Energy Policy 215 (2026) 115341

Contents lists available at ScienceDirect

Energy Policy

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

Perspectives on nuclear power

Jens Weibezahn[a,b,*], Björn Steigerwald[b], Arman Aghahosseini[c], Christian von Hirschhausen[b,d], Mark Z. Jacobson[e], Christian Breyer[c]

[a] Copenhagen School of Energy Infrastructure (CSEI), Copenhagen Business School, Porcelænshaven 16A, 2000 Frederiksberg, Denmark
[b] Workgroup for Infrastructure Policy (WIP), Technische Universität Berlin, Straße des 17. Juni 135, 10623 Berlin, Germany
[c] School of Energy Systems, LUT University, Yliopistonkatu 34, 53850, Lappeenranta, Finland
[d] Department of Energy, Transportation, and Environment, German Institute for Economic Research (DIW Berlin), Anton-Wilhelm-Amo-Straße 58, 10117 Berlin, Germany
[e] Department of Civil & Environmental Engineering, Stanford University, Stanford, CA, USA

HIGHLIGHTS

- Nuclear competitiveness hinges on optimistic cost and financing assumptions.
- Renewables plus flexibility dominate least-cost decarbonisation pathways.
- New nuclear plays only marginal role under realistic system conditions.
- Empirical data contradicts optimistic nuclear deployment scenarios.
- Nordic case shows nuclear role shaped by policy and financing limits.

ARTICLE INFO

JEL classification:
Q42
Q48
Q54
L94
G32

Keywords:
Nuclear power economics
Financing and risk allocation
Renewables-centred least-cost pathways
Storage and flexibility
Levelized cost of electricity
Nordic energy systems
Policy instruments

ABSTRACT

This study reassesses the role of nuclear power in low-carbon electricity transitions under prevailing cost, finance, and system conditions. Using harmonised international data and observed 2024 operational metrics, we conduct a modelling-based stress test that evaluates how nuclear power performs when realistic construction, financial, and flexibility assumptions are applied. The results show that large nuclear power shares in prior modelling studies emerge primarily under optimistic conditions: Low overnight capital cost, reduced financing risk, or constrained renewable energy portfolios. When empirically validated inputs and full flexibility options are included, least-cost system pathways are consistently dominated by renewable energy-based portfolios complemented by storage, demand response, and existing dispatchable assets, while new nuclear power contributes only marginally. Empirical project evidence from recent builds corroborates the modelling results: prolonged construction duration and extended financing exposure significantly elevate effective project cost, irrespective of nominal levelised cost estimates. The Nordic region provides a natural comparative lens, revealing divergent governance models and public acceptance trajectories across Denmark, Sweden, Finland, and Norway, yet a shared economic constraint shaped by financing structure, risk allocation, and system alternatives. Overall, the findings indicate that under current techno-economic parameters and financing environments, renewable-centred energy portfolios form the cost-optimal foundation for power sector decarbonisation. Nuclear power remains a system- and policy-specific option that can contribute where governments assume substantial construction and financing risk and offer long-term capital recovery mechanisms. Transparent modelling assumptions and explicit financing terms are therefore essential for credible assessments of future nuclear deployment.

1. Introduction

The global energy landscape has been disrupted by overlapping crises. The COVID-19 pandemic, Russia's war in Ukraine, the war on Iran, and increasingly frequent extreme weather events have sharpened the urgency of a carbon-neutral energy transition (IEA, 2025; IPCC, 2022). While most governments are accelerating renewables expansion, nuclear power has re-emerged as a focal point of debate, including through its (contested) inclusion in the EU Taxonomy

* Corresponding author at: Copenhagen School of Energy Infrastructure (CSEI), Copenhagen Business School, Porcelænshaven 16A, 2000 Frederiksberg, Denmark.
Email address: jew.eco@cbs.dk (J. Weibezahn).

https://doi.org/10.1016/j.enpol.2026.115341
Received 6 January 2026; Received in revised form 17 April 2026; Accepted 19 April 2026

(European Commission, 2022a). Beyond techno-economic and time-to-operation concerns, questions of bankability and risk allocation have moved centre stage as financing models increasingly shift construction and revenue risks to taxpayers or ratepayers (European Commission, 2022a; Weibezahn and Steigerwald, 2024).

Proponents frame nuclear power as firm, low-carbon capacity that can complement variable renewables, support reliability, and reduce dependence on fossil-fuel imports and renewable fuels of non-biological origin (RFNBOs) (Jenkins et al., 2018; Duan et al., 2022). The lifecycle greenhouse gas emissions of nuclear power are estimated to be between 5.4 and 122 gCO_2/kWh, which can qualify nuclear power as a low-carbon technology, mostly dependent on emissions from the fuel supply chain, especially from uranium ore extraction (Gibon and Hahn Menacho, 2023). Given the current technology choice, an estimate of 20 gCO_2e/kWh can be seen as a realistic upper bound (Gibon and Hahn Menacho, 2023), while wind power and solar photovoltaics reach values of approximately 5–13 gCO_2e/kWh and 13–28 gCO_2e/kWh, respectively (Dashti et al., 2025). National strategies diverge widely: some propose to retain (France, Finland, and Taiwan) or expand (Sweden, the Netherlands, and Poland) nuclear power fleets, while others propose to phase out (Germany) or maintain prohibitions (Denmark) (Glynos and Scharf, 2024; Soytas et al., 2022; WNN, 2025a; Haikola and Anshelm, 2025; Lindvall et al., 2025; Roelofs et al., 2024; Kasińska et al., 2025; Reuters, 2024; Nriezedi-Anejionu, 2024; Bärenbold et al., 2024; WNN, 2025c). These choices reflect different assessments of the role of nuclear power in future systems.

Scientific perspectives are likewise divided. Energy system models and IAMs often assign a role to nuclear power in cost-effective 1.5–2°C pathways (IPCC, 2022; IEA, 2021a), yet tracking studies document delivery challenges and escalating costs (Schneider et al., 2025). Recent modelling community work clarifies why results diverge: outcomes hinge on assumptions about capital costs (first of a kind (FOAK)/next of a kind (NOAK)), discount rates, financing terms, flexibility, and CO_2 limits (Murphy et al., 2023; Cole et al., 2023; Bistline et al., 2023). Standardised input sets (e.g., NREL ATB 2024) and meta-analyses of so-called advanced nuclear reactor concept costs help to bound credible ranges for stress-testing (Mirletz et al., 2024), while new multi-model and system studies explore competitiveness thresholds and demand profile effects (e.g., data centres) (Thellufsen et al., 2024; Hjelmeland et al., 2025). Together, these insights underscore persistent assumption sensitivity and competing narratives.

This perspective adopts an explicitly non-advocacy, evidence-driven stance. We (i) review the position of recent energy system studies on nuclear power, (ii) stress-test model outcomes against nuclear power-specific cost and finance assumptions using transparent and documented parameter ranges, and (iii) assess policy relevance. Assumptions are drawn from peer-reviewed assessments and standardised datasets; where results are assumption-dependent (e.g., FOAK/NOAK capital costs, discount rates and financing terms, operating flexibility, CO_2 constraints), we state this explicitly (IPCC, 2022; IEA, 2021a; Schneider et al., 2025; Murphy et al., 2023; Cole et al., 2023; Bistline et al., 2023; Mirletz et al., 2024; Abou-Jaoude et al., 2024; Thellufsen et al., 2024; Hjelmeland et al., 2025). Recent project experience (e.g., Vogtle 3/4, Olkiluoto 3, Flamanville 3) illustrates the delivery and governance risks that interact with financing, motivating the analysis (EIA, 2024; Satymov et al., 2025; Cour des comptes, 2025). Our question is conditional rather than prescriptive: under what empirically supported conditions, if any, can new nuclear power be competitive in rapidly decarbonising power systems?

2. Perspectives on nuclear power

Electricity systems are in a decisive transition. In 2024, global electricity generation reached approximately 31,255 TWh (approximately 112.52 EJ), with about 61% originating from fossil fuels, 29% from renewable energy (RE) (5% solar photovoltaics (PV), 8% wind power, 15% hydropower), and roughly 10% from nuclear power. In fact, the world's nuclear power output in 2024 (2778 TWh) was virtually the same as in 2006 (2762 TWh) with regional divergences, while RE provided most of the net growth. (Schneider et al., 2025; Energy Institute, 2025).

In 2024, 417 reactors operated in 31 countries, with an average unit size of 904 MW_{el} and an average age of 32.4 years (IAEA, 2025; Schneider et al., 2025). Lifetime extensions contribute substantially to output (e.g., a large fraction of U.S. units are licenced beyond 40 years), but long-term cost and liability uncertainties remain material, as noted above (Bärenbold et al., 2024; Präger et al., 2024; NRC, 2025).

At the national level, observed mixes mirror these patterns. In Germany, electricity generation was 501 TWh in 2024, with approximately 57% RE and 43% fossil fuels (Energy Institute, 2025; AGEB, 2025). Across Europe, rising RE shares coincide with flat or declining nuclear power contributions in most countries, while selected member states pursue life-extension or target new-build programmes.

Policy positions remain heterogeneous and contested (e.g., EU Taxonomy) (European Commission, 2022a). We therefore (i) summarise historical drivers and regional trajectories (Section 2.1), (ii) assess current techno-economics and financing in a system context rather than by levelized cost of electricity (LCOE) alone (Section 2.2), and (iii) examine future concepts and uncertainties (Section 2.3).

2.1. Historical perspective

The development of civilian nuclear power after 1945 was fundamentally shaped by its military origins, Cold War geopolitics, and contested economic expectations (Sorge and Neumann, 2021). The first commercial nuclear reactors were commissioned in the mid-1950s in the Soviet Union, the United Kingdom, and the United States, building on the institutional and technological foundations of the Manhattan Project (Reed, 2021; Holloway, 2008). Early commercial fleets diverged by reactor type and national lineage: Magnox and AGR designs in the United Kingdom, CANDU reactors in Canada, RBMK and VVER types in the Soviet Union, and PWR/BWR families in the United States. These technical choices created path-dependent supply chains and regulatory frameworks (Cowan, 1990; Goldberg and Rosener, 2011).

The installed global nuclear power capacity grew from less than 1 GW before 1960 to more than 100 GW in 1978, surpassing 300 GW by 1988 (IAEA, 2025). This expansion was geographically concentrated: by the late 1980s, four countries, namely, the United States, France, Japan, and the Soviet Union, accounted for more than three-quarters of total capacity (IAEA, 2025). Institutionally, Eisenhower's 1953 Atoms for Peace initiative spurred civilian nuclear programmes and technology transfers, while the Euratom Treaty (1957) embedded nuclear research within European integration. In the United States, the 1974 reorganisation of the Atomic Energy Commission into the Nuclear Regulatory Commission formalised the separation between promotion and regulation (Gross, 1976; Drogan, 2019; European Union, 2012).

From the outset, the economics of nuclear power were debated intensely. Early assessments generally found electricity from nuclear power plants more expensive than that from coal. Löbl (1956) and Baade (1958) attributed this to high capital intensity and unresolved technological uncertainties, implying dependence on direct or indirect public support. Proponents argued, however, that economies of scale and standardisation would lower costs. France became the emblematic case: its standardised pressurised water reactor (PWR) programme cut the average construction times to about six years and stabilised costs relative to contemporaneous international experience (Hecht, 1998).

After India's 1974 nuclear test, the global safeguard regime tightened through the entry into force of the Nuclear Non-Proliferation Treaty (1970) and the creation of the Nuclear Suppliers Group (1975), linking reactor exports to IAEA oversight (Burr, 2014). In the United States, on the contrary, average construction times increased from seven years (projects begun in the late 1960s) to more than twelve years (for those initiated in the late 1970s), while overnight capital costs increased in real terms from roughly 1064 USD_{2004}/kW (about 1457 USD_{2020}/kW) to over 4747 USD_{2004}/kW (more than 6503 USD_{2020}/kW, inflation adjusted with CPI-U) (Koomey and Hultman, 2007). Escalating real interest rates and financial risk premia during the late 1970s compounded the capital intensity of new nuclear power plants. Later, electricity market liberalisation and privatisation, most notably in the United Kingdom, transferred construction risk from ratepayers to investors, further discouraging new projects (Thomas, 2010; Jupe, 2012).

The oil crises of 1973 and 1979 reshaped energy strategies and spurred renewed interest in nuclear power. France launched one of the most ambitious build-outs globally, lifting the share of nuclear electricity from below 10% in 1973 to more than 65% by 1990 (IAEA, 2025). The Soviet Union also expanded, reaching around 25 GW by 1985 (IAEA, 2025). Parallel efforts in reprocessing and fast-breeder development, such as France's *pHénix* and *Superphénix*, the United Kingdom's Dounreay programme and the U.S. Clinch River project, sought to close the fuel cycle and extend uranium resources. High costs, technical setbacks, and political controversy led most such projects to termination by the 1990s (Cochran et al., 2010; MacKenzie et al., 2022). In the United States, however, more than 100 planned units were cancelled between 1972 and 1984, amid escalating costs, tighter regulation, and growing public opposition after the Three Mile Island (1979) accident (Walker, 2005). In Western Europe, large programmes in Sweden and Germany encountered powerful anti-nuclear movements, contributing to moratoria or phase-out decisions in the 1980s (Radkau and Hahn, 2013).

Beyond the headline accidents at Three Mile Island and Chernobyl, earlier incidents such as Windscale (1957), Stationary Low-Power Reactor Number One (SL-1) (1961), and Saint-Laurent (1969, 1980) had already reinforced safety-culture reform and regulatory caution (Horan and Gammill, 1963; Penney et al., 2017; Wakeford, 2017). The major accidents had profound effects on regulation and public acceptance. Following Three Mile Island, the U.S. Nuclear Regulatory Commission introduced additional safety requirements and procedural reforms that lengthened construction schedules and raised compliance costs (Koomey et al., 2017). The Chernobyl disaster (1986) was a watershed moment (Koopmans and Duyvendak, 1995): Italy's 1987 referendum led to a moratorium on its nuclear power programme (Graf von Hardenberg, 2011), Austria (Pelinka, 1983) and Denmark (Sovacool, 2013) reaffirmed national bans, and Germany consolidated itself into a durable political coalition (Peters et al., 1990; Renn and Marshall, 2016). The 1994 Convention on Nuclear Safety institutionalised peer review and transparency under the IAEA, marking the first multilateral framework for reactor-safety governance (Jankowitsch, 1994).

Although new construction slowed, operational performance improved markedly: average capacity factors rose from roughly 60% in the early 1980s to approximately 90% by the late 1990s in leading fleets, driven by enhanced maintenance and outage management (Davis and Wolfram, 2012). By the late 1990s, nuclear power was widely viewed as a mature but stagnant technology. Global capacity plateaued around 350 GW, with growth concentrated in France, Japan, and South Korea. Meanwhile, South Korea's standardised programme demonstrated rapid cost learning and export capability, and China's first commercial unit (Qinshan-1, 1991) signalled the beginning of a new growth centre. In contrast, Spain's 1983 moratorium and Sweden's 1980 referendum embodied the Western European retrenchment (Thomas, 2010; Zhou, 2010).

In liberalised electricity markets, escalating costs and frequent delays discouraged new private investment. Empirical studies documented stark divergences in capital costs: in France and South Korea, standardised designs and stable state involvement kept overnight costs comparatively low (France often in the EUR-equivalent of 2000–3500 USD/kW range; South Korea frequently below 6000 USD/kW for recent builds), while in the United States and Western Europe, new-build costs commonly exceeded 5000 USD/kW (real values from the source-year) (Grubler, 2010; Rothwell, 2022; Cour des comptes, 2012). Simultaneously, post-Chernobyl, public opposition underpinned phase-outs or moratoria in Italy, Germany, and Sweden.

Contrary to early expectations of scale economies, empirical evidence revealed "negative learning", with unit capital costs rising with cumulative capacity, reflecting design modifications, regulatory changes, and project-management complexity (Grubler, 2010).

Taken together, the 1945–2000 trajectories show that large-scale deployment was feasible primarily under strong state intervention (subsidies, industrial policy, centralised planning). Escalating costs, prolonged construction times, and sustained public opposition were recurrent structural features. Long-term waste management remained unsettled: the United States advanced but never completed the Yucca Mountain repository, while Finland's *Onkalo* site selection around 2000 exemplified early success. Dedicated decommissioning and waste funding mechanisms have become standard features of national policy frameworks (Schaffer, 2011; Kojo et al., 2010). By 2000, nuclear power remained geographically concentrated and politically contested, framing today's assessment of its role under rapid energy transition and decarbonisation.

2.2. Current perspective

The global electricity system has undergone significant structural changes and continues to evolve under deep-decarbonisation goals. Recent growth has been led by wind power and solar PV, while global nuclear power output has been broadly flat, with OECD declines offset by China and Russia (Schneider et al., 2025; Energy Institute, 2025). Renewable energy (RE) also dominates new-build investment, reflecting cost decreases, modularity, and shorter construction times; integration is increasingly supported by grid-scale batteries, demand-side management, and emerging renewable-hydrogen options (IPCC, 2022; IEA, 2021a; Schneider et al., 2025). Reviews of scenario outlooks (e.g., IEA WEO) note historical overestimation of nuclear power and underestimation of solar PV, underscoring the value of distinguishing observations from scenarios (Lopez et al., 2025).

Regional trends diverge sharply: China and Russia account for nearly all recent net additions, while OECD capacity continues to decline. New reactors in the United Arab Emirates, India and Türkiye illustrate a modest geographic diffusion driven by state-backed vendor financing and bilateral agreements (IEA, 2024; WNA, 2025).

Against this observed backdrop, the relative cost-competitiveness of new nuclear power has weakened in most OECD contexts. Liberalised markets and the rapid growth of variable RE have shifted investment incentives towards flexible low-capital-cost RE technologies, eroding the economic rationale for the development of new conventional nuclear power plants (MIT, 2003; University of Chicago, 2004; MIT, 2009, 2018; Ingersoll and Carelli, 2021). In not only LCOE cost metrics but also capital expenditures (CAPEX), new RE technologies outperform not only nuclear power but also fossil fuel-based technologies. Although nuclear reactors provide firm capacity and contribute to adequacy, high upfront capital costs and long construction times reduce attractiveness in markets organised around short-run marginal-pricing and low-marginal-cost renewable electricity generation.

Contemporary cost benchmarks are consistent across sources. Lazard (2025) reports unsubsidised central ranges of 38–78 USD/MWh for utility-scale solar PV and 37–86 USD/MWh for onshore wind, while new high capacity nuclear power is typically above the range of 9020–14,820 USD/kW with LCOE around 141–220 USD/MWh (assumption dependent, real USD_{2025}, typical OECD WACC). As a European cross-check, Fraunhofer ISE (2024) reports 2024 ranges of 41–144 €/MWh (PV utility-scale), 43–92 €/MWh (onshore wind power), 55–103 €/MWh (offshore wind power) and 136–499 €/MWh (nuclear power, backend not included). Because LCOE omits system value (capacity credit, flexibility, and network costs), we interpret these benchmarks within power system models rather than as stand-alone rankings.

Beyond construction, operational uncertainty and tail risk also affect economics. Revenues depend on realised capacity factors, which are exposed to forced outages and fleet-wide findings, and to climate-related deratings during heat waves or low-flow conditions; sustained unit downtime can materially depress annual output (Downer and Ramana, 2021; Van Vliet et al., 2012). Long-horizon backend liabilities remain uncertain: Decommissioning and high-level waste disposal pathways are unresolved in many jurisdictions (Bärenbold et al., 2024; NEA, 2016). Liability regimes (e.g., Vienna/Paris conventions) cap operator exposure to catastrophic accidents, effectively socialising low-probability, high-impact losses (Präger et al., 2024; IAEA, 1997; NEA, 2023). In LCOE, these risks appear only indirectly (via WACC and insurance); therefore, we address them explicitly in the financing and sensitivity analysis.

Project evidence aligns with benchmark ranges and risk character. Olkiluoto 3 (Finland) reached commercial operation in 2023 after extended commissioning; Vogtle 3 and 4 (United States) entered operation in 2023/24 with total costs reported in the mid 30 bn. USD; Flamanville 3 (France) had not entered commercial operation at the time of writing, with Cour des comptes estimating costs at around 23.7 bn €$_{2023}$ (Sovacool and Ryu, 2025; Berthélemy and Escobar Rangel, 2015; Lovering et al., 2016). These cases indicate persistent schedule and budget risks relative to modular variable build-outs.

Trends in new-build activity are subdued. Tracking sources show low annual reactor start rates for the 2010s–2020s and only marginal net capacity growth since 2010, with additions largely offset by retirements (IAEA, 2025). Empirical analysis reports negative learning in many programmes and periods, although the results vary by method and sample; some national programmes exhibit more stable costs under strong standardisation and state involvement (Grubler, 2010; Rothwell, 2022; Weibezahn and Steigerwald, 2024). Attempts at standardised modular designs such as the European Pressurised Reactor (EPR) and AP 1000 were intended to reverse the cost escalation, but the available evidence points to persistent cost and schedule risk (Berthélemy and Escobar Rangel, 2015; Lovering et al., 2016).

Decommissioning obligations are expanding as the first generation of commercial reactors approaches retirement (O'Sullivan, 2023). Experience from early dismantling projects, e.g., Germany, France, Japan, and the United States, indicates that actual costs often exceed initial provisions, and timelines can extend over several decades (Bärenbold et al., 2024; Rothwell, 2025). Funding mechanisms vary (segregated decommissioning funds, generation levies, or state guarantees), but adequacy remains debated, especially where early shutdowns coincide with underfunded reserves (NEA, 2016; IAEA, 2023; Bärenbold et al., 2024; Mykhalchyk Hradický and Sabovčík, 2025). These long-tail liabilities reinforce the need for transparent cost provisioning and regulatory oversight throughout plant operation.

More recent policy developments, such as the EU Taxonomy (European Commission, 2022a) and the U.S. Inflation Reduction Act (United States Congress, 2022), have partially reintegrated nuclear power into decarbonisation finance frameworks. These measures mainly stabilise existing assets through production credits and eligibility for green finance rather than stimulating merchant new-build projects (NEA, 2024).

Financing structures are decisive determinants of investability. Empirically, new nuclear power capacity proceeds primarily where states attenuate risk through sovereign balance sheet backing or regulated revenue arrangements; by contrast, classic non-recourse project finance remains exceptional. Sponsors therefore resort to corporate balance sheets, *Mankala*-type consortia, vendor BOO/BOT schemes, state loans or export guarantees, state-owned utilities, and revenue stabilisation instruments such as contracts for difference (CfDs) and Regulated Asset Base (RAB) models (European Commission, 2022a; Weibezahn and Steigerwald, 2024). The RAB approach grants a regulated rate of return on a defined asset base and typically permits intra-construction revenue recovery, reallocating a portion of construction- and cost-overrun risk to consumers subject to cap mechanisms. Two-sided CfDs, by contrast, collar wholesale price exposure during operation and have become a widely deployed instrument for low-carbon generation in the European Union.

Finally, political aspects beyond the energy system must be considered: Exporters of nuclear power plants can use their influence on a country's electricity system in the form of "nuclear power diplomacy", exerting political pressure. A prominent example is *Rosatom*, the state-owned Russian producer of NPPs and fuel rods, exercising its influence on countries such as Türkiye and Hungary (Szulecki and Overland, 2023). Furthermore, nuclear power plants can become targets in conflicts, as seen in the shelling of the Zaporizhzhia NPP by Russia during its war on Ukraine (Tsagkaris et al., 2022) and possibly also in the current war in the Middle East, with the Barakah NPP in the United Arab Emirates becoming a potential target.

2.3. Future perspective

A central claim in current nuclear reactor development is that modularisation, the factory fabrication of large pre-assembled modules followed by rapid on-site installation, creates a possibility to materially reduce overnight capital costs and mitigate schedule risks. In principle, serial production and standardised designs should shorten construction durations, lower financing costs via reduced interest during construction, and should enable learning-by-doing through higher manufacturing throughput (Ingersoll and Carelli, 2021). However, the empirical basis remains limited. Recent projects still exhibit FOAK risks, complex site interfaces, and immature supply chains, which attenuate expected benefits. For so-called small modular reactors (SMRs), Ramana (2021) argues that the putative economies of multiples may be offset by diseconomies of scale (lower thermal efficiency, smaller unit ratings), such that competitive levelized costs require very large production runs and high-capacity factors, conditions not yet demonstrated in liberalised electricity markets. Consequently, early SMR cost projections span wide ranges, reflecting uncertainty in factory yields, module logistics, and the scope of regulatory standardisation (Steigerwald et al., 2023).

Another prominent line of argument concerns fast-spectrum or molten-salt designs, often promoted as systems capable of transmuting transuranic elements and thereby reducing long-lived radiotoxic inventories (NEA, 2023; Frieß et al., 2021; Kooyman, 2021). However, system-level assessments show that net inventory reduction depends on the full closed fuel cycle: reprocessing losses, separation efficiency for minor actinides, fabrication quality, neutron economy and total fleet throughput relative to legacy waste stocks (Frieß et al., 2021). Absent industry-scale reprocessing and consistent minor-actinide loading across a sizeable fleet, the effect on national liabilities remains uncertain. Moreover, transmutation can shift requirements upstream (more complex separations and safeguards) and downstream (repository heat-load management), introducing additional cost and schedule implications that must be evaluated at the system level rather than for an individual reactor (Frieß et al., 2021; Pistner et al., 2024).

Beyond light-water reactors (LWRs), several non-water-cooled concepts are under development at both large- and small scales, including high-temperature gas-cooled reactors (HTGRs), sodium- or lead-cooled fast reactors (SFRs/LFRs), and molten-salt reactors (MSRs). These designs aim to deliver higher outlet temperatures suitable for industrial heat applications, enhanced inherent or passive safety features, and potential flexibility in fuel cycles (Pioro, 2023). However, commercialisation hinges on the establishment of robust supply chains, such as high-assay low-enriched uranium for many designs and advanced materials for high-temperature operation, standardised licencing pathways, and manufacturability at scale. For SMRs in particular, Ramana (2021) emphasises that smaller unit ratings raise the threshold for serial production volumes required to unlock learning effects, while Steigerwald et al. (2023) highlight wide uncertainty bands in projected overnight costs and LCOE, driven by assumptions about batch sizes, factory learning rates, and discount rates.

The emerging quantitative literature confirms that results are scale- and finance-sensitive (Hjelmeland et al., 2025; Mignacca and Locatelli, 2020). Ramana (2021) shows that the loss of economies of scale at the unit level requires learning-by-doing merely to achieve cost parity with contemporary large LWRs. Steigerwald et al. (2023) further finds that, even with optimistic serial-production assumptions, FOAK-to-NOAK cost reductions are not guaranteed, with projected costs overlapping or exceeding those of large reactors once realistic capacity factors and risk premia are included. In practice, realising modularisation benefits also requires licencing harmonisation (to avoid expensive design variants), long-term order books (to sustain factory utilisation), and resolution of supply chain bottlenecks (e.g., HALEU availability and advanced alloys), none of which are yet demonstrated at commercial scale.

Integration into future low-carbon electricity systems will also depend on the ability of so-called advanced reactors to operate flexibly alongside high shares of variable RE and to supply non-electric services such as district heating, hydrogen production, or process heat for industry (WNA, 2025; NEA, 2023).

From a financing perspective, most advanced and SMR projects proceed under direct state sponsorship or cost-sharing arrangements, e.g., the U.S. DOE Advanced Reactor Demonstration Programme and the U.K. Great British Nuclear initiative. Private investment remains limited due to high construction and financing risks and typically increases as project risks are reduced and experience is gained (NEA, 2024).

In sum, advanced modular construction and non-water-cooled reactor concepts promise improvements in constructability, potential safety margins, and potential waste management. However, current evidence indicates substantial uncertainty about the magnitude and timing of cost reductions. Claims of "waste burning" require system-level validation across the entire closed fuel cycle, and the competitiveness of SMRs is dependent on production scale, licencing standardisation, supply chain readiness (including HALEU), and financing that remain to be demonstrated in practice (Steigerwald et al., 2023; Pistner et al., 2024). As these technologies mature, their viability will depend less on individual engineering breakthroughs and more on coordinated regulatory frameworks, international licencing harmonisation, and state-enabled financing, issues explored in the subsequent section on nuclear power within the policy debate.

3. Nuclear in the policy debate: the case of the nordics

In Denmark, the Folketing excluded nuclear power from its national energy planning in 1985, and subsequent strategies prioritised energy efficiency, combined heat and power (CHP), and, increasingly, wind power (Danish Ministry of Energy, 1990; Andersen, 2000). Public acceptance has historically been low, with sub-majority support in national and EU surveys. More recent polling indicates a modest reopening of the debate, but no policy reversal yet (Andersen, 2000; Jamison et al., 1990; Bistline et al., 2025). Techno-economic system studies indicate that, under central assumptions for costs, discount rates, interconnection, and renewable resources, including nuclear power in the Danish power mix increases the total system cost relative to portfolios centred on renewables and flexibility, even where nuclear power can technically meet constraints (Jamison et al., 1990; Thellufsen et al., 2023, 2024; Moen et al., 2025).

Sweden represents a more nuanced case. Following the 1980 referendum and phase-out decision, subsequent political compromises allowed long-term operation, and, in 2010, a parliamentary decision permitted the replacement of existing reactors with new units. However, market liberalisation, ageing assets, and cost pressures led to the closure of four reactors between 2015 and 2020. Current government policy supports continued operation of the remaining six units and expresses openness to new-builds, potentially SMRs, subject to market viability and EU taxonomy compliance (Wikdahl, 1991; Roßegger and Ramin, 2013; WNA, 2026). Energy system modelling under current cost assumptions generally finds limited economic advantage from large new reactors, but some potential niche roles for modular units in high-electrification pathways (WNA, 2026). Scientific energy system analysis did not find a value added for nuclear power for Sweden (Kan et al., 2020).

Finland followed a more pragmatic, industry-led approach. Parliamentary approval for Olkiluoto 3 in 2002 and Hanhikivi 1 in 2010 reflected strong industrial consortium support and state involvement through financing guarantees. The cancellation of Hanhikivi 1 in 2022 after Russia's invasion of Ukraine underscored the geopolitical and supply-chain dimensions of nuclear power investment (Cour des comptes, 2025; Teollisuuden Voima Oyj (TVO), 2023; Satymov et al., 2025). Finnish analyses emphasise that new capacity could contribute to decarbonisation and security of supply but note public finance and just transition trade-offs under constrained budgets (Ministry of Economic Affairs and Employment of Finland, 2022; European Commission, 2022b, 2023; Satymov et al., 2025). Scientific energy system analysis found considerable increases in costs for the energy system in the case of new investments in nuclear power, raising massive concerns for a just transition (Satymov et al., 2025). Public opinion remains relatively stable and supportive, particularly following the completion of Olkiluoto 3 and Finland's progress towards deep geological disposal at *Onkalo* (Kojo et al., 2010; Posiva Oy, 2023).

Norway historically abstained from commercial nuclear power development despite its early reactor research programme. Abundant hydropower, strong interconnection, and political consensus around RE reduced perceived need. Energy system modelling likewise points to RE-dominated cost-optimal pathways under central assumptions (Seljom and Tomasgard, 2017). However, since 2021, the public debate has gradually intensified around potential SMRs for industrial clusters and remote regions. The government commissioned preliminary assessments in 2023, but maintains a technology-neutral policy position with no current plans for the deployment of commercial nuclear power (WNN, 2025b; Adelman and Sains, 2025; Aas-Hansen et al., 2024). Recent survey work suggests continued support for RE and mixed views on large new infrastructure, shaping feasibility constraints (Kaltenborn et al., 2023).

Overall, the Nordic experience illustrates diverse trajectories shaped by institutional histories, resource endowments, and public preferences. Denmark institutionalised a durable non-nuclear pathway; Sweden and Finland retained strategic optionality under different governance models; and Norway remains observational but engaged in exploratory assessment. Across the region, techno-economic studies and policy modelling indicate that cost and financing assumptions, rather than technical feasibility, remain the decisive parameters for the future role of nuclear power.

4. Nuclear in the scientific debate

The role of nuclear power in future decarbonised power systems has been the subject of extensive debate in the scientific literature. Several influential publications in the field of energy system modelling have promoted an expanded role for nuclear power in low-carbon transitions. For example, Sepulveda et al. (2018), Jenkins et al. (2018), and Bistline et al. (2025) emphasise the importance of firm low-carbon resources, including nuclear power, to complement variable RE. Similarly, the MIT (2018) highlights nuclear power as a strategic technology option in carbon-constrained futures, while Lynch et al. (2022) and Syri et al. (2008) provide region-specific analyses pointing to significant potential shares of nuclear power in future electricity mixes. More recently, Duan et al. (2022) present results from a least-cost analysis of flexible nuclear power in deeply decarbonised electricity systems, covering six diverse countries (United States, China, Germany, South Africa, Australia, and Brazil).

In these studies, results with high shares of nuclear power generation are typically driven by ignoring real-world long times between planning and operation of nuclear plants that were previously 10 to 19 years (Jacobson, 2009) but are now 12–23 years worldwide (Jacobson, 2022), optimistic cost assumptions, and oversimplifications in model structure. Duan et al. (2022), for instance, report scenarios in which nuclear power can be built quickly and contributes the majority of generation in fully decarbonised electricity systems, and in some cases approaches 100% of supply under very optimistic cost assumptions. Such outcomes arise in part because the modelling framework employs a limited technology portfolio and relies on nuclear power cost assumptions that are substantially below recent empirical observations, while simultaneously applying conservative assumptions for RE technologies such as solar PV.

To examine the robustness of these findings, we replicate the analysis of Duan et al. (2022) using the same scenario framework and set of countries and are able to reproduce their high-nuclear results under the original assumptions. However, when we rerun the model using more realistic assumptions, drawing on recent industrial, financial, and technical assessments, as well as peer-reviewed literature, we find that nuclear power no longer emerges as an economically significant option in any of the examined countries. Instead, solar PV, wind power, and complementary flexibility options dominate the least-cost pathways. We also extend the analysis by including France, a country with an existing large nuclear power fleet, in order to test whether legacy infrastructure alters cost-optimal pathways. Even in this case, the marginal role of new nuclear power investment remains limited under realistic cost assumptions.

These findings align with the results of integrated assessment models (IAMs) assessed by the Intergovernmental Panel on Climate Change (IPCC). Luderer et al. (2021), for example, shows that across a wide range of IAM scenarios, nuclear power contributes a moderate but declining share in most global mitigation pathways, with its role highly sensitive to assumed costs, construction times, and social acceptance. The consistency between detailed power system modelling under updated assumptions and broader IAM scenario ensembles indicates that the economic role of nuclear power is structurally constrained under current and foreseeable cost trajectories.

In summary, while parts of the modelling literature have promoted scenarios with very high nuclear power penetration, closer inspection shows that such results are strongly assumption-driven. When using empirically grounded cost and technology parameters, the contribution of nuclear power to the least-cost decarbonisation pathways is considerably smaller and, in many cases, negligible compared to RE and flexibility resources.

4.1. Cost assumptions on current and future nuclear and renewable technologies

The technologies considered in Duan et al. (2022) are subject to markedly different capital cost trajectories. Over the past two decades, the LCOE for solar PV and wind power has declined steeply, largely driven by learning effects, economies of scale, and globalised supply chains. Between 2010 and 2021, the LCOE of utility-scale PV fell by more than 85% and onshore wind power by nearly 55%, with costs expected to continue declining in the coming decades (IPCC, 2022; Lazard, 2025). By contrast, nuclear power has experienced persistently rising capital costs, reflecting complex construction processes, regulatory requirements, and schedule delays. Model results, therefore, depend critically on the assumptions made about these divergent cost dynamics. In this respect, Duan et al. (2022) tend to overestimate the present and future costs of solar PV, while underestimating the costs of nuclear power in their optimistic scenario.

The history of nuclear power economics has been characterised by high and increasing capital expenditures. Davis (2012) documents that nuclear power has consistently failed to achieve cost competitiveness with alternative generation technologies, a conclusion supported by historical analyses of the United States (Joskow, 1982) and France (Grubler, 2010). Recent assessments confirm that this trend has not reversed (Rothwell, 2022). Indeed, private investment in new nuclear power construction has largely disappeared in liberalised markets, with projects proceeding only under direct state ownership (e.g., France, Russia, China), regulated markets with captive customers (United States pre-restructuring), or heavy reliance on subsidies (e.g., Germany during earlier phases of its nuclear power programme).

Data from the IPCC scenario database illustrate this persistence of high costs. The average capital costs for new nuclear power increased slightly from 7421 USD_{2010}/kW_{el} in the 2019 dataset to 7478 USD_{2010}/kW_{el} in the 2022 update, confirming the expectation of only modest cost increases rather than reductions in the IAM community (Huppmann et al., 2019; Byers et al., 2022). Against this backdrop, the assumptions used in Duan et al. (2022) appear overly optimistic. Their value for “near current” nuclear power plants of 6317 USD_{2010}/kW_{el} lies at the very bottom of the empirical range of recent so-called “Generation III” light water reactors. More strikingly, their assumption of 4000 USD_{2010}/kW_{el} for “newly proposed designs” (so-called “advanced nuclear” or “Generation IV” concepts) is implausible, given the lack of any commercial deployment to date (Pistner et al., 2024).

Observed cost data further underscore the discrepancy. In 2012, the so-called “Generation III” reactors reported overnight capital costs between 5385 and 8199 USD_{2012}/kW_{el}. By 2025, this range had increased to 9020–14,820 USD_{2025}/kW_{el}, implying an average nominal growth of 2.6–6.2% annually over the past decade (Lazard, 2025). The U.S. Vogtle project in Georgia illustrates the scale of costs and schedule risks with a capacity of 2.23 GW: total costs were estimated to exceed 30 bn USD, reaching about 34 bn USD by 2022 (15,250 USD/kW), following a planning and construction period of roughly 18 years (WNN, 2022). Comparable delays and overruns have been documented for Olkiluoto 3 in Finland (18 years), Flamanville in France (18 years to date), and Hinkley Point C in the United Kingdom (12 years minimum) Weibezahn and Steigerwald (2024); Jacobson (2020). Such real-world evidence makes the assumption of rapid and inexpensive deployment in Duan et al. (2022) unrealistic.

By contrast, the assumptions applied to solar PV in Duan et al. (2022) are conservative. For “near current” costs, they employ the U.S. EIA value of 1331 USD_{2019}/kW_{el}, which is about 50% higher than observed investment costs for utility-scale PV in most global regions (Lazard, 2021). Their 2050 projection of 624 USD_{2019}/kW_{el}, based on NREL estimates, is likewise overstated relative to international benchmarks. For example, the IEA (2021a) projects utility-scale PV capital costs by 2050 of 420 USD_{2020}/kW_{el} in the United States, 340 USD_{2020}/kW_{el} in the EU, 280 USD_{2020}/kW_{el} in China, and 220 USD_{2020}/kW_{el} in India under its Net Zero Emissions scenario.

Together, these data highlight that the nuclear power-intensive results of Duan et al. (2022) are highly sensitive to cost assumptions. Empirically observed capital cost trajectories for nuclear power have been rising, while those for solar PV and wind power have been falling rapidly. Substituting more realistic input values for both technologies, therefore, leads to markedly different modelling outcomes, with RE dominating cost-optimal decarbonisation pathways, and nuclear power playing, at most, a minor role.

4.2. Re-estimation of model results using an energy system model

To assess the credibility of the findings presented by Duan et al. (2022), four scenarios were simulated using the LUT Energy System Transition Model (LUT-ESTM), a linear optimisation framework with the objective of minimising total annual system cost. A detailed description of the model is provided in Bogdanov et al. (2019) and its comparison with other models is discussed in Prina et al. (2020). The four scenarios replicate the system design used in Duan et al. (2022), but apply ten incremental CO_2 emission reduction constraints in the power sector of the selected countries. France was additionally included in this analysis, due to its high share of nuclear power generation in the current electricity mix. The complete set of countries is shown in Fig. 1, together with the corresponding scenario descriptions.

A wide range of technologies is considered for representing the most realistic optimisation of the power system with the existing technologies.

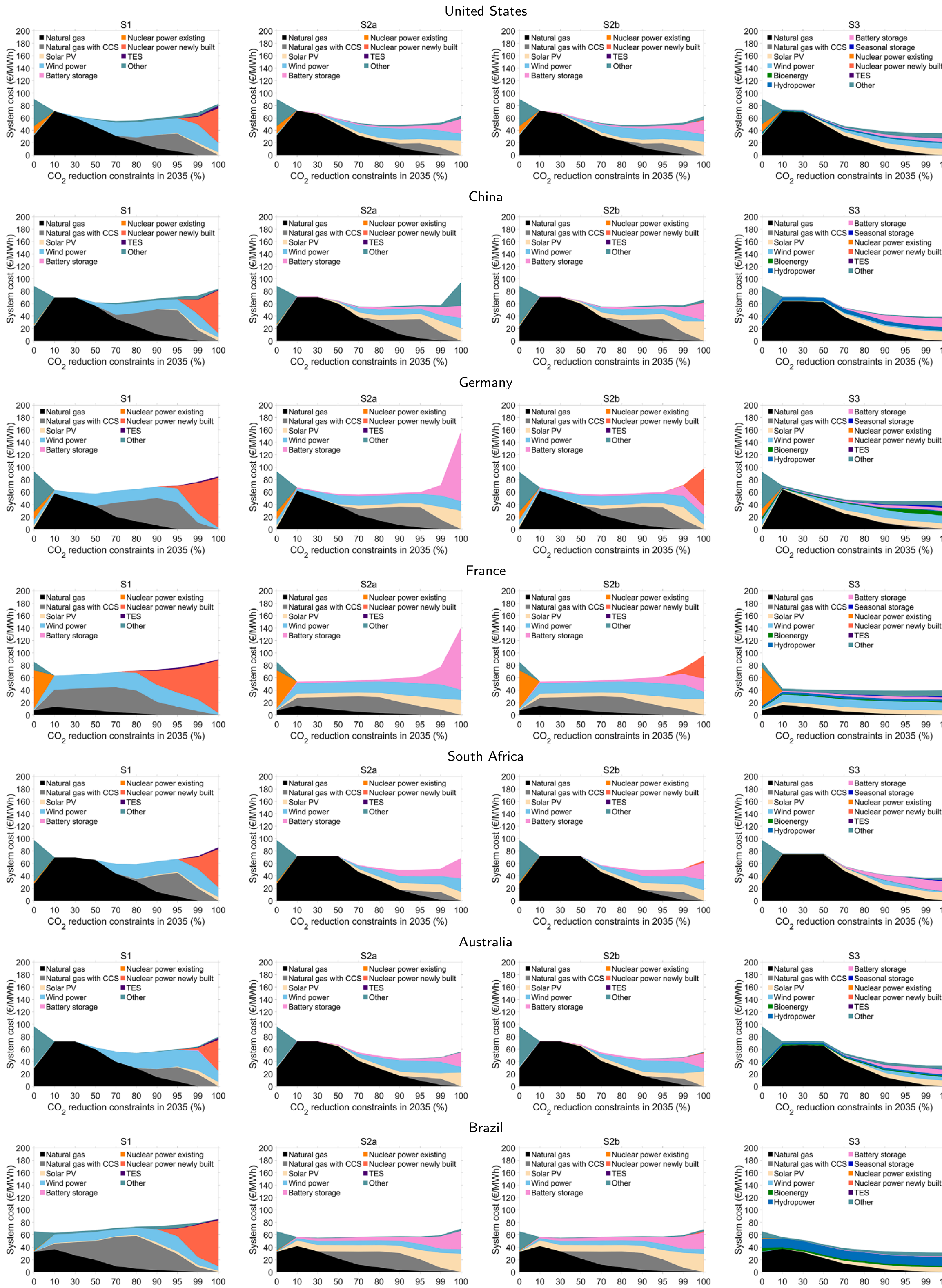

Fig. 1. Model results from LUT-ESTM. Oversimplified (left; S1) vs. simplified (right; S3) power sector technology portfolio with cost assumptions taken from Duan et al. (2022) (left) and according to assumptions regularly used for scenarios applying LUT-ESTM (right), and an oversimplified technology portfolio with standard RE costs and realistic nuclear power costs (centre left; S2a) and unrealistically low nuclear power costs (centre right; S2b). **S1**: reproduction of Duan et al. (2022) for the demand data in 2035: oversimplified technology portfolio and unrealistically low nuclear power costs, and outdated renewables costs. **S2a**: S1 but with realistic nuclear power and RE cost assumptions in 2035 according to Lazard (2021). The cost assumptions for battery storage and natural gas with carbon capture transport and sequestration (CCS) are taken from the NZE 2050 scenario of the IEA (2021a). It is crucial to note that the IEA cost assumptions only include carbon capture; thus, 40 EUR/tCO_2 is assumed for transportation and sequestration of CO_2 to address this gap. **S2b**: S2a but with unrealistically low nuclear power costs. **S3**: full power sector portfolio and cost assumptions of the LUT-ESTM for 2035.

However, such an energy system analysis is still simplified since the impact of sector coupling (Brown et al., 2018; Mathiesen et al., 2015; Gea-Bermúdez et al., 2021; Osorio-Aravena et al., 2023; Göke et al., 2023) and additional system flexibility (Khalili et al., 2025) are neglected. A constant carbon cost of 68 €/tCO_2 is applied for all the scenarios.

Although Duan et al. (2022) report their principal results for the 2019 power system, demand data for the year 2035 were used in this analysis. This choice reflects the long construction periods of nuclear power plants, with the average construction time currently estimated at 9.4 years over the last decade (Schneider et al., 2025). For consistency, however, the cost assumptions of the original study were retained in scenario S1. Projected electricity demand, hourly load profiles, RE resource data, and other system inputs are taken from Bogdanov et al. (2019). In line with the original study, all newly installed nuclear power capacity is assumed to be of the advanced type.

The comparison of scenarios highlights the critical influence of technology portfolio breadth and cost assumptions. As illustrated in Fig. 1, an oversimplified system design combined with optimistic nuclear power cost assumptions and outdated RE cost inputs results in outcomes that exaggerate the role of nuclear power while inflating system costs. For instance, the assumption in Duan et al. (2022) that all countries begin from a natural gas–dominated system neglects existing infrastructure, leading to unrealistic system configurations. This is particularly problematic in cases such as Brazil, where hydropower already accounts for a dominant share of electricity generation.

When realistic technology costs from Lazard (2021) are applied while maintaining the limited technology portfolio (S2a), the model selects no new nuclear power capacity, but system costs remain excessively high. This outcome is attributable to the exclusion of crucial flexibility providers such as hydropower, bioenergy, and long-duration storage. In scenario S2b, where RE is costed realistically, but nuclear power is assumed at implausibly low levels from IEA (2021a), nuclear power contributes marginally, but only for achieving the final 1% of CO_2 emission reductions. By contrast, the inclusion of a broad range of power sector technologies and the most up-to-date cost assumptions (S3) results in a least-cost pathway dominated by RE, with nuclear power playing no meaningful role. It must be emphasised, however, that even this design remains restricted to the power sector only, excluding the wider benefits of sector coupling (Brown et al., 2018; Mathiesen et al., 2015; Gea-Bermúdez et al., 2021; Osorio-Aravena et al., 2023; Göke et al., 2023). Table 1 summarises the key cost assumptions across scenarios. These inputs demonstrate how different capital cost trajectories fundamentally alter model outcomes, underscoring the importance of transparent and empirically grounded assumptions.

It should further be noted that nuclear power contributes to the solutions in scenario S2b only for single-node systems (Germany, France, and South Africa). In multi-node systems (e.g., the United States, China, Brazil, and Australia), intra-country electricity exchange eliminates the need for nuclear power generation and reduces both storage overutilisation and RE curtailment. To further probe the sensitivity of the results, two variations of scenarios were tested, named S1b and S3b, as they vary the main S1 and S3 scenarios. In S3b, advanced nuclear power capacity was allowed under the S3 framework, with the nuclear power cost assumptions of Duan et al. (2022); even under these conditions, nuclear power did not enter the cost-optimal solution. Conversely, in S1b, the S1 configuration was modified to include additional flexibility providers such as hydropower, bioenergy, and seasonal storage. Here, only Germany exhibited a marginal nuclear power contribution, with all other countries able to balance the system without nuclear power input. Still, no flexibility from sector coupling has been assumed for the results for Germany, which is expected to further shift the results towards RE.

Overall, the results indicate that when realistic costs and a comprehensive technology portfolio are applied, nuclear power does not emerge as a cost-effective option in the power systems examined. Instead, high shares of RE, supported by existing hydropower, bioenergy, and advanced storage technologies, dominate the least-cost pathways.

Table 1
Key cost assumptions for scenarios.

Technologies		Units	S1	S2a	S2b	S3
Solar PV	CAPEX	USD/kW_{el}	1331	480	480	266
	OPEX fix	USD/(kW_{el} a)	15	7	7	6
	OPEX var	USD/kWh_{el}	–	–	–	–
	Lifetime	Years	25	35	35	35
Wind onshore	CAPEX	USD/kW_{el}	1319	996	996	1084
	OPEX fix	USD/(kW_{el} a)	26	26	26	22
	OPEX var	USD/kWhel	–	–	–	–
	Lifetime	Years	25	20	20	30
Nuclear advanced	CAPEX	USD/kW_{el}	1651	–	4739	–
	OPEX fix	USD/(kW_{el} a)	32	–	152	–
	OPEX var	USD/kWh_{el}	0.002	–	0.004	–
	Fuel cost	USD/kWh_{th}	0.006	–	0.003	–
	Lifetime	Years	40	–	40	–
Nuclear conventional	CAPEX	USD/kW_{el}	–	9708	9708	6357
	OPEX fix	USD/(kW_{el} a)	–	114	114	111
	OPEX var	USD/kWh_{el}	–	0.004	0.004	0.003
	Fuel cost	USD/kWh_{th}	–	0.003	0.003	0.003
	Lifetime	Years	–	40	40	40
Steam turbine	CAPEX	USD/kW_{el}	1855	1013	1013	1013
	OPEX fix	USD/(kW_{el} a)	34	20	20	20
	OPEX var	USD/kWh_{el}	–	–	–	–
	Lifetime	Years	30	30	30	30
Battery storage	CAPEX	USD/kWh_{el}	366	144	144	100
	OPEX fix	USD/(kWh_{el} a)	12	2	2	2
	OPEX var	USD/kWh_{el}	–	–	–	–
	Lifetime	Years	10	20	20	20
Battery storage interface	CAPEX	USD/kW_{el}	49	49	49	49
	OPEX fix	USD/(kW_{el} a)	1	1	1	1
Th. energy storage	CAPEX	USD/kWh_{th}	28	26	26	26
	OPEX fix	USD/(kWh_{th} a)	–	0.4	0.4	0.4
	OPEX var	USD/kWh_{th}	–	–	–	–
	Lifetime	Years	30	30	30	30

Note: Cost assumptions in S2a and S2b are taken mainly from Lazard (2021) and the IEA (2021b), and the remaining assumptions are based on the LUT database (Manjong et al., 2021), either in absolute cost values or in relative development for projections. Additionally, cost assumptions for battery storage and battery storage interface are considered separately for the case of the S3. Similarly, it is assumed that the same battery storage interface costs are to be added for other scenarios. All scenarios use a weighted average cost of capital (WACC) of 7% for all technologies in accordance with the mean assumption in Duan et al. (2022). CAPEX is assumed as overnight CAPEX, including the cost of financing expenditures during permitting, construction, and installation periods.

5. Conclusions

This study assessed the role of nuclear power in rapidly decarbonising power systems using observed market data, harmonised cost benchmarks (price-year consistent), and a transparent modelling framework. Three results emerge.

First, based on observed 2024 system data, most incremental electricity generation and capacity additions were delivered by wind power and solar photovoltaics, while global nuclear power output was broadly flat, even compared to 2006 data, and concentrated in existing fleets. Contemporary cost benchmarks indicate substantially lower central levelized costs of electricity for utility-scale solar photovoltaics and onshore wind power than for new large nuclear power under typical OECD financing conditions. Because the levelized cost of electricity omits system value (capacity credit, flexibility, and networks), these comparisons were interpreted within a system-cost framework rather than as stand-alone rankings.

Second, replication and stress tests of the share of nuclear power in energy system model designs show strong assumption sensitivity. Under the original input set with optimistic nuclear power and conservative renewable energy costs and a restricted technology portfolio, the least-cost solution features high nuclear power shares. When inputs are aligned to 2021-real benchmarks, financing terms are made explicit, and widely deployed flexibility options are included, least-cost systems shift to portfolios centred on renewable energy with storage, demand response, and existing dispatchable resources. Adding a country with a large nuclear power legacy does not materially change this outcome for new nuclear power under central assumptions. Nuclear power enters the least-cost mixes only under specific conditions: markedly lower nuclear power capital expenditures or financing costs, higher fuel and/or carbon prices, or binding constraints on renewable energy deployment, transmission expansion, or flexibility.

Third, empirical project experience and prevailing financing practices are consistent with the modelled patterns. Long construction times and delivery risks increase effective financing costs for new nuclear power projects, and projects typically proceed where risk is attenuated by sovereign balance sheets or regulated revenue models. By contrast, modular renewable energy projects benefit from shorter lead times and faster learning cycles. For existing fleets, life-extension can be cost-effective relative to new builds, subject to safety, refurbishment, and liability considerations.

Policy implications follow directly. Credible transition strategies should (i) ground modelling in observation based costs and clearly stated financing terms; (ii) evaluate options on a system-cost basis that internalises flexibility, while maintaining optionality for firm low-carbon resources where local constraints make them valuable; and (iii) treat new nuclear power as a contingent option whose competitiveness depends on verifiable reductions in capital expenditures, demonstrable schedule performance, and durable de-risking frameworks.

Limitations of this work include a primary focus on the power sector, a simplified treatment of sector coupling, and uncertainty in long-horizon backend and liability costs. Future research should quantify resilience and adequacy benefits across portfolios and test results under alternative market designs and costs of capital regimes.

Overall, the evidence indicates that under current cost and financing conditions, renewable energy-centred portfolios with complementary flexibility dominate least-cost pathways, while the role of new nuclear power is conditional and system-specific.

CRediT authorship contribution statement

Jens Weibezahn: Writing – review & editing, Writing – original draft, Supervision, Investigation, Data curation, Conceptualization, Methodology. **Björn Steigerwald:** Writing – review & editing, Writing – original draft, Investigation, Data curation. **Arman Aghahosseini:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization, Software, Validation. **Christian von Hirschhausen:** Writing – original draft, Supervision. **Mark Z. Jacobson:** Writing – review & editing. **Christian Breyer:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Conceptualization, Data curation, Formal analysis, Investigation, Software, Visualization.

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.

Acknowledgements

Financial support from the Copenhagen School of Energy Infrastructure (CSEI) is acknowledged. The activities of CSEI are funded jointly in cooperation between Copenhagen Business School and energy sector partners. Additionally, we want to thank the reviewers for their constructive feedback on earlier drafts of this paper. The usual disclaimer applies.

Data availability

Data will be made available on request.

References

Aas-Hansen, O., Saele, S.O., Kristiansen, H., Amosova, N., Kickhofel, J., Hesthammer, J., 2024. Norsk Kjernekraft and the Advancement of Nuclear in Norway. In: Proceedings of the International Conference on Small Modular Reactors and Their Applications, https://conferences.iaea.org/event/374/papers/30956/files/12411-ID_241_Norsk.

Abou-Jaoude, A., Larsen, L.M., Guaita, N., Trivedi, I., Joseck, F., Lohse, C., Hoffman, E., Stauff, N., Shirvan, K., Stein, A., 2024. Meta-Analysis of Advanced Nuclear Reactor Cost Estimations. Technical Report INL/RPT–24-77048, Idaho National Laboratory, https://doi.org/10.2172/2371533.

Adelman, O., Sains, A., 2025. Norwegian Government Moves Ahead with Potential Commercial Nuclear Project. S&P Global. https://www.spglobal.com/commodity-insights/en/news-research/latest-news/electric-power/040925-norwegian-government-moves-ahead-with-potential-commercial-nuclear-project.

AGEB, 2025. Energieverbrauch in Deutschland Im Jahr 2024. Technical Report, Arbeitsgemeinschaft Energiebilanzen E.V. https://ag-energiebilanzen.de/wp-content/uploads/AGEB_Jahresbericht2024_20250801_dt.pdf.

Andersen, H., 2000. Energy Policy in Denmark: A Historical Perspective. Aarhus University Press.

Baade, F., 1958. Welt-Energiewirtschaft: Atomenergie - Sofortprogramm Oder Zukunftsplanung. Rowohlt.

Berthélemy, M., Escobar Rangel, L., 2015. Nuclear reactors' construction costs: the role of lead-time, standardization and technological progress. Energy Policy 82, 118–130. https://doi.org/10.1016/j.enpol.2015.03.015

Bistline, J., Bragg-Sitton, S., Cole, W., Dixon, B., Eschmann, E., Ho, J., Kwon, A., Martin, L., Murphy, C., Namovicz, C., Sowder, A., 2023. Modeling nuclear energy's future role in decarbonized energy systems. iScience 26, 105952. https://doi.org/10.1016/j.isci.2023.105952

Bistline, J., Molar-Cruz, A., Blanford, G., Diamant, A., 2025. Value of voluntary carbon markets in energy systems decarbonization. NPJ Clim. Action 4, 50. https://doi.org/10.1038/s44168-025-00257-y

Bogdanov, D., Farfan, J., Sadovskaia, K., Aghahosseini, A., Child, M., Gulagi, A., Oyewo, A.S., de Souza Noel Simas Barbosa, L., Breyer, C., 2019. Radical transformation pathway towards sustainable electricity via evolutionary steps. Nat. Commun. 10, 1077. https://doi.org/10.1038/s41467-019-08855-1

Brown, T., Schlachtberger, D., Kies, A., Schramm, S., Greiner, M., 2018. Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable european energy system. Energy 160, 720–739. https://doi.org/10.1016/j.energy.2018.06.222

Burr, W., 2014. A scheme of 'control': the United States and the origins of the nuclear suppliers' group, 1974–1976*. Int. Hist. Rev. 36, 252–276. https://doi.org/10.1080/07075332.2013.864690

Byers, E., Krey, V., Kriegler, E., Riahi, K., Schaeffer, R., Kikstra, J., Lamboll, R., Nicholls, Z., Sandstad, M., Smith, C., van der Wijst, K., Lecocq, F., Portugal-Pereira, J., Saheb, Y., Stromann, A., Winkler, H., Auer, C., Brutschin, E., Lepault, C., Müller-Casseres, E., Gidden, M., Huppmann, D., Kolp, P., Marangoni, G., Werning, M., Calvin, K., Guivarch, C., Hasegawa, T., Peters, G., Steinberger, J., Tavoni, M., van Vuuren, D., Al Khourdajie, A., Forster, P., Lewis, J., Meinshausen, M., Rogelj, J., Samset, B., Skeie, R., 2022. AR6 Scenarios Database. https://doi.org/10.5281/zenodo.5886912

Bärenbold, R., Bah, M.M., Lordan-Perret, R., Steigerwald, B., Von Hirschhausen, C., Wealer, B., Weigt, H., Wimmers, A., 2024. Decommissioning of commercial nuclear power plants: insights from a multiple-case study. Renew. Sustain. Energy Rev. 201, 114621. https://doi.org/10.1016/j.rser.2024.114621

Cochran, T.B., Feiveson, H.A., Patterson, W., Pshakin, G., Ramana, M.V., Schneider, M., Suzuki, T., Hippel von, F., 2010. Fast Breeder Reactor Programs: History and Status. Technical Report Research Report 8, International Panel on Fissile Materials. http://fissilematerials.org/library/2010/02/fast_breeder_reactor_programs_.html.

Cole, W., Murphy, C., Ho, J., Bistline, J., Sowder, A., 2023. The potential role for new Nuclear in the U.S. Power system: a view from electricity system modelers. Electr. J. 36, 107250. https://doi.org/10.1016/j.tej.2023.107250

Cour des comptes, 2012. The Costs of the Nuclear Power Sector. Thematic Public Report. Cour Des Comptes. https://www.ccomptes.fr/sites/default/files/EzPublish/thematic_public_report_costs_nuclear_.

Cour des comptes, 2025. La Filière EPR: Une Dynamique Nouvelle, Des Risques Persistants. Technical Report, Cour Des Comptes. https://www.ccomptes.fr/fr/publications/la-filiere-epr-une-dynamique-nouvelle-des-risques-persistants.

Cowan, R., 1990. Nuclear power reactors: a study in technological lock-in. J. Econ. Hist. 50, 541–567. https://doi.org/10.1017/S0022050700037153

Danish Ministry of Energy, 1990. Energi 2000 – Handlingsplan for en bæredygtig udvikling. Technical Report.

Dashti, M., Sahin, H., Sacchi, R., Rocco, M., Breyer, C., 2025. Prospective life cycle assessment of Baseload hydrogen based on solar photovoltaics and wind power including underground hydrogen storage. Sustain. Prod. Consum. 61, 209–230. https://doi.org/10.1016/j.spc.2025.10.017

Davis, L.W., 2012. Prospects for nuclear power. J. Econ. Perspect. 26, 49–66. https://doi.org/10.1257/jep.26.1.49

Davis, L.W., Wolfram, C., 2012. Deregulation, consolidation, and efficiency: evidence from US nuclear power. Am. Econ. J. Appl. Econ. 4, 194–225. https://doi.org/10.1257/app.4.4.194

Downer, J., Ramana, M.V., 2021. Empires built on sand: on the fundamental implausibility of reactor safety assessments and the implications for nuclear regulation. Regul. Gov. 15, 1304–1325. https://doi.org/10.1111/rego.12300

Drogan, M., 2019. The Atoms for Peace Program and the Third World. Cah. du monde russe 60, 441–460. https://doi.org/10.4000/monderusse.11249

Duan, L., Petroski, R., Wood, L., Caldeira, K., 2022. Stylized least-cost analysis of flexible nuclear power in deeply decarbonized electricity systems considering wind and solar resources worldwide. Nat. Energy. https://doi.org/10.1038/s41560-022-00979-x

EIA, 2024. Plant Vogtle unit 4 begins commercial operation. https://www.eia.gov/todayinenergy/detail.php?id=6163.

Energy Institute, 2025. Statistical Review of World Energy 2025. Technical Report, Energy Institute. https://www.energyinst.org/statistical-review.

European Commission, 2022a. EU taxonomy: complementary Delegated Act to the EU Taxonomy: Inclusion of Nuclear Energy and Natural Gas. Technical Report, European Commission. https://finance.ec.europa.eu/publications/eu-taxonomy-complementary-climate-delegated-act-accelerate-decarbonisation_en.

European Commission, 2022b. EU Cohesion Policy: more than €465 million for a just climate transition in Finland. https://ec.europa.eu/commission/presscorner/api/files/document/print/pl/ip_22_7802/IP_22_7802_EN.pdf.

European Commission, 2023. 2023 Country Report – Finland. Technical Report, European Commission, DG ECFIN. https://economy-finance.ec.europa.eu/system/files/2023-06/ip250_en.pdf.

European Union, 2012. Consolidated version of the treaty establishing the European Atomic Energy Community (Euratom). https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:12012A/TXT.

Fraunhofer ISE, 2024. Stromgestehungskosten Erneuerbare Energien in Deutschland. Technical Report, Fraunhofer ISE. https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/DE2024_ISE_Studie_Stromgestehungskosten_Erneuerbare_Energien.pdf.

Frieß, F., Arnold, N., Liebert, W., Müllner, N., 2021. Sicherheitstechnische Analyse Und Risikobewertung Von Konzepten Zu Partitionierungs- Und Transmutationsanlagen Für Hochradioaktive Abfälle. BASE – Forschungsberichte zur Sicherheit der nuklearen Entsorgung BASE-002/21, urn:nbn:de:0221-2021030826033. Bundesamt für die Sicherheit der nuklearen Entsorgung (BASE). https://www.base.bund.de/shareddocs/downloads/de/berichte/kt/gutachten-partitionierung-und-transmutation.html.

Gea-Bermúdez, J., Jensen, I.G., Münster, M., Koivisto, M., Kirkerud, J.G., Chen, Y.K., Ravn, H., 2021. The role of sector coupling in the green transition: a least-cost energy system development in northern-central Europe towards 2050. Appl. Energy 289, 116685. https://doi.org/10.1016/j.apenergy.2021.116685

Gibon, T., Hahn Menacho, A., 2023. Parametric life cycle assessment of nuclear power for simplified models. Environ. Sci. Technol. 57, 14194–14205. https://doi.org/10.1021/acs.est.3c03190

Glynos, D., Scharf, H., 2024. Postponing germany's nuclear phase-out: a smart move in the European energy crisis? Energy Policy 192, 114208. https://doi.org/10.1016/j.enpol.2024.114208

Goldberg, S., Rosener, R., 2011. Nuclear Reactors: Generation to Generation. Technical Report, American Academy of Arts & Sciences. https://www.amacad.org/sites/default/files/academy/pdfs/nuclearReactors.pdf.

Gross, L.C., 1976. The Energy Reorganization Act of 1974: more power to the people? Loyola Univ. Chic. Law J. 7, 410–430. https://lawecommons.luc.edu/luclj/vol7/iss2/7/.

Grubler, A., 2010. The costs of the French nuclear scale-up: a case of negative learning by doing. Energy Policy 38, 5174–5188. https://doi.org/10.1016/j.enpol.2010.05.003

Göke, L., Weibezahn, J., Kendziorski, M., 2023. How flexible electrification can integrate fluctuating renewables. Energy 278, 127832. https://doi.org/10.1016/j.energy.2023.127832

Haikola, S., Anshelm, J., 2025. Winds of change in Swedish energy policy - the limits to neoliberalism as policy paradigm and as political rationality. Energy Res. Soc. Sci. 127, 104269. https://doi.org/10.1016/j.erss.2025.104269

Graf von Hardenberg, W., 2011. Nuclear power, no thanks! the aftermath of Chernobyl in Italy and the Nuclear power referendum of 1987. Arcadia. https://doi.org/10.5282/RCC/2649

Hecht, G., 1998. The Radiance of France: Nuclear Power and National Identity after World War II, Inside technology, MIT Press.

Hjelmeland, M., Nøland, J.K., Backe, S., Korpås, M., 2025. The role of nuclear energy and baseload demand in capacity expansion planning for low-carbon power systems. Appl. Energy 377, 124366. https://doi.org/10.1016/j.apenergy.2024.124366

Holloway, D., 2008. Stalin and the Bomb: The Soviet Union and Atomic Energy, 1939-1956. Yale University Press, https://doi.org/10.2307/j.ctvf3w23z

Horan, J.R., Gammill, W.P., 1963. The health Physics aspects of the SL-1 accident. Health Phys. 9, 177–186. https://doi.org/10.1097/00004032-196302000-00006

Huppmann, D., Kriegler, E., Krey, V., Riahi, K., Rogelj, J., Rose, S., Weyant, J., Bauer, N., Bertram, C., Bosetti, V., Calvin, K., Doelman, J., Drouet, L., Emmerling, J., Frank, S., Fujimori, S., Gernaat, D., Grubler, A., Guivarch, C., Haigh, M., Holz, C., Iyer, G., Kato, E., Keramidas, K., Kitous, A., Leblanc, F., Liu, J.Y., Löffler, K., Luderer, G., Marcucci, A., McCollum, D., Mima, S., Popp, A., Sands, R., Sano, F., Strefler, J., Tsutsui, J., Van Vuuren, D., Vrontisi, Z., Wise, M., Zhang, R., 2019. IAMC 1.5°c Scenario Explorer and Data Hosted by IIASA. https://doi.org/10.5281/zenodo.3363345

IAEA, 1997. Vienna Convention on civil liability for nuclear damage (1963) as amended by the 1997 protocol. https://www.iaea.org/publications/documents/infcircs/vienna-convention-civil-liability-nuclear-damage.

IAEA, 2023. Global Status of Decommissioning of Nuclear Installations. IAEA Nuclear Energy Series NW-T-2.16. International Atomic Energy Agency. https://www.iaea.org/publications/15197/global-status-of-decommissioning-of-nuclear-installations.

IAEA, 2025. Nuclear Power Reactors in the World. Number IAEA-RDS-2/45 in Reference Data Series No. 2, International Atomic Energy Agency, https://www.iaea.org/publications/15943/nuclear-power-reactors-in-the-world.

IEA, 2021a. Net Zero by 2050: A Roadmap for the Global Energy Sector. Technical Report, International Energy Agency. https://www.iea.org/reports/net-zero-by-2050.

IEA, 2021b. World Energy Outlook 2021. Technical Report, International Energy Agency. https://www.iea.org/reports/world-energy-outlook-2021.

IEA, 2024. Electricity 2024: Analysis and Forecast to 2026. Technical Report, International Energy Agency. https://www.iea.org/reports/electricity-2024.

IEA, 2025. World Energy Outlook 2025. Technical Report, International Energy Agency. https://www.iea.org/reports/world-energy-outlook-2025.

Ingersoll, D.T., Carelli, M.D., 2021. Handbook of Small Modular Nuclear Reactors. Elsevier, https://doi.org/10.1016/C2019-0-00070-2

IPCC, 2022. Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Technical Report, Cambridge University Press, https://doi.org/10.1017/9781009157926

Jacobson, M.Z., 2009. Review of solutions to global warming, AIR pollution, and energy security. Energy Environ. Sci. 2, 148–173. https://doi.org/10.1039/B809990C

Jacobson, M.Z., 2020. 100% Clean, Renewable Energy and Storage for Everything, 1 ed. Cambridge University Press, https://doi.org/10.1017/9781108786713

Jacobson, M.Z., 2022. No Miracles Needed: How Today's Technology Can Save Our Climate and Clean Our Air, 1 ed. Cambridge University Press, https://doi.org/10.1017/9781009249553

Jamison, A., Eyerman, R., Cramer, J., Læssøe, J., 1990. The Making of the New Environmental Consciousness: A Comparative Study of the Environmental Movements in Sweden, Denmark and the Netherlands. Edinburgh University Press.

Jankowitsch, O., 1994. The convention on nuclear safety. Nucl. Law Bull. No. 54 1994 (2), 9–22. https://www.oecd-nea.org/jcms/pl_21947/nuclear-law-bulletin-no-54-volume-1994/2.

Jenkins, L.M., Zhou, Z., Ponciroli, R., Vilim, R.B., Ganda, F., de Sisternes, F., Botterud, A., 2018. The benefits of nuclear flexibility in power system operations with renewable energy. Appl. Energy 222, 872–884. https://doi.org/10.1016/j.apenergy.2018.03.002

Joskow, P.L., 1982. Problems and prospects for nuclear energy in the United States. In: Daneke, G.A. (Ed.), Energy, Economics, and the Environment: Toward a Comprehensive Perspective. DC Heath and Co, pp. 231–254. INIS Reference Number: 14729440.

Jupe, R., 2012. The privatization of British energy: risk transfer and the state. Account. Organ. Soc. 37, 116–129. https://doi.org/10.1016/j.aos.2011.12.002

Kaltenborn, B.P., Keller, R., Krange, O., 2023. Attitudes toward wind power in norway–solution or problem in renewable energy development? Environ. Manag. 72, 922–931. https://doi.org/10.1007/s00267-023-01870-5

Kan, X., Hedenus, F., Reichenberg, L., 2020. The cost of a future low-carbon electricity system without nuclear power – the case of Sweden. Energy 195, 117015. https://doi.org/10.1016/j.energy.2020.117015

Kasińska, N., Mielcarek, A., Sierchuła, J., Szczerbowski, R., Ceran, B., 2025. Technical and economic comparative analysis of nuclear power plants: ap1000 and SMR. Energies 18, 4749. https://doi.org/10.3390/en18174749

Khalili, S., Lopez, G., Breyer, C., 2025. Role and trends of flexibility options in 100% renewable energy system analyses towards the power-to-x economy. Renew. Sustain. Energy Rev. 212, 115383. https://doi.org/10.1016/j.rser.2025.115383

Kojo, M., Kari, M., Litmanen, T., 2010. The socio-economic and communication challenges of spent nuclear fuel management in Finland. Prog. Nucl. Energy 52, 168–176. https://doi.org/10.1016/j.pnucene.2009.06.008

Koomey, J., Hultman, N.E., 2007. A reactor-level analysis of busbar costs for US nuclear plants, 1970–2005. Energy Policy 35, 5630–5642. https://doi.org/10.1016/j.enpol.2007.06.005

Koomey, J., Hultman, N.E., Grubler, A., 2017. A reply to "historical construction costs of global nuclear power reactors". Energy Policy 102, 640–643. https://doi.org/10.1016/j.enpol.2016.03.052

Koopmans, R., Duyvendak, J.W., 1995. The political construction of the nuclear energy issue and its impact on the mobilization of anti-nuclear movements in western Europe. Soc. Probl. 42, 235–251. https://doi.org/10.2307/3096903

Kooyman, T., 2021. Current state of partitioning and transmutation studies for advanced nuclear fuel cycles. Ann. Nucl. Energy 157, 108239. https://doi.org/10.1016/j.anucene.2021.108239

Lazard, 2021. Levelized Cost of Energy Analysis. LCOE Version 15.0, Lazard Inc. https://www.lazard.com/media/sptlfats/lazards-levelized-cost-of-energy-version-150-vf.pdf.

Lazard, 2025. Levelized Cost of Energy+. LCOE+ Version 18.0, Lazard Inc. https://www.lazard.com/media/uounhon4/lazards-lcoeplus-june-2025.pdf.

Lindvall, D., Sörqvist, P., Lindeberg, S., Barthel, S., 2025. The polarization of energy preferences – a study on social acceptance of wind and nuclear power in Sweden. Energy Policy 198, 114492. https://doi.org/10.1016/j.enpol.2024.114492

Lopez, G., Pourjamal, Y., Breyer, C., 2025. Paving the way towards a sustainable future or lagging behind? An ex-post analysis of the international energy agency's World Energy Outlook. Renew. Sustain. Energy Rev. 212, 115371. https://doi.org/10.1016/j.rser.2025.115371

Lovering, J.R., Yip, A., Nordhaus, T., 2016. Historical construction costs of global nuclear power reactors. Energy Policy 91, 371–382. https://doi.org/10.1016/j.enpol.2016.01.011

Luderer, G., Madeddu, S., Merfort, L., Ueckerdt, F., Pehl, M., Pietzcker, R., Rottoli, M., Schreyer, F., Bauer, N., Baumstark, L., Bertram, C., Dirnaichner, A., Humpenöder, F., Levesque, A., Popp, A., Rodrigues, R., Strefler, J., Kriegler, E., 2021. Impact of declining renewable energy costs on electrification in low-emission scenarios. Nat. Energy 7, 32–42. https://doi.org/10.1038/s41560-021-00937-z

Lynch, A., Perez, Y., Gabriel, S., Mathonniere, G., 2022. Nuclear fleet flexibility: modeling and impacts on power systems with renewable energy. Appl. Energy 314, 118903. https://doi.org/10.1016/j.apenergy.2022.118903

Löbl, O., 1956. Wirtschaftlichkeit DER Atomenergie. Elektrotech. Z. (ETZ) 77, 460.

MacKenzie, N.G., Knox, S., Hannon, M., 2022. Fast breeder reactor technology and the entrepreneurial state in the UK. Bus. Hist. 64, 1494–1509. https://doi.org/10.1080/00076791.2020.1809653

Manjong, N.B., Oyewo, A.S., Breyer, C., 2021. Setting the pace for a sustainable energy transition in Central Africa: the case of Cameroon. IEEE Access 9, 145435–145458. https://doi.org/10.1109/ACCESS.2021.3121000

Mathiesen, B.V., Lund, H., Connolly, D., Wenzel, H., Østergaard, P.A., Möller, B., Nielsen, S., Ridjan, I., Karnøe, P., Sperling, K., Hvelplund, F.K., 2015. Smart energy systems for coherent 100% renewable energy and transport solutions. Appl. Energy 145, 139–154. https://doi.org/10.1016/j.apenergy.2015.01.075

Mignacca, B., Locatelli, G., 2020. Economics and finance of small modular reactors: a systematic review and research agenda. Renew. Sustain. Energy Rev. 118, 109519. https://doi.org/10.1016/j.rser.2019.109519

Ministry of Economic Affairs and Employment of Finland, 2022. Just Transition Fund to mitigate effects of reduced peat energy use in Finland: programme out for comments. https://tem.fi/en/-/just-transition-fund-to-mitigate-effects-of-reduced-peat-energy-use-in-finland-proposed-programme-now-out-for-comments.

Mirletz, B., Vimmerstedt, L., Stehly, T., Stright, D., Cohen, S., Cole, W., Duffy, P., Feldman, D., Kurup, P., Ramasamy, V., Zuboy, J., Oladosu, G., Hoffmann, J., Eberle, A., Roberts, O., Mulas Hernando, D., Avery, G., Rosenlieb, E., Schleifer, A., Akindipe, D., Witter, E., Fuchs, B., Zuckerman, G., Zolan, A., Abou Jaoude, A., Larson, L., Lohse, C., Guaita, N., Trivedi, I., Joseck, F., Hedalen, T., Rakov, B., Sekar, A., 2024. 2024 Annual Technology Baseline (ATB) Cost and Performance Data for Electricity Generation Technologies. https://doi.org/10.25984/2377191

MIT, 2003. The future of Nuclear Power. Technical Report, Massachusetts Institute of Technology. http://web.mit.edu/nuclearpower/pdf/nuclearpower-full.pdf.

MIT, 2009. Update of the MIT 2003 future of Nuclear Power. Technical Report, Massachusetts Institute of Technology. https://energy.mit.edu/wp-content/uploads/2009/05/MITEI-The-Future-of-Nuclear-Power-Update.pdf.

MIT, 2018. The future of Nuclear Energy in a Carbon-Constrained World. Technical Report, Massachusetts Institute of Technology. http://energy.mit.edu/wp-content/uploads/2018/09/The-Future-of-Nuclear-Energy-in-a-Carbon-Constrained-World.pdf.

Moen, K.A., Hjelmeland, M., Nøland, J.K., 2025. The total costs of energy transitions with and without nuclear energy. Appl. Energy 402, 126888. https://doi.org/10.1016/j.apenergy.2025.126888

Murphy, C., Cole, W., Bistline, J., Bragg-Sitton, S., Dixon, B., Eschmann, E., Ho, J., Kwon, A., Martin, L., Namovicz, C., Sowder, A., 2023. Nuclear Power's future Role in a Decarbonized U.S. Electricity System. Technical Report NREL/TP-6A20-84451, National Renewable Energy Laboratory (NREL), https://doi.org/10.2172/1988235. https://www.nrel.gov/docs/fy23osti/84451.pdf.

Mykhalchyk Hradický, J., Sabovčík, R., 2025. Decommissioning without financial fallout: reforming public nuclear funds. Energy Policy 206, 114723. https://doi.org/10.1016/j.enpol.2025.114723

NEA, 2016. Costs of Decommissioning Nuclear Power Plants. Technical Report, OECD Nuclear Energy Agency. https://www.oecd-nea.org/jcms/pl_14910/costs-of-decommissioning-nuclear-power-plants.

NEA, 2023. Summary Report of the 16th Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation (16IEMPT). Technical Report, OECD Nuclear Energy Agency. https://www.oecd-nea.org/jcms/pl_103618/summary-report-of-the-16th-information-exchange-meeting-on-actinide-and-fission-product-partitioning-and-transmutation-16iempt.

NEA, 2024. Effective Frameworks and Strategies for Financing Nuclear New Build. Technical Report, OECD Nuclear Energy Agency. https://www.oecd-nea.org/jcms/pl_96124/effective-frameworks-and-strategies-for-financing-nuclear-new-build.

NRC, 2025. Subsequent license renewal (SLR) for nuclear power plants. https://www.nrc.gov/reactors/operating/licensing/renewal/subsequent-license-renewal.html.

Nriezedi-Anejionu, C., 2024. Carbon reduction and nuclear energy policy u-turn: the necessity for an international treaty on small modular reactors (SMR) new nuclear technology. Carbon Manag. 15, 2396585. https://doi.org/10.1080/17583004.2024.2396585

Osorio-Aravena, J.C., Aghahosseini, A., Bogdanov, D., Caldera, U., Ghorbani, N., Mensah, T.N.O., Haas, J., Muñoz-Cerón, E., Breyer, C., 2023. Synergies of electrical and sectoral integration: analysing geographical multi-node scenarios with sector coupling variations for a transition towards a fully renewables-based energy system. Energy 279, 128038. https://doi.org/10.1016/j.energy.2023.128038

O'Sullivan, P., 2023. Nuclear decommissioning: addressing the past and ensuring the future. IAEA Bull. 64 (1), 4–7. https://www.iaea.org/bulletin/nuclear-decommissioning-addressing-the-past-and-ensuring-the-future.

Pelinka, A., 1983. The nuclear power referendum in Austria. Elect. Stud. 2, 253–261. https://doi.org/10.1016/S0261-3794(83)80032-8

Penney, W., Schonland, B.F.J., Kay, J.M., Diamond, J., Peirson, D.E.H., 2017. Report on the accident at Windscale No. 1 pile on 10 October 1957. J. Radiol. Prot. 37, 780–796. https://doi.org/10.1088/1361-6498/aa7788

Peters, H.P., Albrecht, G., Hennen, L., Stegelmann, H.U., 1990. 'chernobyl' and the nuclear power issue in West German public opinion. J. Environ. Psychol. 10, 121–134. https://doi.org/10.1016/S0272-4944(05)80123-9

Pioro, I., 2023. Handbook of Generation IV Nuclear Reactors. Elsevier, https://doi.org/10.1016/C2019-0-01219-8

Pistner, C., Englert, M., von Hirschhausen, C., Böse, F., Steigerwald, B., Gast, L., Donderer, R., 2024. Analysis and Evaluation of the Development Status, Safety and Regulatory Framework for So-Called Novel Reactor Concepts. Research Reports on Nuclear Safety BASE-031/24, urn:nbn:de:0221-2024090546049. Federal Office for the Safety of Nuclear Waste Management (BASE). https://www.base.bund.de/shareddocs/downloads/en/expert-info/f/final-report-novel-reactor-concepts.html.

Posiva Oy, 2023. Posiva Annual Report 2023. Technical Report, Posiva Oy. https://www.posiva.fi/material/sites/posivaraportit/20242504-1104-H0sev57fz/x9za57k9d/Posiva_Annual_Report_2023.pdf.

Prina, M.G., Manzolini, G., Moser, D., Nastasi, B., Sparber, W., 2020. Classification and challenges of bottom-up energy system models - a review. Renew. Sustain. Energy Rev. 129, 109917. https://doi.org/10.1016/j.rser.2020.109917

Präger, F., Breyer, C., Fell, H.J., Von Hirschhausen, C., Kemfert, C., Steigerwald, B., Traber, T., Wealer, B., 2024. Evaluating nuclear power's suitability for climate change mitigation: technical risks, economic implications and incompatibility with renewable energy systems. Front. Environ. Econ. 3, 1242818. https://doi.org/10.3389/frevc.2024.1242818

Radkau, J., Hahn, L., 2013. Aufstieg Und Fall Der Deutschen Atomwirtschaft. Oekom Verlag.

Ramana, M.V., 2021. Small modular and advanced nuclear reactors: a reality check. IEEE Access 9, 42090–42099. https://doi.org/10.1109/ACCESS.2021.3064948

Reed, B.C., 2021. Manhattan Project. In: Encyclopedia of Nuclear Energy. Elsevier, pp. 78–91. https://doi.org/10.1016/B978-0-12-819725-7.00042-8

Renn, O., Marshall, J.P., 2016. Coal, nuclear and renewable energy policies in Germany: from the 1950s to the "energiewende". Energy Policy 99, 224–232. https://doi.org/10.1016/j.enpol.2016.05.004

Reuters, 2024. Poland's First Nuclear Plant Seen Starting Operations in 2040, Minister Says. Reuters. https://www.reuters.com/world/europe/polands-first-nuclear-plant-seen-starting-operations-2040-minister-says-2024-05-07/.

Roelofs, F., Breijder, P., Hania, R., De With, G., De Haas, G.J., Van Den Broek, J., Schram, R., 2024. Highlights and outlook of the Dutch PIONEER 2021–2024 r&d program. Nucl. Eng. Des. 417, 112873. https://doi.org/10.1016/j.nucengdes.2023.112873

Rothwell, G., 2022. Projected electricity costs in international nuclear power markets. Energy Policy 164, 112905. https://doi.org/10.1016/j.enpol.2022.112905

Rothwell, G., 2025. Contingency in nuclear power plant decommissioning cost estimation. Energy Econ. 149, 108721. https://doi.org/10.1016/j.eneco.2025.108721

Roßegger, S., Ramin, S., 2013. Explaining the ending of Sweden's nuclear phase-out policy: a new approach by referring to the advocacy coalition framework theory. Innovation: Eur. J. Soc. Sci. Res. 26 (4), 323–343. https://doi.org/10.1080/13511610.2012.699648

Satymov, R., Ruggiero, S., Steigerwald, B., Weibezahn, J., Duić, N., Ahola, J., Bogdanov, D., Breyer, C., 2025. Who will foot the bill? The opportunity cost of prioritising nuclear power over renewable energy for the case of Finland. Energy 337, 138630. https://doi.org/10.1016/j.energy.2025.138630

Schaffer, M.B., 2011. Toward a viable nuclear waste disposal program. Energy Policy 39, 1382–1388. https://doi.org/10.1016/j.enpol.2010.12.010

Schneider, M., Hazemann, J., Godoy, E., Dvorak, P., Gorchakov, D., Gürbüz, Ö., Hrdy, B., Jobin, P., Judson, T., Müllner, N., Kobayashi, Y., Ramana, M.V., Stier, S., Schleicher-Tappeser, R., Ting, Y.C., Suzuki, T., Wimmers, A., Winkler, H., Ahmed, M., Schneider, N., Stienne, A., Meinass, F., 2025. The World Nuclear Industry Status Report 2025. Technical Report, Mycle Schneider Consulting. https://www.worldnuclearreport.org/IMG/pdf/wnisr2025-v2.pdf.

Seljom, P., Tomasgard, A., 2017. The impact of policy actions and future energy prices on the cost-optimal development of the energy system in Norway and Sweden. Energy Policy 106, 85–102. https://doi.org/10.1016/j.enpol.2017.03.011

Sepulveda, N.A., Jenkins, J.D., De Sisternes, F.J., Lester, R.K., 2018. The role of firm low-carbon electricity resources in deep decarbonization of power generation. Joule 2, 2403–2420. https://doi.org/10.1016/j.joule.2018.08.006

Sorge, L., Neumann, A., 2021. Warheads of energy: exploring the linkages between civilian nuclear power and nuclear weapons in seven countries. Energy Res. Soc. Sci. 81, 102213. https://doi.org/10.1016/j.erss.2021.102213

Sovacool, B.K., 2013. Energy policymaking in Denmark: implications for global energy security and sustainability. Energy Policy 61, 829–839. https://doi.org/10.1016/j.enpol.2013.06.106

Sovacool, B.K., Ryu, H., 2025. Beyond economies of scale: learning from construction cost overrun risks and time delays in global energy infrastructure projects. Energy Res. Soc. Sci. 123, 104057. https://doi.org/10.1016/j.erss.2025.104057

Soytas, U., Magazzino, C., Mele, M., Schneider, N., 2022. Economic and environmental implications of the nuclear power phase-out in Belgium: insights from time-series models and a partial differential equations algorithm. Struct. Change Econ. Dyn. 63, 241–256. https://doi.org/10.1016/j.strueco.2022.10.001

Steigerwald, B., Weibezahn, J., Slowik, M., Von Hirschhausen, C., 2023. Uncertainties in estimating production costs of future nuclear technologies: a model-based analysis of small modular reactors. Energy 281, 128204. https://doi.org/10.1016/j.energy.2023.128204

Syri, S., Lehtila, A., Ekholm, T., Savolainen, I., Holttinen, H., Peltola, E., 2008. Global energy and emissions scenarios for effective climate change mitigation—deterministic and stochastic scenarios with the TIAM model. Int. J. Greenh. Gas Control 2 (2), 274–285. https://doi.org/10.1016/j.ijggc.2008.01.001

Szulecki, K., Overland, I., 2023. Russian nuclear energy diplomacy and its implications for energy security in the context of the war in Ukraine. Nat. Energy 8, 413–421. https://doi.org/10.1038/s41560-023-01228-5

Teollisuuden Voima Oyj (TVO), 2023. Regular electricity production has started at Olkiluoto 3 EPR. https://www.tvo.fi/en/index/news/pressreleasesstockexchangereleases/2023/regularelectricityproductionhasstartedatolkiluoto3epr.html.

Thellufsen, J.Z., Lund, H., Mathiesen, B.V., Madsen, P.T., Østergaard, P.A., Nielsen, S., Sorknæs, P., Wenzel, H., Østergaard, J., Münster, M., Rosendal, M.B., Madsen, H., Morthorst, P.E., Sørensen, P.B., Andresen, G.B., Gøtske, E.K., Pedersen, T.T., Victoria, M., 2023. Fakta Om Atomkraft I Danmark - Version 2: Input Til en Faktabaseret Diskussion Af Fordele Og Ulemper Ved Atomkraft Som en Del Af Den Grønne Omstilling I Danmark. Technical Report. https://orbit.dtu.dk/en/publications/fakta-om-atomkraft-i-danmark-version-2-input-til-en-faktabaseret-/.

Thellufsen, J.Z., Lund, H., Mathiesen, B.V., Østergaard, P.A., Sorknæs, P., Nielsen, S., Madsen, P.T., Andresen, G.B., 2024. Cost and system effects of nuclear power in carbon-neutral energy systems. Appl. Energy 371, 123705. https://doi.org/10.1016/j.apenergy.2024.123705

Thomas, S., 2010. Competitive energy markets and nuclear power: can we have both, do we want either? Energy Policy 38, 4903–4908. https://doi.org/10.1016/j.enpol.2010.04.051

Tsagkaris, C., Matiashova, L., Isayeva, A., 2022. The impacts of putting the Zaporizhzhia nuclear power plant in the line of fire. Public Health Chall. 1, e26. https://doi.org/10.1002/puh2.26

United States Congress, 2022. H.R.5376 - 117th Congress (2021–2022): an act to provide for reconciliation pursuant to title II of S. Con. Res. 14. https://www.congress.gov/bill/117th-congress/house-bill/5376.

University of Chicago, 2004. The Economic future of Nuclear Power. Technical Report, University of Chicago. https://www.nrc.gov/docs/ML1219/ML12192A420.pdf.

Van Vliet, M.T.H., Yearsley, J.R., Ludwig, F., Vögele, S., Lettenmaier, D.P., Kabat, P., 2012. Vulnerability of US and european electricity supply to climate change. Nat. Clim. Change 2, 676–681. https://doi.org/10.1038/nclimate1546

Wakeford, R., 2017. A double diamond anniversary—kyshtym and Windscale: the nuclear Accidents of 1957. J. Radiol. Prot. 37, E7–E13. https://doi.org/10.1088/1361-6498/aa7e87

Walker, J.S., 2005. Three Mile Island: A Nuclear Crisis in Historical Perspective, 1. paperb. pr ed. Univ. Of California Press.

Weibezahn, J., Steigerwald, B., 2024. Fission for funds: the financing of nuclear power plants. Energy Policy 195, 114382. https://doi.org/10.1016/j.enpol.2024.114382

Wikdahl, C.E., 1991. Sweden: nuclear power policy and public opinion. IAEA Bull. 33, 47–49. https://www.iaea.org/sites/default/files/publications/magazines/bulletin/bull33-1/33104792933.pdf.

WNA, 2026. Nuclear Power in Sweden. Technical Report, World Nuclear Association. https://world-nuclear.org/information-library/country-profiles/countries-o-s/sweden.

WNA, 2025. World Nuclear Performance Report 2025. Technical Report, World Nuclear Association. https://world-nuclear.org/news-and-media/press-statements/world-nuclear-performance-report-2025-nuclear-delivers-record-breaking-year-in-electricity-generation.

WNN, 2022. Further delay in startup of Vogtle ap1000s. World Nuclear News. https://www.world-nuclear-news.org/articles/further-delay-in-startup-of-vogtle-ap1000s.

WNN, 2025a. Belgium reverses phase-out policy as Denmark reconsiders nuclear. World Nuclear News. https://www.world-nuclear-news.org/articles/belgium-reverses-phase-out-policy-as-denmark-reconsiders-nuclear.

WNN, 2025b. Proposal for Norwegian SMR power plant progresses. World Nuclear News. https://world-nuclear-news.org/articles/proposal-for-norwegian-smr-power-plant-progresses.

WNN, 2025c. Taiwan's pro-nuclear vote fails to hit turnout threshold. World Nuclear News. https://www.world-nuclear-news.org/articles/low-turnout-invalidates-taiwan-referendum-result.

Zhou, Y., 2010. Why is China going nuclear? Energy Policy 38, 3755–3762. https://doi.org/10.1016/j.enpol.2010.02.053