Working Group on Small Reactors, 2018) • Multi-factor learning curve model (Stewart and Shirvan, 2022) • Capital Asset Pricing Model (CAPM) (Nuclear Energy Agency (NEA), 2022)	**(M) Performance metrics** • Construction costs CC (b£) • Levelised cost of electricity to consumers $LCOE$ (£/MWh) • Investor rate of return IRR (%) • Investment value-at-risk VaR (b£) • Government investment GC (b£)

With P (MW) the plant power, k (£/MW) the capital costs per unit of power, k^* (£/MW/yr) the cost overruns, T (yr) and T^* (yr) the construction time on schedule and with delays, respectively, r (%) the project WACC, M (yr) the plant lifetime, λ (%) the load factor, and c_0 (£/MW/yr) and c_1 (£/MWh) the fixed and variable operation costs, respectively. 8760 (h/yr) corresponds to the number of hours in a year.

Assuming perfect competition, the selected bid's strike price is assumed to reduce the NPV to zero, which allows to calculate the project strike price X in function of the project planned costs and the WACC:

$$X = \frac{c_0}{8760\lambda} + c_1 + \frac{k \times P \times (e^{rT} - 1)}{\lambda \times P \times 8760 \times (1 - e^{-rM})} \tag{10}$$

If construction risks were to be ex-ante reflected on the strike price, the later would be impacted as follows:

$$X = \frac{c_0}{8760\lambda} + c_1 + \frac{e^{r(T^*-T)} k P (e^{rT} - 1) + k^* P (e^{r(T^*-T)} - 1)}{\lambda P \times 8760 \times (1 - e^{-rM})} \tag{11}$$

Construction costs The project's construction costs, calculated in Eq. (12), correspond to the OCC, including cost overruns, as well as interest during construction (IDC), i.e., the interest accrued on the debt during the construction period before the project begins operation.

$$\begin{aligned} CC =& kP((1-\alpha)T + \alpha \overbrace{e^{R_d(T^*-T)} \frac{e^{R_d T} - 1}{R_d}}^{\text{IDC}}) \\ &+ k^* P((1-\alpha)(T^* - T) + \alpha \overbrace{\frac{e^{R_d(T^*-T)} - 1}{R_d}}^{\text{IDC}}) \end{aligned} \tag{12}$$

Levelised cost to consumers Under CfD, as shown in the formula below, the levelised cost to consumer $LCOE$ (£/MWh) over the project lifetime equals the strike price X and does not depend on the STPR ρ.

$$LCOE = \frac{\int_0^M X \times 8760 \lambda P e^{-\rho t}}{\int_0^M 8760 \lambda P e^{-\rho t}} = X \tag{13}$$

Investor rate of return (IRR) The IRR is defined for a project by $NPV(IRR) = 0$. Under a perfectly competitive process, the strike price is set in Eq. (10) so that if the project is delivered on time, the NPV calculated in Eq. (9) is zero. So, for a project delivered on schedule, the IRR is equal to the project WACC r. However, in the event of delays or cost overruns, the additional costs and shortfalls erode investors' returns and the IRR decreases. For a given lead time, the IRR can be calculated by solving Eq. (14).

$$\begin{aligned} NPV(IRR) = 0 =& -e^{r(T^*-T)} \int_0^T k P e^{IRR \times t} dt \\ &- \int_T^{T^*} (kPT + k^* P t) e^{IRR \times t} dt \\ &+ \int_{T^*}^{T^*+M} P[8760\lambda(X - c_1) - c_0] e^{-IRR \times t} dt \end{aligned} \tag{14}$$

Value-at-risk (VaR) The value-at-risk (VaR) of the project is calculated as the project's NPV under the most adverse conceivable costs and delay scenario. This is defined as the 95th percentile worst-case NPV from the probability distribution or, equivalently, the NPV calculated under the most adverse scenario outlined in Table 1.

Government investment Government injected capital through equity investments GC (£) up to the date of commissioning is calculated as follows:

$$\begin{aligned} GC =& (1-\alpha)\alpha_g K e^{R_g(T^*-T)} \frac{e^{R_g T} - 1}{R_g} \\ &+ (1-\alpha)\alpha_g k^* P \frac{e^{R_g(T^*-T)} - 1}{R_g} \end{aligned} \tag{15}$$

A.4. Regulated asset base (RAB)

The RAB is a regulated revenue mechanism under which investors' returns at time t, $r \times R_t$, are proportional to the asset value R_t over time, and earned from construction start to decommissioning. Regulated returns are charged to consumers through their electricity bills.

The model also includes risk-sharing measures with consumers in the event of cost overruns, measured by a cost-sharing ratio σ, and a funding cap γ beyond which investors are no longer liable for covering remote overruns, and the government injects backstop equity to bring the project to completion. Fig. 7 represents cash flows occurring during an EPR pair project under RAB, either on schedule (left) or in the case of an 8-year delay (right), assuming that $\sigma = 50\%$ and $\gamma = 150\%$. In the model, cost overruns are assumed to grow linearly with the project delay according to the formula:

$$Pk^* = \frac{K^* - K}{T^* - T} \tag{16}$$

Meaning that the time at which the funding cap is reached is:

$$\bar{T} = T + \frac{(\gamma - 1)K}{Pk^*} \tag{17}$$

During the lead time and before the cap is reached, the cost overruns are financed by the investors, but only $\sigma\%$ of these costs are incremented to the asset value R_t on which investors earn agreed returns, which equals $K + \sigma(K^* - K)$. After the cap is reached, the government finances the project by injecting equity which is not added to the asset value, capping it at $K(1 + \sigma * (\gamma - 1))$. The asset value at the time of commissioning R_{T^*} is therefore equal to:

$$R_{T^*} = min(K + \sigma(K^* - K), K(1 + \sigma * (\gamma - 1))) \tag{18}$$

The analysis assumes straight-line depreciation of the asset over its lifetime, meaning that the value of the asset decreases by an equal amount each year over its useful life. The asset depreciation D over its lifetime M is defined as:

$$D = \frac{R_{T^*}}{M} \tag{19}$$

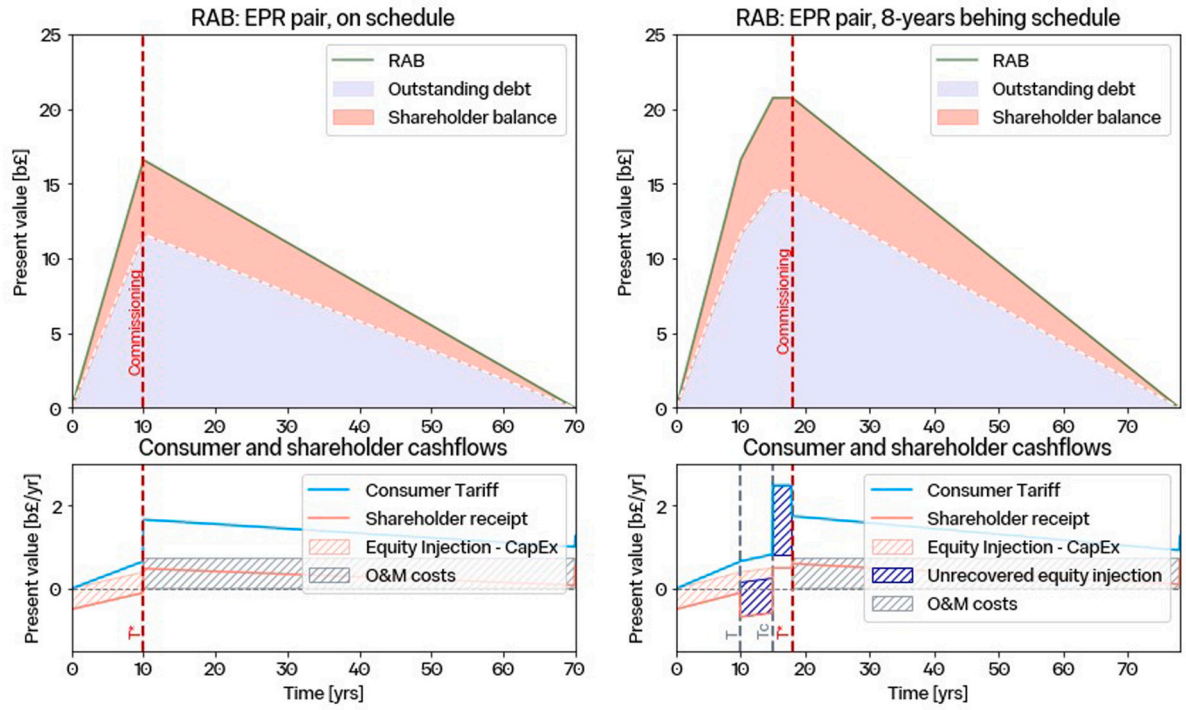


Fig. 7. Cost overrun management under a regulated asset base (RAB) model.

The equation below describes the evolution of the asset value R_t, which may be more directly referred to as the RAB, across successive project phases: during the planned construction period up to T, potentially extended by delays until the funding cap at $\bar{T}$, and possibly further until commissioning at T^*. Following commissioning, the plant operates until the end of its lifetime at $T^* + M$.

$$R_t = \begin{cases} kPt & \text{, if } t < T \\ K + \sigma k^* P(t - T) & \text{, if } T < t < \bar{T} \\ K(1 + \sigma(\gamma - 1)) & \text{, if } \bar{T} < t < T^* \\ R_{T^*} - D(t - T^*) & \text{, if } T^* < t < T^* + M \end{cases} \tag{20}$$

The cash flows for different stakeholders over the life of the project and contingencies are equated below. In the equations, parameters in bold indicate cost overrun management.

During operation, consumer charges cover the operation and maintenance (O&M) costs, depreciation of the asset, and returns to investors, leading to a levelised cost of electricity (LCOE - £/MWh) at time t equal to:

$$LCOE_t = \frac{c_0}{8760\lambda} + c_1 + \frac{r \times R_t + D}{\lambda} \tag{21}$$

The tariff to consumers as a whole CT_t (£/yr) is therefore expressed over the project lifetime in Eq. (22). Beyond the cap $t > \bar{T}$, it is assumed that the government injected equity $k^* P$ is passed down to consumers through their electricity bills or increased taxes.

$$CT_t = \begin{cases} rR_t & \text{, if } t < \bar{T}, \\ rK^* + \boldsymbol{k_p^* P} & \text{, if } \bar{T} < t < T^*, \\ c_0 P + c_1 \times 8760\lambda P + rR_t + D & \text{, if } T^* < t < T^* + M \end{cases} \tag{22}$$

Investor cash flows IC_t (£/yr) over the project lifetime, considering both equity owners and creditors, are evaluated in Eq. (23).

$$IC_t = \begin{cases} kP(rt - 1) & \text{, if } t < T \\ rR_t - \boldsymbol{k^* P} & \text{, if } T < t < \bar{T} \\ rR_{T^*} & \text{, if } \bar{T} < t < T^* \\ rR_t + D & \text{, if } T^* < t < T^* + M \end{cases} \tag{23}$$

When considering only equity funding, shareholder net receipts SC_t (£/yr) over the project lifetime are obtained in Eq. (24). The cost of equity equivalent, combining private and public shares, is defined as $\bar{R}_e = \alpha_g R_g + (1 - \alpha_g) R_e$. When covering cost overruns, the fraction σ of the cost which is shared with the consumer is financed by raising additional capital for the project, covered by additional debt and equity, at an additional cost for shareholders of $\sigma(1 - \alpha)k^* P$. The remainder of the cost $(1 - \sigma)k^* P$ is fully funded by the shareholders from their own resources, totalling $\sigma(1 - \alpha)k^* P + (1 - \sigma)k^* P = (\mathbf{1} - \boldsymbol{\alpha\sigma})\boldsymbol{k^* P}$.

$$SC_t = \begin{cases} (1 - \alpha)kP(\bar{R}_e t - 1) & \text{, if } t < T, \\ (1 - \alpha)\bar{R}_e R_t - \boldsymbol{(1 - \alpha\sigma)k^* P} & \text{, if } T < t < \bar{T}, \\ (1 - \alpha)\bar{R}_e R_{T^*} & \text{, if } \bar{T} < t < T^*, \\ (1 - \alpha)(\bar{R}_e R_t + D) & \text{, if } T^* < t < T^* + M \end{cases} \tag{24}$$

As for the state only, government net cash flows GC_t (£/yr) as an investor holding α_g of the shares and potentially stepping in to cover remote cost overruns above the funding cap are expressed as follows:

$$GC_t = \begin{cases} \alpha_g(1 - \alpha)k_p P(R_g t - 1) & \text{, if } t < T, \\ R_g \alpha_g(1 - \alpha)R_t - \boldsymbol{\alpha_g(1 - \alpha\sigma)k_p^* P} & \text{, if } T < t < \bar{T}, \\ \alpha_g(1 - \alpha)R_g K^* - \boldsymbol{k_p^* P} & \text{, if } \bar{T} < t < T^*, \\ \alpha_g(1 - \alpha)(R_g R_t + D) & \text{, if } T^* < t < T^* + M \end{cases} \tag{25}$$

Construction costs: Construction costs, calculated in Eq. (26), include overnight capital costs (OCC), and interest during construction (IDC), i.e. under RAB, the interest paid on the asset value to investors (both shareholders and creditors).

$$CC = \overbrace{K^*}^{\text{OCC}} + \overbrace{\int_0^{T^*} rR_t dt}^{\text{IDC}} \tag{26}$$

Levelised cost to consumers The levelised cost to consumers $LCOE$ (£/MWh) integrates all consumer cash flows paid over the project lifetime, including for the time-value of money through a STPR ρ, using the commissioning date as a reference point. The accumulated

Table 5
Sources and justifications for problem parameters in contemplated futures listed in Table 1.

Parameter	Data	Source
Large-scale nuclear reactor (LR) costs		
Overnight capital costs (£$_{2024}$/kWe)	5000–9000	Based on recent EPR reactor construction in Europe (Olkiluoto (FIN), Flamanville (FR), Hinkley Point C (UK)), FOAK projects in their respective countries faced large delays and overruns (Buongiorno et al., 2018; Newbery et al., 2019).
Construction time (yrs)	10–18	Based on recent EPR reactor construction in Europe (Olkiluoto (FIN), Flamanville (FR), Hinkley Point C (UK)), FOAK projects in their respective countries faced large delays and overruns (Buongiorno et al., 2018; Newbery et al., 2019).
Load factor (%)	88	A ~90% load factor is typical for good performance of a traditional large-scale reactor. 88% corresponds to the load factors achieved by the Taishan-II (CHN) and Olkiluoto (FIN) EPR reactors in 2023 (International Atomic Energy Agency (IAEA), 2025).
Fuel costs (£$_{2024}$/MWh)	4.5	Industry estimates of the O&M costs of Dutch large-scale nuclear plants (Converted from €$_{2011}$ to £$_{2024}$) (Bles et al., 2011).
O&M - Fixed costs (£$_{2024}$/kW/yr)	80	Industry estimates of the O&M costs of Dutch large-scale nuclear plants (Converted from €$_{2011}$ to £$_{2024}$) (Bles et al., 2011). Consistent with recent UK studies (Newbery et al., 2019).
O&M - Variable costs (£$_{2024}$/MWh)	13.5	CE Delft report on the costs of Dutch large-scale nuclear plants (Converted from €$_{2011}$ to £$_{2024}$) (Bles et al., 2011). Consistent with recent UK studies (Newbery et al., 2019).
Small Modular Reactor (SMR) costs		
Overnight capital costs (£$_{2024}$/kWe)	6500–9750	Rolls-Royce SMR OCC probability distribution study (Monte Carlo, 5th–95th percentiles) (Agar et al., 2018).
Construction time (yrs)	2.5–7	SMR construction time ranges given in a government-commissioned report from the Expert Finance Working Group on SMRs (Expert Finance Working Group on Small Reactors, 2018)
Load factor (%)	55-93	Low-end value originates from NESO Future Energy Scenarios 2023 simulations (National Energy System Operator (NESO), 2023). High-end value corresponds to SMR vendor claims.
Fuel costs (£$_{2024}$/MWh)	4	A 10% reduction from LR fuel costs is assumed due to longer fuel cycles. This assumption is design-dependant. Fuel costs have little influence on end results.
O&M - Fixed costs (£$_{2024}$/kW/yr)	105	30% increase in O&M costs for SMRs vs. LRs due to loss of economies of scale, a central assumption from a review of existing SMR cost studies (Mignacca and Locatelli, 2020).
O&M - Variable costs (£$_{2024}$/MWh)	17.5	30% increase in O&M costs for SMRs vs. LRs due to loss of economies of scale, a central assumption from a review of existing SMR cost studies (Mignacca and Locatelli, 2020).
NOAK OCC co-siting economies (%)	10	10% OCC reduction by siting multiple SMR NOAK units at the same location, a low-end conservative assumption from a review of existing SMR cost studies (Mignacca and Locatelli, 2020).
Learning-by-doing		
LR cost structure		Cost structure of American PWR12 reactors with median experience (Stewart and Shirvan, 2022)
SMR cost structure		SMR-adjusted cost structure for median modularisation impacts as outlined in a McKinsey report (Bertram et al., 2019)
Learning rates	Slow - Fast	Designed to reflect learning American experience (Stewart and Shirvan, 2022), and mirror historic reactor series (Fig. 2). Conservative assumptions are made to account for limiting learning emerging from existing industrial know-how (See Appendix A)
LR delay reduction rate	8%–20%	EDF claims 25%–45% construction acceleration between HPC's first and second units (Hinkley Point C., 2022). A conservative margin and halved learning rate are applied to industry claims. Learning impacts only potential additional delays beyond the scheduled 10-year construction time.
Macroeconomic and Financial data		
Risk-free rate (%)	1–5	Reflecting 10-year gilt yields over the past 30 years (UK Debt Management Office (UK Debt Management Office (UKDMO), 2025)).
Asset Beta	0–1	0 asset beta for nuclear power advocated by a 2022 NEA report (Nuclear Energy Agency (NEA), 2022), to 0.65 attributed to EDF activities in 2018 (Performance Review Body of the Single European Sky (PRB), 2019), to a standard unit value.
Systemic risk (%)	5	Based on Rachel and Summers' evaluation of U.S. equity spreads (1970–2015), which remain near historical averages despite local volatility (Rachel and Summers, 2019).
Credit spread (%)	2	Based on Rachel and Summers' evaluation of U.S. corporate bond spreads (1970–2015), credit spreads for investment-grade assets (BBB/Baa and above) remain stable at 2% (Rachel and Summers, 2019).
Social discount rate (%)	1.4	1.4% SDR for climate mitigation assets, based on the 2006 Stern Review (Stern, 2007).

consumer payments to commissioning A (£) and the net present value of future payments to investors F (£), are expressed as follows:

$$A = \int_0^{T^*} rR_t e^{\rho t} dt + e^{\rho(\bar{T}-T)} \int_{\bar{T}}^{T^*} k^* e^{\rho t} dt \tag{27}$$

$$F = \int_0^{M} (rR_t + D) e^{-\rho t} dt \tag{28}$$

The net present value of future energy generation E (MWh) is then calculated:

$$E = \lambda P \times 8760 \int_0^{M} e^{-\rho t} dt \tag{29}$$

Finally, the levelised cost to consumer $LCOE$ (£/MWh) covers for O&M costs, and consumer tariffs to investors before and after the commissioning date:

$$LCOE = c_0 P + c_1 \times 8760 \lambda P + \frac{A+F}{E} \tag{30}$$

Investor rate of return (IRR) The IRR is defined for a project by $NPV(IRR) = 0$. For a project delivered on schedule, all investor expenses are incremented in the RAB on which they earn agreed returns at the WACC r. Therefore, if on schedule, the project NPV is zero and the IRR is equal to the project WACC r. However, in the event of delays or cost overruns, cost overruns only partially incremented to the RAB erode investors' returns and the IRR decreases. For a given delay, the IRR can be calculated by solving Eq. (31):

$$0 = \int_0^{T^*+M} IC_t e^{-IRRt} dt \tag{31}$$

Value-at-risk (VaR) The value-at-risk VaR of the project is calculated as the project IRR under the greatest conceivable delay for the project, defined as 95th quantile of the delay probability distribution.

Government investment Government investment $\bar{GC}$ (£) is measured by integrating all government cash flows up to the date of commissioning, accounting for invested capital, earned returns on that capital during construction, and potential equity injection if remote cost overruns occur.

$$GC = \int_0^{T^*} GC_t dt \tag{32}$$

A.5. From project to programme...

The models in Appendices A.3 and A.4 evaluate the economic performance of a single NPP project from multiple stakeholder perspectives. To assess the entire UK nuclear programme, these project performances are aggregated into the metrics outlined below. The timeframe of the programme, with one project starting T_0 years after another, is accounted from the consumers' perspective by offsetting the value of the STPR ρ by T_0 years. From the investors' perspective, there is no impact, as all the variables are considered in real terms.

Construction costs The total construction cost of the UK nuclear programme is the sum of the construction costs of each of its singular projects, calculated in real term:

$$\bar{CC} = \sum_1^n CC_i \tag{33}$$

Levelised cost to consumers The levelised cost to consumers of nuclear-generated electricity during the programme is calculated as the weighted average levelised cost of electricity (LCOE) for each plant, relative to its energy production:

$$\bar{LCOE} = \frac{\sum_1^n E_i \times CC_i}{\sum_1^n E_i} \tag{34}$$

Investor rate of returns (IRR) The aggregated IRR for the nuclear programme is measured as the weighted average IRR of the projects, with the deployed capacity accounting for the relative scale of each investment:

$$\bar{IRR} = \frac{\sum_1^n P_i \times IRR_i}{\sum_1^n P_i} \tag{35}$$

Value-at-risk (VaR) The total VaR of the UK nuclear programme is the sum of the value-at-risks of each individual project, calculated in real terms. Risk-sharing effects due to plants being owned by multiple investors are not considered here, with the VaR measuring the full risk potential arising from the assets.

$$\bar{VaR} = \sum_1^n VaR_i \tag{36}$$

Government investment Government investment is measured as a percentage of GDP per annum, considering a GDP of £2700 billion in 2024 and a conservative real growth rate g of 0.7%, which corresponds to the current rate and the lower margin of future estimates (Office for Budget Responsibility (OBR), 2024). The calculation considers four periods: 2025–2029, 2030–2034, 2035–2039, and 2040–2044. The investment in a project is compared in relative terms to the GDP at the time of the investment decision.

$$\bar{GC} = avg\Big(\overbrace{\frac{\sum_{i=1}^{n_1} GC_i}{\sum_{t=1}^{5} GDP(1+g)^t}}^{\text{2025-2029}}, \overbrace{\frac{\sum_{i=1}^{n_2} GC_i}{\sum_{t=1}^{5} GDP(1+g)^{t+5}}}^{\text{2030-2034}}, \overbrace{\frac{\sum_{i=1}^{n_3} GC_i}{\sum_{t=1}^{5} GDP(1+g)^{t+10}}}^{\text{2035-2039}}, \overbrace{\frac{\sum_{i=1}^{n_4} GC_i}{\sum_{t=1}^{5} GDP(1+g)^{t+15}}}^{\text{2040-2044}}\Big) \tag{37}$$

Appendix B. Data appendix

See Table 5.

Data availability

No data was used for the research described in the article.

References

Agar, A.S., Fry, A.J., Goodfellow, M.J., Goh, Y.M., Newnes, L.B., 2018. Expected accuracy range of cost estimates for small modular reactors at the early concept design stage. In: International Conference on Nuclear Engineering, American Society of Mechanical Engineers. V009T16A055. http://dx.doi.org/10.1115/ICONE26-81799.

Bertram, N., Fuchs, S., Mischke, J., Palter, R., Strube, G., Woetzel, McKinsey & Company, 2019. Modular construction: From projects to products. URL https://www.mckinsey.com/capabilities/operations/our-insights/modular-construction-from-projects-to-products.

Bles, M., Afman, M., Benner, J., Blom, M., Croezen, H., Rooijers, F., Schepers, B., 2011. Nuclear Energy: The Difference Between Costs and Prices. Technical Report., CE Delft, URL https://cedelft.eu/publications/nuclear-energy-the-difference-between-costs-and-prices/.

Buongiorno, J., Parsons, J., Corradini, M., Petti, D., 2018. The future of nuclear energy in a carbon-constrained world. URL https://energy.mit.edu/research/future-nuclear-energy-carbon-constrained-world/.

Carelli, M.D., Mycoff, C.W., Garrone, P., Locatelli, G., Mancini, M., Ricotti, M.E., Trianni, A., Trucco, P., 2008. Competitiveness of small-medium, new generation reactors: a comparative study on capital and o & m costs. In: International Conference on Nuclear Engineering. pp. 499–506. http://dx.doi.org/10.1115/ICONE16-48931.

Government of the Czech Republic, 2024. Nuclear tender enters the next stage: Government invites binding offers for the construction of several nuclear units. URL https://www.mpo.gov.cz/en/guidepost/for-the-media/press-releases/.

Department for Business, Energy & Industrial Strategy (DBEIS), 2019. Statement on suspension of work on the wylfa newydd nuclear project. URL https://www.gov.uk/government/speeches/statement-on-suspension-of-work-on-thewylfa-newyddnuclear-project.

Department for Energy Security and Net Zero (DESNZ), 2024a.. Alternative routes to market for new nuclear projects consultation (closed). URL https://www.gov.uk/government/consultations/alternative-routes-to-market-for-new-nuclear-projects.

Department for Energy Security and Net Zero (DESNZ), 2024b. Civil nuclear: Roadmap to 2050. URL https://www.gov.uk/government/publications/civil-nuclear-roadmap-to-2050.

Department for Energy Security and Net Zero (DESNZ), 2024c. Contracts for difference (CfD) allocation round 6: Results. URL https://www.gov.uk/government/publications/contracts-for-difference-cfd-allocation-round-6-results/.

Électricité de France (EDF), 2024. EDF first-half 2024 results press conference. URL https://www.edf.fr/sites/groupe/files/2024-08/half-year-results-transcript-of-the-presentation-2024-08-01.pdf.

Environmental Audit Committee (EAC) Chair, 2024. Letter from the EAC chair to the secretary of state for energy security and net zero, relating to small modular reactors in the transition from fossil fuels. URL https://committees.parliament.uk/work/7965/small-modular-reactors-in-the-transition-from-fossil-fuels/publications/3/correspondence/.

Expert Finance Working Group on Small Reactors, 2018. Market framework for financing small nuclear. URL https://www.gov.uk/government/publications/market-framework-for-financing-small-nuclear.

Hinkley Point C., 2022. Build and repeat: Efficiency through replication.

H.M. Treasury, 2022. The green book: Central government guidance on appraisal and evaluation. URL https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-government.

International Atomic Energy Agency (IAEA), 2025. Power Reactor Information System. PRIS, Vienna.

Lempert, R.J., Popper, S.W., Bankes, S.C., 2003. Shaping the next one hundred years: New methods for quantitative, long-term policy analysis. URL https://www.rand.org/pubs/monograph_reports/MR1626.html.

Locatelli, G., Bingham, C., Mancini, M., 2014. Small modular reactors: A comprehensive overview of their economics and strategic aspects. Prog. Nucl. Energy 73, 75–85. http://dx.doi.org/10.1016/j.pnucene.2014.01.010.

Macron, E., 2022. Reprendre en main notre destin énergétique. URL https://www.elysee.fr/emmanuel-macron/2022/02/10/reprendre-en-main-notre-destin-energetique.

Mignacca, B., Locatelli, G., 2020. Economics and finance of small modular reactors: A systematic review and research agenda. Renew. Sustain. Energy Rev. http://dx.doi.org/10.1016/j.rser.2019.109519, URL https://www.sciencedirect.com/science/article/pii/S1364032119307270.

National Audit Office (NAO), 2017. Hinkley point C.. URL https://www.nao.org.uk/reports/hinkley-point-c/.

National Energy System Operator (NESO), 2023. Future energy scenarios: ESO pathways to net zero. URL https://www.neso.energy/publications/future-energy-scenarios-fes/fes-documents.

Newbery, D.M., 1997. Determining the regulatory asset base for utility price regulation. Util. Policy 6, 1–8. http://dx.doi.org/10.1016/S0957-1787(96)00015-X.

Newbery, D., Pollitt, M., Reiner, D., Taylor, S., 2019. Financing low-carbon generation in the UK: The hybrid RAB model. In: Energy Policy Research Group. University of Cambridge, URL https://www.econ.cam.ac.uk/research-files/repec/cam/pdf/cwpe1969.pdf.

Nuclear Energy Agency (NEA), 2022. New perspectives for financing nuclear new build: : Financing, market design and project management in nuclear new build. URL https://www.oecd-nea.org/jcms/pl_96132.

Nuclear Sector Deal, 2020. Nuclear new build cost reduction. URL https://www.niauk.org/wp-content/uploads/2022/01/New-Build-Cost-Reduction-Sector-Deal-Working-Group.pdf.

Office for Budget Responsibility (OBR), 2023. Fiscal risks and sustainability. URL https://obr.uk/frs/fiscal-risks-and-sustainability-july-2023/.

Office for Budget Responsibility (OBR), 2024. Economic and fiscal outlook. URL https://obr.uk/efo/economic-and-fiscal-outlook-march-2024/.

Organisation for Economic Co-operation and Development (OECD), 2018. Annual Survey of Large Pension Funds and Public Pension Reserve Funds 2018. OECD Publishing, Paris, http://dx.doi.org/10.1787/ecc4a85d-en.

Penn, I., Plumer, B., 2024. Hungry for energy, amazon, google and microsoft turn to nuclear power. N. Y. Times URL https://www.nytimes.com/2024/11/29/technology/big-tech-nuclear-energy.html.

Performance Review Body of the Single European Sky (PRB), 2019. Study on cost of capital methodology review.

Polityka Insight Baker McKenzie, 2023. Nuclear Poland. How to bring reactors to Poland ?.

Rachel, L., Summers, L.H., 2019. On falling neutral real rates, fiscal policy, and the risk of secular stagnation. In: Brookings Papers on Economic Activity. URL https://www.brookings.edu/articles/on-falling-neutral-real-rates-fiscal-policy-and-the-risk-of-secular-stagnation/.

RAND Corporation, 2013. Making good decisions without predictions, robust decision making for planning under deep uncertainty. Research Brief URL https://www.rand.org/pubs/research_briefs/RB9701.html.

RAND Corporation, 2024. Water planning for the uncertain future: Robust decision making. URL https://www.rand.org/pubs/tools/TL320/tool/robust-decision-making.html.

Réseau de transport d'électricité (RTE), 2025. Registre des capacités certifiées. URL https://www.services-rte.com/fr/visualisez-les-donnees-publiees-par-rte/registre-des-capacites-certifiees.html.

Stern, N., 2007. The Economics of Climate Change: The Stern Review. Cambridge University Press. Published for the Government of the United Kingdom, http://dx.doi.org/10.1017/CBO9780511817434.

Stewart, W.R., Shirvan, K., 2022. Capital Cost Evaluation of Advanced Water-Cooled Reactor Designs with Consideration of Uncertainty and Risk. Technical Report MIT-ANP-TR-194., Centre for Advanced Nuclear Energy Systems (CANES), URL https://canes.mit.edu/media/capital-cost-evaluation-of-advanced-water-cooled-reactor-designs-with-consideration-of-uncertainty-and-risk.

The White House, 2024. Biden-harris administration establishes bold u.s. government targets for safely and responsibly expanding U.S. nuclear energy and announces framework for action to achieve these targets. URL https://www.whitehouse.gov/ostp/news-updates/.

UK Debt Management Office (UKDMO), 2025. Historical average daily conventional gilt yields.

UK Parliament, 2022. Nuclear energy (financing) act 2022.

US Department of Energy (DOE), 2023. Pathways to commercial liftoff: Advanced nuclear. URL https://liftoff.energy.gov/advanced-nuclear-2/.

Whittington, G., 1994. Current cost accounting: Its role in regulated utilities. Fisc. Stud. 15, 88–101, URL http://www.jstor.org/stable/24437302.

Workman, M., Darch, G., Denisart, B., Roberts, D., Wilkes, M., Brown, S., Kruitwagen, L., 2024. A robust decision-making approach in climate policy design for possible net zero futures. Environ. Sci. Policy 162, 103886. http://dx.doi.org/10.1016/j.envsci.2024.103886.

World Nuclear Industry Status Report, 2024. World nuclear power reactors 1951–2024.