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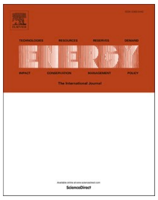

# Who will foot the bill? The opportunity cost of prioritising nuclear power over renewable energy for the case of Finland

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ABSTRACT

In an effort to decarbonise their energy systems, several countries have declared intentions to triple their nuclear power capacity by 2050 at the United Nations Framework Convention on Climate Change Conference of the Parties 28. The expansion of nuclear power includes plans for so-called small modular reactors, intended for electricity generation as well as combined heat and power production. This study aims to demonstrate the cost differences between nuclear-based and renewables-based energy-industry systems using the Finnish energy system as a case study. Four nuclear power expansion scenarios are examined, imposing 13.2 GW of nuclear power capacity into Finland's energy supply mix, with various capacities of small- and large-scale nuclear power plants alongside combined heat and power production from small-scale nuclear plants. These nuclear tripling scenarios are compared to a reference scenario that simulates a free cost optimisation with zero emissions target. The nuclear scenarios show 71–84% higher annualised system cost of 18.4–19.7 b€ compared to a renewables-based system costing 10.7 b€ in 2050. The reference scenario does not include the installation of new nuclear power capacities, indicating that new nuclear power plants are not part of a cost-optimal system. Additionally, the energy-industry system outlined in the reference scenario possesses fewer risks compared to nuclear tripling scenarios, particularly given that SMR technologies are not yet commercially available. The findings have important implications for energy justice, especially in terms of the significant opportunity cost presented by the nuclear decarbonisation pathway.

## 1. Introduction

There is a growing discourse on energy transition to low-carbon sources, with proponents advocating for both highly renewable energy (RE) systems [1] and the expansion of nuclear power [2,3]. At the United Nations Framework Convention on Climate Change Conference of the Parties 28 (COP28) 25 countries have declared their intent to triple their nuclear energy capacity by 2050 [4]. This commitment comes in spite of the risks associated with nuclear power in terms of cost, long lead times, waste disposal challenges, safety concerns, proliferation, considerable operational risks in war zones, and uranium supply uncertainties [5–9]. The COP28 declaration commits to triple global nuclear energy capacity from 2020 to 2050 by mobilising investments and supporting the construction of various nuclear power technologies, including small-capacity reactors, known as small modular reactors (SMR), although these technologies are not yet commercially viable [10].

New nuclear power plants may struggle to secure sufficient fuel for their entire operational lifetimes due to rising demand for uranium and limited reserves [11]. A recent evaluation of uranium supply found that known resources have not increased despite growing exploration efforts [12,13]. There are concerns over dependency on Russian technology [14,15] and warnings of impending scarcity if nuclear capacity is tripled [16]. These challenges render nuclear-centric energy planning less

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viable than 100% RE [17]. Additionally, plant construction and decommissioning, along with uranium mining, significantly contribute to the life cycle environmental impacts of nuclear power [18]. Furthermore, when considering the total energy consumption of the nuclear fuel cycle, it is projected to reach an ‘energy cliff’ [11] where the energy input equals the energy output, resulting in no net gain from nuclear power.

While many studies advocate for 100% RE-based systems [19,20], others see nuclear power as a viable option or a necessary complement to RE [21–24]. However, nuclear power is unlikely to meet the expectations for rapid capacity expansion to align with climate goals [5,25,26]. SMRs have been proposed as a cost-effective alternative to conventional reactors, but their lack of large-scale deployment and limited operational experience presents challenges. SMRs, akin to traditional nuclear power plants, require lengthy regulatory approvals, licensing, and operational testing to ensure safety [25], and their economic viability remains uncertain [27,28]. Despite these challenges, SMRs may have various applications, including replacing diesel in desalination, powering remote areas [29], supporting existing plants and integrating with RE [30], or reducing emissions in industries such as Canadian tar sands exploitation [31].

Optimised operational strategies, such as load-following [32], adjusting refuelling schedules, may enable SMRs to complement variable RE sources such as solar photovoltaics (PV), although their contribution to ancillary services may be limited [33]. Operating SMRs alongside substantial RE capacity or in hybrid configurations could improve their economic viability [34]. However, over-insistence on nuclear power may ultimately delay the energy transition.

Conversely, 100% RE-based systems are increasingly recognised as a more affordable option for decarbonisation [20] than nuclear power-centric systems, relying on improved energy storage and grid management, as documented for increasing periods of 100% RE in California [35]. Innovations, such as load frequency control, hydrogen storage, and Carnot batteries, are considered pivotal to maintain system stability and addressing long-term storage needs [36–38]. Recent progress in energy return on investment [39], variability mitigation, and grid-stabilising technologies coupled with declining RE costs further reinforce the viability of 100% RE-based systems [20].

With growing calls to deploy SMRs to address climate change [40] and energy security [41,42], it is essential to evaluate the economic costs and energy justice [43] implications of decarbonisation pathways. This study conducts a techno-economic assessment of scaling up nuclear power versus transitioning to a highly RE system using Finland as a case study. The results are interpreted through a socio-technical transitions and justice studies framework. Finland is a valuable case study due to its considerable nuclear power capacity (4.4 GW, representing 41% of its electricity supply) and strong political support for nuclear power projects [44], particularly for SMRs [45]. This case study offers insights that can inform decarbonisation strategies in other regions.

Finland’s current electricity mostly comes from RE and nuclear power, as shown in Fig. 1. Electricity generation capacity at the end of 2024 is made up of 4.4 GW nuclear power, 8.3 GW onshore wind power, 0.1 GW offshore wind power, 1.1 GW solar PV, 3.0 GW hydropower, 2.1 GW bioenergy-based combined heat and power (CHP) plants, and 3 GW fossil CHP and power plants.

Wind power has grown from 627 MW in 2014 to 8.36 GW in 2024 [47], with a compound annual growth rate (CAGR) of 30%. Up to 70% of the total wind power capacity in Finland was built without government subsidies [48]. The total capacity of wind power projects under planning is over 107 GW as of early 2025 [49], with 6.5 GW fully permitted and under construction. Solar PV has grown from 11 MW to 1.2 GW within the same period [47], with a CAGR of 60%. Moreover, the Finnish transmission system operator reports receiving 400 GW of grid connection inquiries with 50% onshore wind power, 25% offshore wind power, and 25% solar PV [50,51].

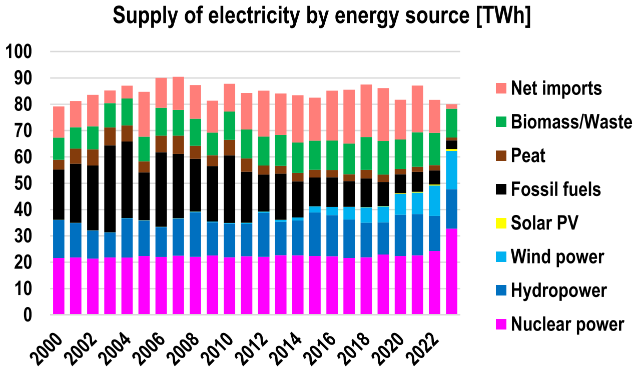

**Fig. 1.** Electricity supply mix in Finland [46].

Nuclear power expanded from 2.8 GW to 4.4 GW in 2023 [52] and its share of total electricity generation in Finland grew from under 30% to slightly over 40%, diverging from the global trend [53]. The construction of the latest nuclear reactor, Olkiluoto 3, started in 2005 and the planned start of commercial operation was 2010 [54]. After repeated delays, the unit was operational 13 years late. The final capital expenditure (CAPEX) of 11 b€ equals a cost overrun of 266% over the initial cost estimate of 3 b€ [55]. Another nuclear power plant (Hanhikivi) that began planning in 2009 was cancelled in spring 2022 [56], due to the Russian invasion of Ukraine, as the project was based on a Russian-designed reactor. This context highlights the complexities of nuclear power project development in Europe, where various financing models are being explored to mitigate risks and facilitate growth [7].

Several studies have shown the feasibility of a highly RE-based system in Finland [57–64]. Child and Breyer [58] and Pilpola et al. [61] show that carbon-neutrality can be achieved without nuclear power, and adding nuclear power increases energy system costs. Research on SMRs in energy systems is limited. SMR suitability and cost-effectiveness for district heating (DH) in Helsinki have been evaluated by Värri and Syri [65], demonstrating cost-effectiveness when used solely as a boiler. SMR-CHP profitability is heavily dependent on electricity prices, with an assumed CAPEX of 9408 €/kW$_{\mathrm{el}}$. Pursiheimo et al. [66] assert a cost-effectiveness of SMR-CHP compared to heat pumps in the Helsinki Metropolitan Area, projecting lower CAPEX for SMRs than heat pumps by 2030. Their assumption of lower SMR CAPEX relies on uncertain development timelines, as SMRs have not yet reached commercial maturity for stationary power generation. Chalkiadakis et al. [67] modelled an SMR-electrolyser system, estimating a levelised cost of electricity (LCOE) between 46 and 52 €/MWh, assuming an SMR CAPEX of 3000 €/kW. Poudel and Gokaraju [68] found that integrating in DH improves SMRs’ power flexibility, with optimal RE penetration at 50%. Xie et al. [69] determined that SMR adoption becomes cost-effective above a CO$_2$ pricing threshold dependent on SMRs’ LCOE, with higher LCOE requiring higher CO$_2$ pricing, assuming an SMR CAPEX of approximately 4000 €/kW.

A research gap exists in comparing energy-industry systems, which refer to energy systems with detailed energy-intensive industry representation including feedstock supplies, with high penetration of RE versus systems with substantially expanded nuclear power capacity. Although Kan et al. [70] and Thellufsen et al. [71] conducted studies comparing such systems, tripling of nuclear power, as envisioned at COP28, was not considered. This study addresses this gap by analysing the techno-economics of an energy transition with enforced nuclear power capacities in an optimisation model, contextualised with a technology-neutral cost-based optimisation. The novelty of this analysis lies in the realistic timelines for SMR and large-scale nuclear plant deployments, alongside declining SMR CAPEX projections. A sensitivity analysis is also performed using different weighted average cost of capital (WACC) values for nuclear power technologies. The findings are contextualised within the energy justice framework to derive comprehensive conclusions about the two energy transition pathways.

The study is organised as follows: Section 2 outlines the conceptual framework, emphasising the integration of energy justice into energy transition pathway analyses. Section 3 details the methods, including the LUT Energy System Transition Model (LUT-ESTM) and scenario assumptions. Section 4 presents the results, focusing on primary energy demand, system costs, and energy generation. Section 5 discusses the findings in the context of energy justice, and Section 6 concludes with key insights from the study and policy recommendations.

## 2. Conceptual framework

### 2.1. Socio-technical transitions

The transition to a low-carbon society necessitates both technological innovation and societal change. The multi-level perspective (MLP) framework analyses socio-technical transitions within society, conceptualising them as interactions across three levels: niche innovations, socio-technical regimes, and the socio-technical landscape [72]. This framework has been applied to various domains, including energy transitions, where it explains the timing and acceleration of transitions through niche-regime-landscape interactions [73]. The MLP conceptualises niches as protected spaces for radical innovations, while the socio-technical regime represents the dominant practices, institutions, and technologies that define energy, food, or mobility systems that are resistant to change due to path dependencies and vested interests. Beyond these, the socio-technical landscape represents external forces such as cultural values, climate policy, or sudden shocks, such as the energy crises of the early 2020s, that influence actors within incumbent energy regimes [74]. Sustainability transitions occur when landscape pressures destabilise the incumbent regimes, creating windows of opportunity for niche innovations to scale up and potentially reconfigure an existing socio-technical regime [75].

Socio-technical transitions occur in four phases: emergence, stabilisation, acceleration, and reconfiguration [76]. In the emergence phase, radical innovations such as RE technologies or SMRs emerge within protected niches, such as pilot or research and development projects, where they are shielded from dominant market pressures. These niches foster experimentation, learning, and network-building among actors [77]. The stabilisation phase sees these innovations gain traction in niche markets, and dominant designs begin to emerge. Through continued learning and standardisation, actors refine technologies and costs decline, although they remain largely peripheral to mainstream systems [78]. The acceleration phase marks the entry of radical innovations into mainstream markets, driven by performance improvements, economies of scale, and supportive policy frameworks. RE technologies, such as wind power and solar PV, have already entered this phase, achieving competitiveness against fossil fuels due to significant cost reductions, technological advancements, and supportive policy frameworks. The last phase of transitions involves broad and gradual socio-technical transformation, affecting technology, infrastructure, user practices, industries, policies, and cultural norms, culminating in a whole-system reconfiguration [79]. In the power sector, this phase entails interconnected and cumulative shifts across generation, networks, and consumption [80]. In the reconfiguration phase, 100% RE systems will fully replace fossil fuels. To achieve this deep transformation, the full implementation of complementary innovations, such as energy storage, smarter grids, demand response, network expansion [72], and sector coupling [81–84] is necessary.

In recent years, a growing debate among transition researchers has highlighted the urgency to accelerate low-carbon transitions and the critical trade-offs for rapid and just outcomes [85,86]. Building on ongoing discussions about the pace of the current energy transition [87], research has identified two central tensions that policymakers must carefully navigate: cost-effectiveness and justice considerations [88]. These tensions underscore the inherent complexity of designing transition strategies that are both economically viable and socially equitable.

### 2.2. Energy justice

The techno-economic focus of energy system models has prompted debates about their adequacy in representing societal dimensions [89]. To address these limitations, incorporating energy justice principles has been suggested. The concept of ’energy justice‘ emerged in 2013 [90], when researchers started to conceptualise energy justice and propose theoretical frameworks. McCauley et al. [91] outlined energy justice as three core principles: distributive, recognitional, and procedural.

Energy systems often exacerbate inequalities by benefiting powerful stakeholders while harming marginalised communities. Distributive justice acknowledges the unequal allocation of benefits and burdens, as well as the uneven distribution of responsibilities. It seeks to address two key questions: Where are the injustices? and how to resolve them? [92]. Examples [93] include Germany’s solar feed-in tariff, which excluded tenants and not all found ways to finance the initial investments, and in Norway’s electric vehicles, with disadvantages to lower-income groups and public transport users who cannot afford them.

Some researchers argue that distributive injustices are evident in nuclear power systems, as demonstrated in France, where industrial stakeholders reap economic benefits while taxpayers and local communities bear long-term environmental and financial risks [93]. Although SMRs are marketed as cost-effective and flexible, they entail high costs [27,28]. If such costs are passed on to low-income households, this may further exacerbate existing inequalities in energy access.

Economic considerations are integral to the distributive justice considerations of different decarbonisation pathways. The higher costs of certain solutions may lead to increased energy prices, disproportionately affecting lower-income households that typically spend a larger portion of their income on energy and have less access to energy-efficient technologies [94]. Therefore, when considering alternative decarbonisation pathways it is important to identify opportunity costs, which can be defined as the value of the best alternative foregone when a particular option is chosen [95]. Prioritising nuclear power means sacrificing the benefits of a faster, more cost-effective, and lower-risk RE-based system. Opportunity costs highlight the trade-offs inherent in decarbonisation pathways, raising critical questions about whether resources might be more efficiently directed toward alternative climate mitigation strategies.

Recognition justice involves identifying and accounting for the perspectives and needs of those impacted by energy transitions. According to Jenkins et al. [92], recognition justice emphasises the fair representation of individuals, protection from physical threats, and the guarantee of full and equal political rights. A lack of recognition can manifest as cultural domination, degradation, or misrecognition, where individuals’ perspectives are distorted or dismissed. Recognitional justice advocates for acknowledging and valuing diverse viewpoints shaped by social, cultural, ethnic, racial, and gender differences, addressing the questions *Who is ignored?* And *How should we recognise?* [92]. It also highlights the importance of including local knowledge systems in decision-making, as communities often have unique insights into energy project impacts. Integrating community knowledge into planning, including for SMRs, is crucial to address specific needs and prevent marginalisation. Sovacool et al. [91] highlight France’s nuclear-driven all-electric society and Germany’s solar PV investments, both of which disproportionately impacted low-income households by creating a “double effect” of exclusion and increased costs.

Finally, procedural justice evaluates the fairness and inclusivity of decision-making processes in energy transitions, particularly those decisions that affect people’s lives. It is not just about the end results, but about how decisions are made and whether all stakeholders can participate [92]. Procedural justice addresses the questions: *Is there a fair process?* And *Which new processes?* [92]. Procedural justice relies on both formal legal systems and softer influences such as norms, practices, and values. Three mechanisms promote inclusion [92]: mobilising local knowledge, enhancing information disclosure, and improving institutional representation. For instance, indigenous communities, such as the Sami in the Nordics, highlight the importance of integrating local knowledge in decision-making to mitigate the impacts of energy projects, such as wind farms [96].

## 3. Methods

The energy system transition of Finland is simulated using LUT-ESTM [97]. The model optimises the energy-industry system transition in five-year time steps until 2050 in hourly resolution with Finland comprised of seven regions to represent the energy demand and supply diversity across the country. The model uses linear optimisation to find the lowest annualised system cost for each timestep, considering about 150 technologies for power, heat, and fuel conversion, transport and industry sector, and various storage and transmission options. The latest version of LUT-ESTM incorporates SMR and SMR-CHP, as shown in Fig. 2.

To represent the expansion of nuclear power according to the COP28 declaration, scenarios are simulated by fixing nuclear power capacity to 13.2 GW by 2050, with SMR and SMR-CHP introduced alongside the traditional large-scale nuclear power plants.

### *3.1. Nuclear power assumptions*

SMRs are assumed to be pressurised water-cooled reactors standardised at 300 MW power capacity, allowing a cost scaling factor based on literature [98–100] that ensures a reliable cost estimate. SMR-CHPs are assumed to have a power capacity of 42 MW and a heat capacity of 140 MW to match the size requirements of Finnish DH systems, based on Lindroos et al. [101] who localised their case study to Helsinki. Large-scale nuclear power plants are assumed to standardise at the scale of the latest 1660 MW Olkiluoto 3 unit [102]. The scaling, sizes, and efficiencies are according to the discussion in Finland [65,101].

SMR-CHPs are assumed to be installed exclusively in large municipalities that could economically house a baseload SMR-CHP [29], with a capacity factor of 85% and a DH load coverage of 80% [101]. It is assumed that they have reliable cooling infrastructure, including stable water supply, to effectively dissipate the reactor's excess heat, and that emergency buffer zones with exclusion areas are available. However, dimensioning DH systems can be challenging due to the highly variable heat demand profile, with a significant disparity between summer and winter. Given these considerations, only municipalities that have a DH demand above 1380 $\mathrm{GWh_{th}}$ (140 $\mathrm{MW_{dh}}$·8760 h·85%/80%) are suitable to have an SMR-CHP, as shown in Table 1.

The COP28 declaration's ambiguity regarding power capacity or energy supply targets for 2050 necessitated consideration of both metrics. One scenario variation triples the nuclear power capacity, and the other variation triples the combined nuclear power and thermal capacity. Moreover, there are uncertainties related to the build-out of large-scale nuclear power plants, due to their long lead times. Consequently, two more variations were considered: one with two more large-scale nuclear power plants being built (one in Hanhikivi and one in Loviisa, after the old Loviisa reactors are decommissioned) and another with three more being built (Olkiluoto 4). The Loviisa reactors, which are Soviet-era designs that historically rely on Russian uranium, are assumed to receive a 10-year life extension. While the plant is in the process of switching to Westinghouse fuel [103], this change still carries some risk [104]. Olkiluoto 1 and 2 are assumed to receive 20-year life

**Table 1**
SMR-CHP spatial distribution.

| Municipality | DH demand [$\mathrm{GWh_{th}}$] | SMR-CHP units |
|---|---|---|
| Helsinki | 6260 | 4 |
| Espoo | 1926 | 1 |
| Tampere | 1912 | 1 |
| Vantaa | 1715 | 1 |
| Oulu | 1625 | 1 |
| Turku | 1552 | 1 |

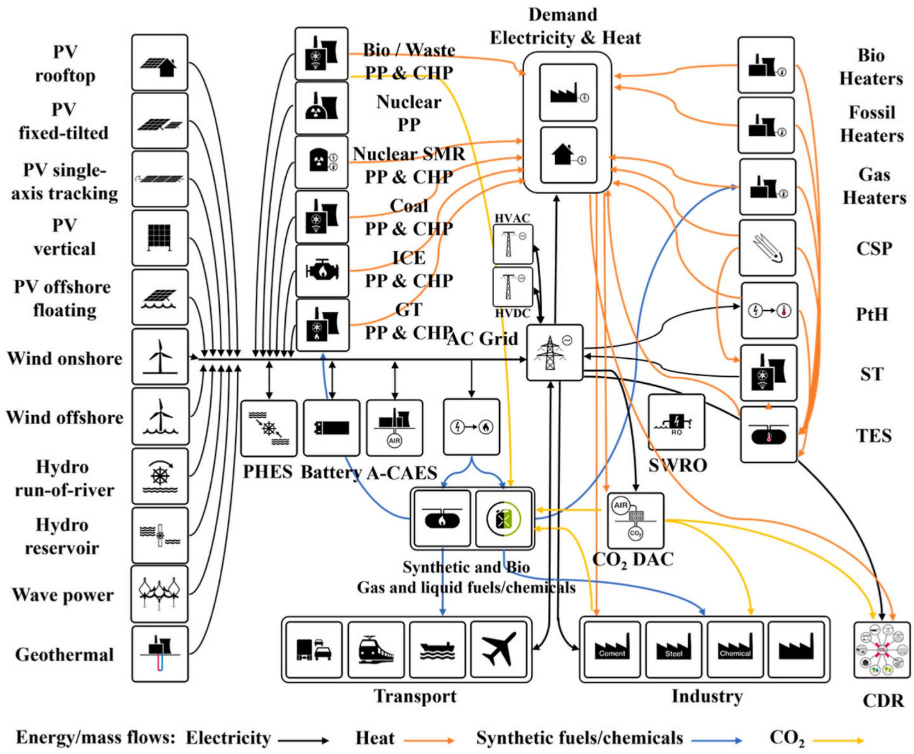

**Fig. 2.** Schematic diagram of LUT-ESTM.

extensions. The number of SMRs in each scenario is adopted to bring the installed sum to 13.2 GW. Notably, decommissioning costs are excluded from the cost assumptions, as this aspect of the nuclear power lifecycle remains poorly understood due to limited experience [105].

The reference scenario, called Best Policy Scenario (**BPS-ref**), simulates a technology-neutral cost optimisation, not excluding nuclear power. In total, five different scenarios are investigated in this study, summarised in Table 2.

The key factor in cost optimisation is accurately representing technology costs. The costs assumed for nuclear power are presented in Table 3, all other technologies are listed in the Supplementary Material (SM) Tables S19–S22. Large-scale nuclear power plant costs are assumed to slightly increase throughout the transition, based on the CAPEX of Olkiluoto 3 [55]. The actual cost developments in France and the United Kingdom for the same reactor type indicate this as a conservative assumption [106,107], while an identical reactor type at the same site may have the potential to stabilise the cost at the level of Olkiluoto 3 [9]. The chosen CAPEX is supported by Lazard's lower estimate [108], though their higher estimate suggests 64% higher CAPEX.

SMR and SMR-CHP, being unproven commercially, initially have high costs that gradually decrease, eventually undercutting large nuclear plants. Their availability is projected from 2035, given current development stages. The SMR CAPEX for 2050 is calculated according to Equation (1), obtained from Refs. [27,28].

$$\boldsymbol{CAPEX_{SMR,n}} = \boldsymbol{CAPEX_{ref}} \cdot \left(\frac{\boldsymbol{P_{SMR}}}{\boldsymbol{P_{LNPP}}}\right)^{b} \cdot (1 - \boldsymbol{LR})^{d} \tag{1}$$

by applying a 0.55 scaling factor (*b*) to large-scale nuclear plant $CAPEX_{ref}$, within the range of Ramana and Mian [98] and the Nuclear Energy Agency [99] of 60% and 50%, respectively, with projections based on a 10% learning rate (*LR*), both following Steigerwald et al. [28] and The German Federal Office for the Safety of Nuclear Waste Management (BASE) [27]. About 880 SMR units with a power capacity of 300 MW ($P_{SMR}$) each are assumed to be built globally by 2050 for the experience curve-based cost projection, with 9.78 doublings (*d*). This CAPEX projection assumes installed capacity of SMR of 264 GW until 2050, which is about 63% of the global nuclear power capacity installed in 2022 [109]. Whether the nuclear industry is able to scale that fast is not questioned in this study, which remains unlikely [5,6,53,110,111]. Weighted average cost of capital (WACC) for most technologies is assumed to be 7%, except for residential prosumers' PV and batteries to which 4% WACC is applied, and coal power, heat, and CHP technologies for which WACC is set to 10%, reflecting risks of building new coal capacities when strict policies on coal use are declared [112]. WACC for nuclear power and SMR technologies is assumed to be 10% throughout all years to account for the higher economic risk associated with nuclear power in general, with a very high risk of cost overruns [113], and commercially unavailable SMRs in particular.

All nuclear technologies are assumed to have a 40-year lifetime and a ten year extension possible at 1000 €/kW [114]. Operational expenditures for maintaining and staffing a nuclear power plant are relatively low, accounting for just 2% of the initial investment. Additionally, the cost of uranium is approximately 7–8 €/MWh of electricity produced, relatively low when put in context with other thermal power plants, where natural gas or bioenergy fuel costs would add 50–70 €/MWh of electricity.

**Table 2**
Scenarios considered in the study.

| | 2 New Large Nuclear Plants | 3 New Large Nuclear Plants | No favouring |
|---|---|---|---|
| Tripling Nuclear Energy | NE2 | NE3 | |
| Tripling Nuclear Power | NP2 | NP3 | |
| Free cost optimisation | | | BPS-ref |

### 3.2. Renewable energy assumptions

The potential of RE sources is based on [64]. Onshore wind power is assumed to be installable on up to 4% of the total unprotected land area of Finland with an installation density of 8.4 MW/km$^2$, giving a total potential of 102 GW. Notably, this is much smaller than the grid connection inquiries reported by Fingrid (~200 GW) [50,51], implying that more land can be used for onshore wind power. Similarly, 6% of the unprotected land area is assumed for solar PV with an installation density of 100 MW/km$^2$, giving a total of 1818 GW. Comprehensive assessment of the technical wind power and solar PV electricity generation potential in Finland led to about 1650 TWh and 1300 TWh, respectively [115]. The offshore wind power potential is assumed to be 2 GW for all regions with coastal access. The sustainable bioenergy potential is 121.3 TWh$_{th}$/a, with 6.1 TWh municipal solid waste, 58.1 TWh solid wood, 36.5 TWh forestry residues (must burn), 5.8 TWh biodiesel, and 14.8 TWh biogas [116]. The bioenergy potential translates to about 21.9 MWh$_{th}$ per capita. In comparison, globally sustainable bioenergy potential equals roughly 3.5 MWh$_{th}$ per capita (for 100 EJ for 8 billion people) [117] and about 4.6 MWh$_{th}$ per capita for entire Europe [118]. The hydropower potential is assumed to be fully tapped, with some potential for repowering of dams, totalling 4.7 GW. Grid capacities are predefined for 2020 and 2025 but, beyond 2025, grid expansion can proceed without delay, implying that all necessary planning procedures and permits are obtained in a timely manner. The model has the flexibility to increase grid capacity as needed, but inter-regional capacities cannot more than double in each five-year period.

### 3.3. Energy demand

Final energy consumption in power, heat, transport, and industry sectors is fixed among the scenarios, and shown in Fig. 3.

The transport sector transition is an exogenous input and the share of transportation modes and the rate of the shifts in mobility are taken from Ref. [119]. Road transport is assumed to be fully electrified, with some heavy-duty trucks possibly running on hydrogen by 2050 and long-haul marine and aviation transport switching to e-fuels. The fuels and energy carriers in the transport sector assumed in all scenarios are shown in Fig. 4.

The industrial production output and energy consumption per unit of output for cement, steel, chemicals, aluminium, and pulp and paper are taken from Refs. [120,121]. The industry sector is mostly electrified, for example with electric arc furnaces, or indirectly electrified with a switch to e-hydrogen and e-chemicals, for example for iron ore reduction or feedstock for the chemical industry. The energy and feedstock flow to the industry is shown in Fig. 5.

A detailed breakdown of the shares of transport modes and industrial production routes is available in the SM Tables S5–S18.

## 4. Results

### 4.1. Primary energy demand

Nuclear scenarios yield significantly higher primary energy demand (PED) due to inefficiencies in converting uranium to electricity (Fig. 6). The BPS-ref scenario reduces PED by shifting from thermal plants, while nuclear options increase PED by 39–42% from 2020 to 2050. Scenarios with three large-scale nuclear plants require less uranium than those with more SMRs, as the former have 38% efficiency compared to the latter's 31%.

Nuclear scenarios phase out fossil fuels a bit earlier than the BPS-ref. Coal and oil consumption patterns remain consistent across scenarios, driven by transport and steel sector demands. However, the BPS-ref

**Table 3**
Financial assumptions for nuclear technologies.

| | | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|
| Large Nuclear | CAPEX [€/kW] | 6003 | 6875 | 7000 | 7000 | 7000 | 7000 | 7000 |
| | OPEX$_{fix}$ [€/kW/a] | 113.1 | 131.9 | 131.9 | 131.9 | 131.9 | 131.9 | 131.9 |
| | OPEX$_{var}$ [€/kWh] | 0.0025 | 0.0025 | 0.0025 | 0.0025 | 0.0025 | 0.0025 | 0.0025 |
| | Efficiency | 37% | 37% | 38% | 38% | 38% | 38% | 38% |
| SMR | CAPEX [€/kW] | | | | 10,500 | 8100 | 6450 | 5300 |
| | OPEX$_{fix}$ [€/kW/a] | | | | 210 | 162 | 129 | 106 |
| | OPEX$_{var}$ [€/kWh] | | | | 0.006 | 0.006 | 0.006 | 0.006 |
| | Efficiency | | | | 31% | 31% | 31% | 31% |
| SMR-CHP | CAPEX [€/kW$_{el}$] | | | | 16,000 | 12,500 | 10,000 | 8200 |
| | OPEX$_{fix}$ [€/kW$_{el}$/a] | | | | 320 | 250 | 200 | 164 |
| | OPEX$_{var}$ [€/kWh$_{el}$] | | | | 0.0105 | 0.0105 | 0.0105 | 0.0105 |
| | Efficiency$_{el}$ | | | | 19% | 19% | 19% | 19% |
| | Efficiency$_{th}$ | | | | 63% | 63% | 63% | 63% |
| Uranium | OPEX$_{var}$ [€/kWh$_{th}$] | | | | 0.0026 | | | |

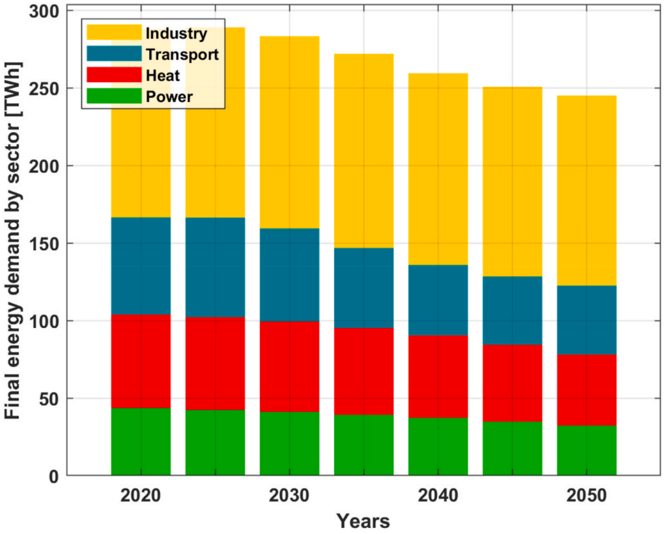

**Fig. 3.** Final energy demand among all scenarios.

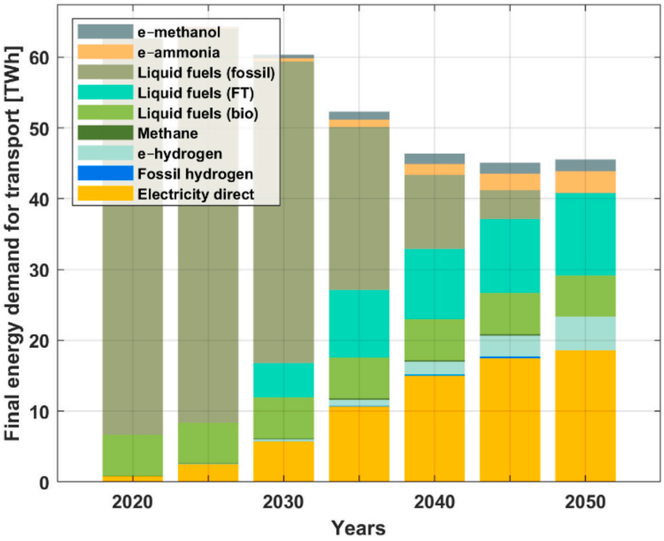

**Fig. 4.** Transport sector final energy demand among all scenarios.

scenario uses more natural gas in 2040 for steam methane reforming. Consequently, by 2050, the BPS-ref scenario results in 3–6% higher cumulative $CO_2$ emissions compared to nuclear scenarios.

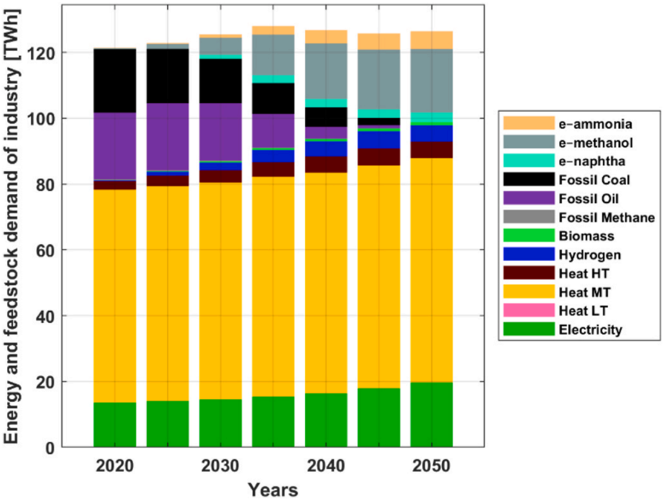

**Fig. 5.** Final energy and feedstock demand in industry among all scenarios.

### *4.2. Installed power capacities and generation*

Installed power capacities increase manifold in all scenarios to satisfy the increasing electricity demand because of widespread electrification (Fig. 7). The installed capacity in the BPS-ref ends up over 50% higher compared to the nuclear scenarios, owing to lower capacity factors of RE sources. The power capacity tripling scenarios (NP2 and NP3) have 13.2 GW of installed power generation capacity, while the power and thermal capacity tripling scenarios (NE2 and NE3) have 12 GW of power capacity and 1.2 GW nuclear thermal capacity in the SMR-CHPs. The nuclear power capacity present in the BPS-ref in 2050 is the Olkiluoto 3 plant, which was connected to the grid in 2023 and is expected to remain operational for at least 40 years, beyond the simulation horizon of this study.

Nuclear power represents 40% of the total electricity supply in the nuclear scenarios in 2050, while in the BPS-ref, wind power and solar PV dominate the electricity supply, representing 54% and 30%, respectively (Fig. 8). Total electricity generation grows 3.5 times in all scenarios. The variable RE supply in the BPS-ref leads to 2.4 TWh of electricity curtailment by 2050, representing 1.0% of the generated electricity, while curtailment in the nuclear scenarios stays below 1%.

The regional distributions of power generation capacities in the BPS-ref, NE3, and NE2 in 2050 are shown in Fig. 9. To reiterate, the BPS-ref performs a technology-neutral cost optimisation, finding the lowest cost configuration for the whole country, maximising installations in regions that minimise the system cost. The nuclear power scenarios also optimise the system costs, but with an imposed set and distribution of

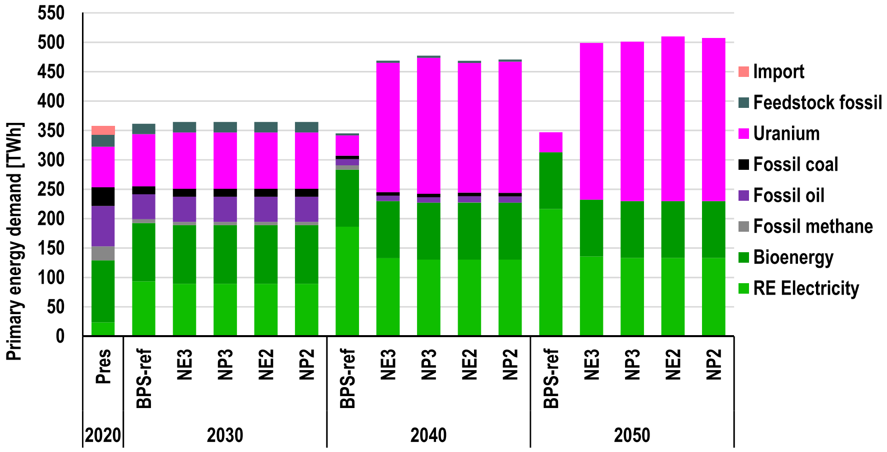

**Fig. 6.** Primary energy demand across all scenarios.

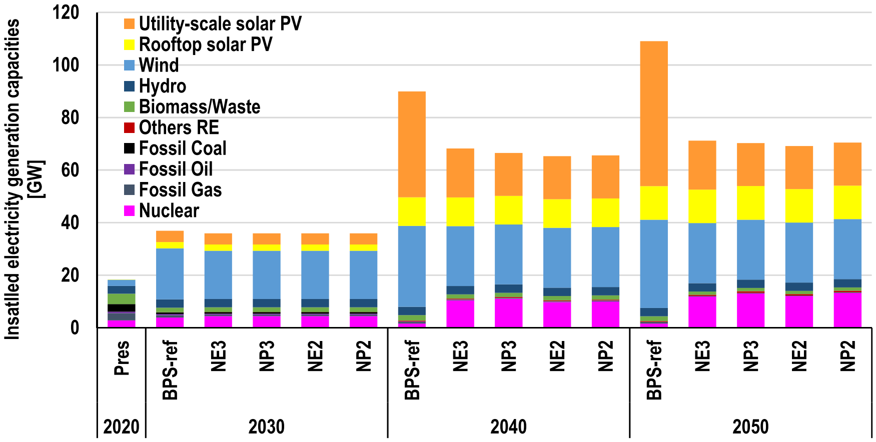

**Fig. 7.** Installed electricity generation capacities across all scenarios.

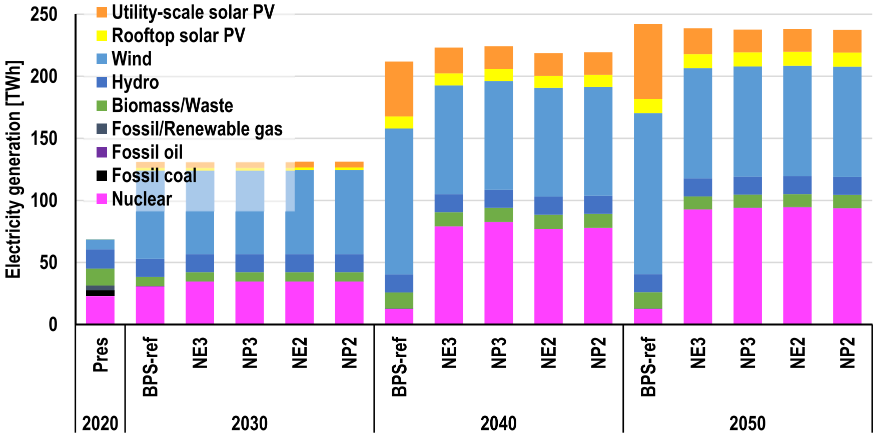

**Fig. 8.** Electricity generation across all scenarios.

planned nuclear power capacities, as described in section 3.1.

It is important to note that demand centres are concentrated in the south of the country. In the BPS-ref scenario, more power generation capacities are installed closer to the demand centres, while the nuclear scenarios are constrained to work around the fixed nuclear power and SMR-CHP capacities.

The interregional high voltage transmission capacities by 2050 are shown in Fig. 10. In the NE3 scenario, the most transmission capacity is installed by 2050, partially related to the location of the Hanhikivi and Olkiluoto nuclear power plants that mostly need to transmit electricity to the capital region. Although the BPS-ref scenario also transmits the northern wind electricity to the southern demand centres, the more even distribution of installed capacities maintains slightly smaller transmission capacities.

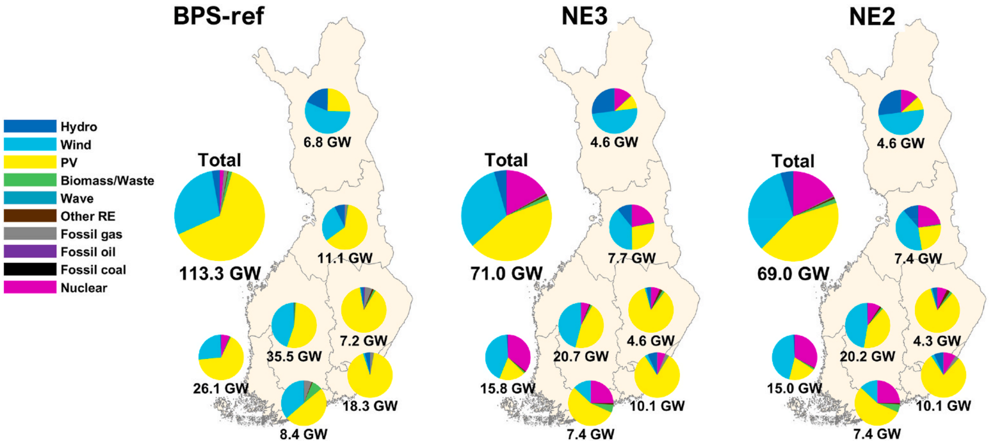

**Fig. 9.** Regional distribution of installed power generation capacities by 2050 in the BPS-ref, NE3, and NE2 scenarios.

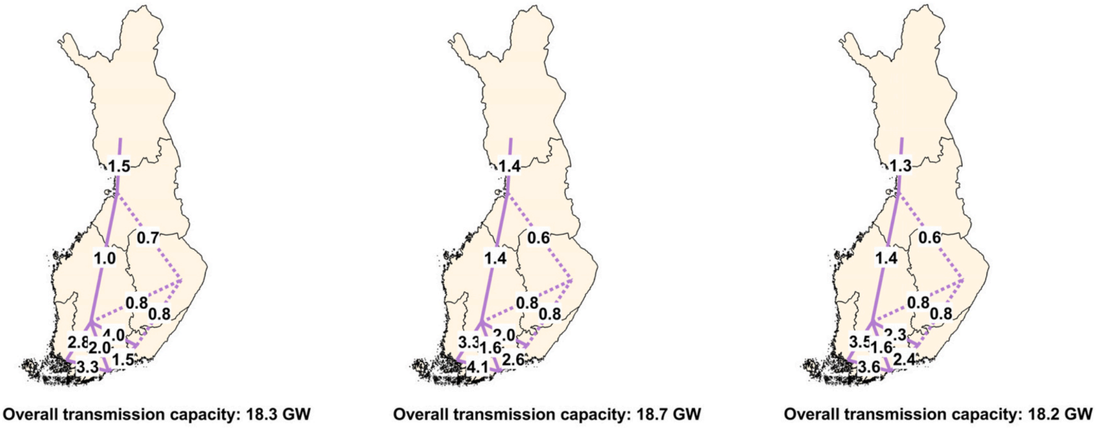

**Fig. 10.** Interregional transmission capacities by 2050 in the BPS-ref (left), NE3 (centre), and NE2 (right) scenarios.

### 4.3. *Heat sector*

The BPS-ref scenario shows higher heating capacities, installing 25 GW by 2050 compared to 19.3–19.6 GW in nuclear scenarios (Fig. 11). Without nuclear-based heating more electric heaters are incorporated to balance electricity supply and demand, and 14% higher biomass and waste heating capacities for additional flexibility. Electric heating capacities in all scenarios are part of the industrial and DH networks by 2050. Electric heaters are well suited for the electrification of the pulp and paper production, so the model installs large capacities for that sector but also uses them to supply heat to the DH network. All heat pumps are on individual heating (IH) level for households in all scenarios by 2050, while biomass-based heaters are split between DH and IH, with over 70% in IH.

Total heat generation is comparable across scenarios (Fig. 12), with nuclear scenarios producing 6% more, and the distribution remains

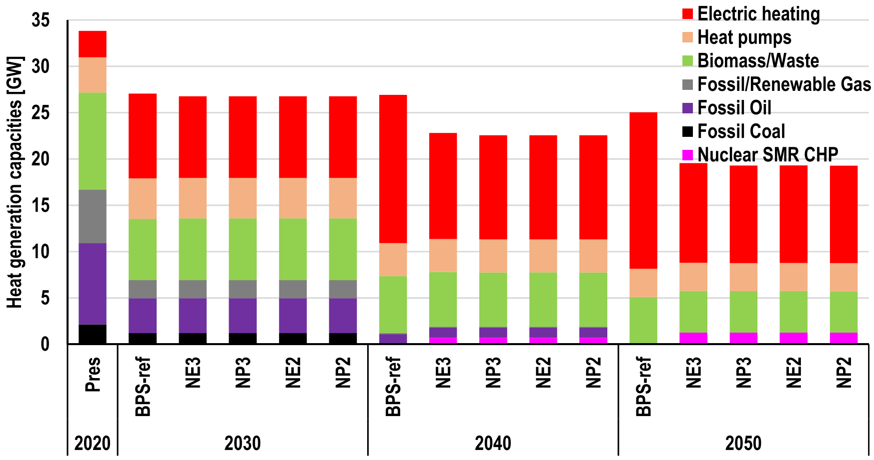

**Fig. 11.** Installed heat generation capacities across all scenarios.

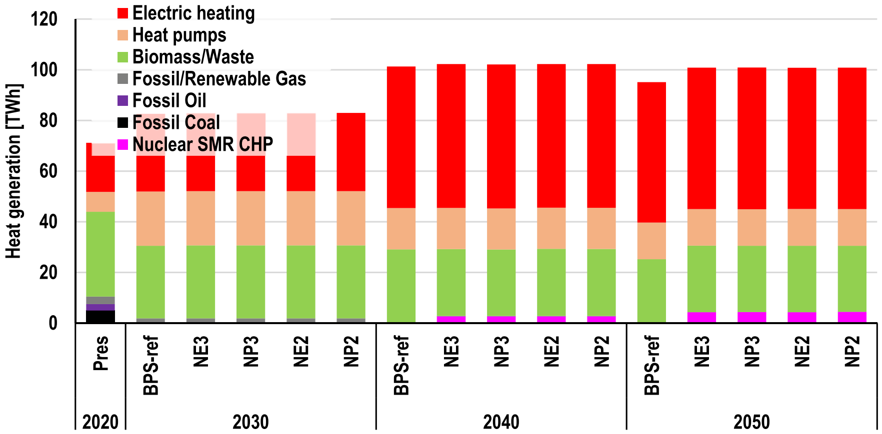

**Fig. 12.** Heat generation across all scenarios.

similar, with electric heaters dominating at 58% in BPS-ref and 55% in nuclear scenarios. SMR-CHP units contribute 4% of the heat supply in the nuclear scenarios.

### *4.4. Fuel synthesis*

Similar dynamics are present in fuel conversion capacities, where BPS-ref installs larger electrolyser capacities, which provide valuable flexibility to the system (Fig. 13). Electrolysers are very apt at fast ramping to align with the availability of low-cost electricity, buffering excess hydrogen in storage for subsequent processing in Fischer-Tropsch, e-ammonia, or e-methanol synthesis units. Fuel conversion capacities are shown in installed capacity of fuel output, e.g., 2 GW of methanol synthesis units can reach an output of 2 $GWh_{MeOH,LHV}$ per hour. Electrolyser efficiencies are assumed to increase from 62% in 2020 to 70% by 2050.

Fuel production shares remain largely consistent across scenarios, with a minor divergence in the 2040s. During this period, BPS-ref generates 10% of hydrogen via steam methane reforming with carbon capture, possibly due to insufficient power capacity and the cost-effectiveness of this method compared to power capacity expansion. $CO_2$ for the production of hydrocarbons is sourced from point-source capture units from the pulp and paper mills, cement factories, and biomass and waste-to-energy plants.

### *4.5. Storage systems*

Nuclear scenarios install no utility-scale batteries. The BPS-ref incorporates utility-scale batteries with 2.1 GWh capacity, contributing 0.55 TWh annually by 2050, representing 0.2% of total electricity supply. Vehicle-to-grid batteries also provide 0.39 TWh to the grid in the BPS-ref, though they have no throughput in the nuclear scenarios (Fig. 14). Nevertheless, vehicle-to-grid capacities are projected to grow regardless of the scenario. Hours of power shortage are mitigated by dispatchable biomass power plants, and excess electricity is consumed by electrolysers and thermal energy storage units via power-to-heat. SMR units are assumed to have a limited flexibility, which can also contribute to the balancing of electricity supply and demand.

Similarly, the BPS-ref relies more heavily on thermal storage capacities compared to the nuclear scenarios in 2050 (Fig. 15). Medium temperature thermal energy storage (TES MT) units reach 9 GWh of storage capacity by 2050 in the BPS-ref and help match the variable RE supply with the heat demand in the pulp and paper industry. District heating level energy storage capacities (TES DH) grow to 102 GWh by 2025, but drop to 90 GWh by 2045, and decline further thereafter in all scenarios. In the short term, cost-effective TES DH are used to buffer the excess electricity via the power-to-heat route; however, towards 2050, alternative forms of flexibility, including vehicle-to-grid batteries, utility-scale batteries, and electrolysers, increasingly take over this role. Notably, the high use of hydrogen storage can be observed in the BPS-ref, providing crucial flexibility to the system, buffering the excess hydrogen coming from electrolysers. Hydrogen storage in the BPS-ref reaches staggering 400 GWh.

Detailed results for storage capacities are available in Figs. S6 and S7 in the SM.

Increase of nuclear power generation and CHP capacities allows the

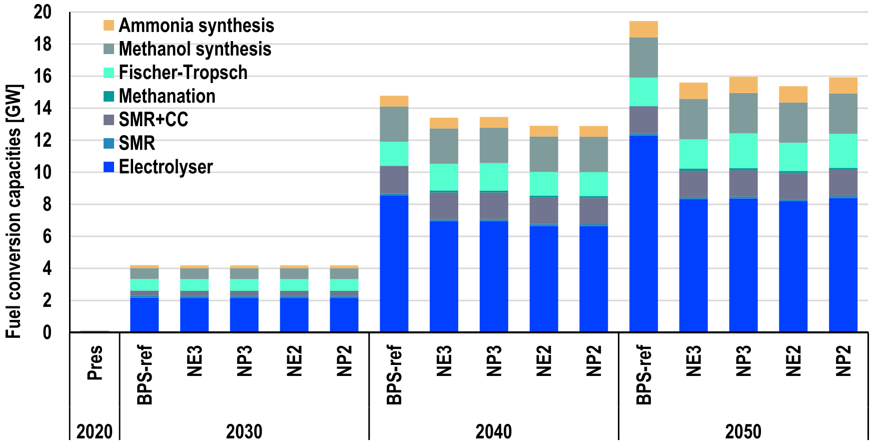

**Fig. 13.** Installed fuel conversion capacities across all scenarios.

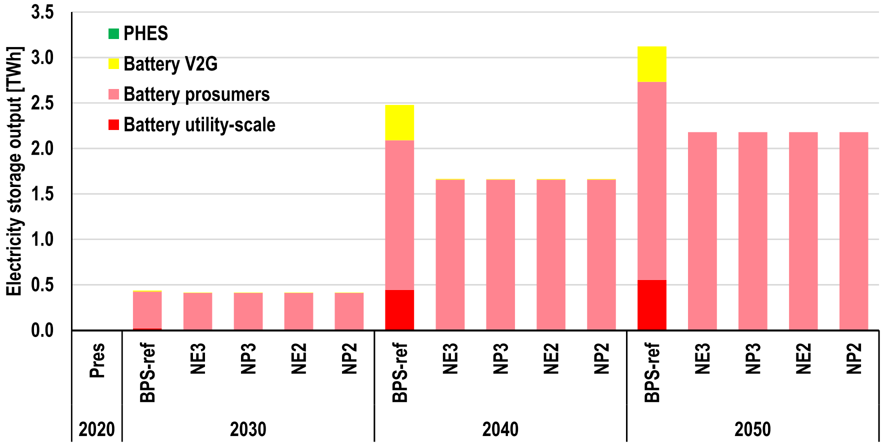

**Fig. 14.** Electricity storage throughput across all scenarios.

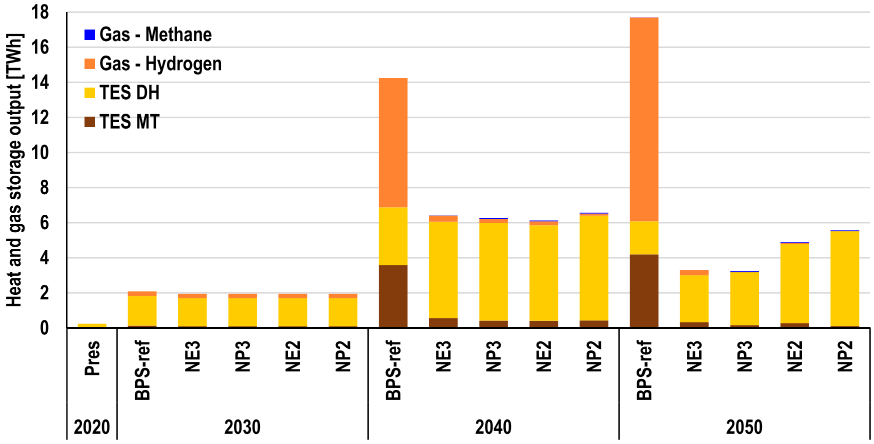

**Fig. 15.** Thermal energy and gas storage throughput across all scenarios.

system to provide baseload energy supply and substantially reduce storage and sector coupling technologies capacities, such as power-to-heat and water electrolysers. However, cost reductions of these technologies do not necessarily lead to a reduction of the overall system cost in comparison to the BPS-ref.

### *4.6. System costs*

All nuclear scenarios show higher annualised system costs, with 71–84% higher costs in 2050 and with cumulative CAPEX 52–65% higher compared to the BPS-ref (Fig. 16). The CAPEX figure shows the rate and extent of nuclear power fixed installation levels, with most installations in 2040, approximating a sigmoid curve introduction of fixed capacities. Unlike the BPS-ref, where the annual system costs decline over the years, the annual system costs in the nuclear scenarios grow from 13.6 b€ in 2020 to 18.4–19.7 b€ by 2050. Although the system phases out inefficient thermal power plants and expensive fossil fuels, the system costs still grow due to high capital investments required by nuclear power plants. The difference in cost between the two decarbonisation pathways would represent 2.3% of the national GDP in

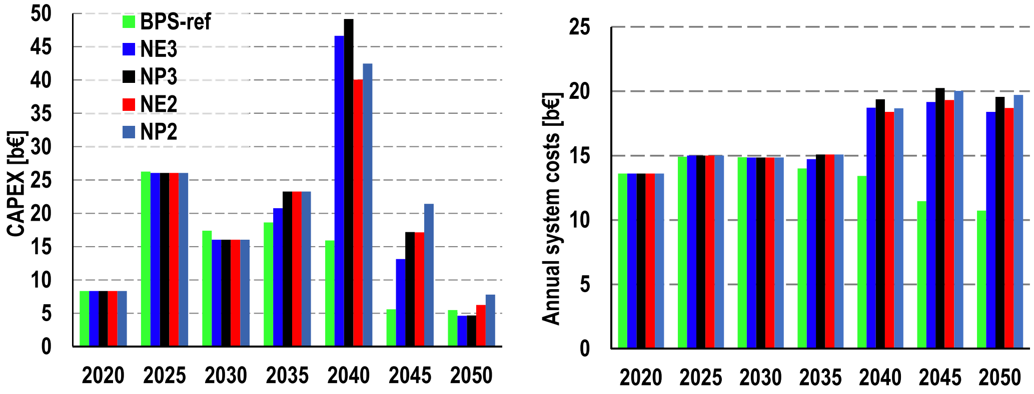

**Fig. 16.** Capital expenditures (left) and annual system costs (right) across all scenarios.

2050, if the current GDP of 274.9 b€ [122] continues growing at 1% CAGR. Nuclear power capacity tripling scenarios exhibit 5–6% higher annual system cost in 2050 compared to nuclear energy capacity tripling scenarios.

The simulation results show the reduction in LCOE of the BPS-ref scenario from 90.4 €/MWh to 35.3 €/MWh in 2020–2050. The LCOE reduction in nuclear power scenarios is observed only until 2035, after which it reverses and increases to 70.1–75.8 €/MWh. As a result of the high CAPEX and OPEX of nuclear power plants, the LCOEs in the nuclear scenarios are 99–115% higher compared to the BPS-ref (Fig. 17) in 2050. However, LCOE in all scenarios decline compared to the current system, as electricity imports and fossil fuels are phased out.

Levelised cost of final energy (LCOFE), on the other hand, only declines in the BPS-ref. The LCOFEs in the nuclear scenarios end up 72–84% higher compared to the BPS-ref in 2050, echoing the developments in annual system costs.

## 5. Discussion

The technology-neutral cost optimisation in the BPS-ref scenario does not install new nuclear capacity, suggesting that RE can meet energy demand more cost-effectively. This result aligns with socio-technical transition studies indicating that renewables have entered the acceleration phase, characterised by rapid uptake and declining costs [123].

Conversely, nuclear scenarios maintain lower installed electricity generation capacity and require less flexibility than the BPS-ref, but cost significantly more, echoing the findings of [70,71]. Tripling nuclear energy capacities by 2050 is technically feasible, showing no signs of overcapacity or excessive curtailment, contingent on the assumption that SMRs become commercially available by 2035. However, this study assumes optimistic CAPEX of large-scale nuclear power plants [124] and SMRs [125]. The recent cancellation of a promising SMR project in Utah, USA, which had an estimated CAPEX of 20,139 USD/kW [126] indicates that SMRs are still in the experimentation phase. Nevertheless, municipal utilities in Finland, such as those in Helsinki and Kuopio, are exploring SMR projects [127].

This study assigned a WACC of 10% to nuclear technologies and 7% for others, reflecting nuclear projects' high economic risks, such as cost overruns [113], construction delays [128], possible changes in legislation for liability insurance adjustments [129], and overall technical risks. Private companies investing in nuclear power risk a 25–30% downgrade in their credit rating, according to Moody's [130]. The WACC significantly impacts projects with substantial initial investments, contributing to the elevated real cost of nuclear power.

However, nuclear projects are often subsidised by governments, lowering financial costs [7]. Major data centre operators are also showing interest in nuclear power [131], but a viable unsubsidised business case remains uncertain. SMR developers claim modular construction and mass production will help to avoid cost overruns. To investigate this potential, the nuclear scenario with the lowest system cost, NE3, was re-run with lower WACC for nuclear power (7% and 5%). However, even with reduced WACC, tripling nuclear energy capacity remained more expensive than the BPS-ref (Fig. 18).

Applying a uniform WACC of 7% across all technologies, the NE3 scenario was 50% more expensive than the BPS-ref. Even with an unrealistically low WACC of 5%, implying substantial subsidies, the system remained 37% more expensive. These findings suggest that the cost savings associated with SMRs may not be sufficient to offset nuclear power's high costs, even with favourable financing conditions that may require further subsidies not assumed for any technology in this study.

Moreover, investments in nascent SMR technologies risk creating significant technological lock-in and opportunity costs due to pressures to stick with sub-optimal decarbonisation solutions, even if better alternatives emerge. Finally, while RE promotes decentralised innovation and participation from diversified actors, SMRs require centralised, large-scale investments and new regulatory frameworks, reinforcing existing socio-technical regimes.

A crucial aspect omitted from the simulation is the cost of decommissioning nuclear power plants [132]. The Nuclear Energy Agency estimated decommissioning costs to be about 700 €/kW [133], while the International Atomic Energy Agency estimates the decommissioning costs of a single nuclear reactor on 500–2000 mUSD [134]. Assuming 700 €/kW decommissioning cost for all nuclear power plants in this study, including SMRs, the annual system costs of the nuclear scenarios would increase by approximately 5%. This would further exacerbate the

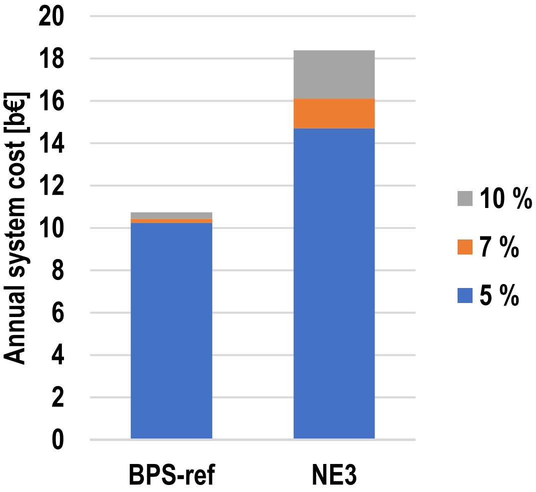

**Fig. 18.** Annual system cost in 2050 with different WACC applied to nuclear power and CHP technologies in BPS-ref and NE3 scenarios.

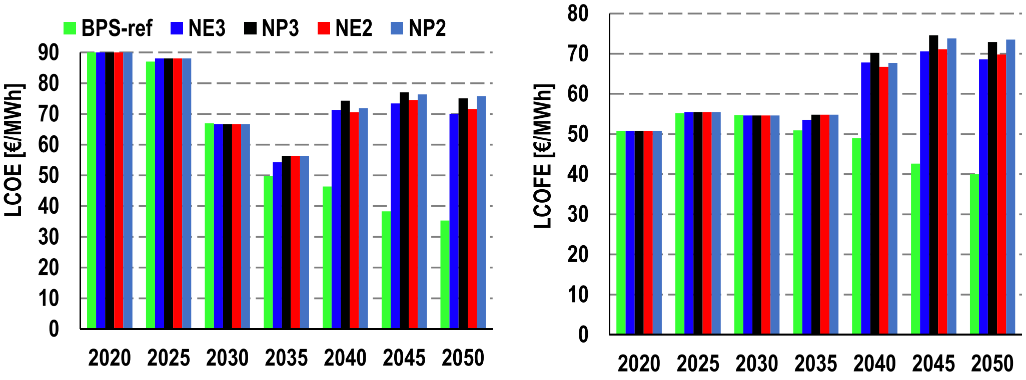

**Fig. 17.** Levelised cost of electricity (left) and final energy (right) across all scenarios.

cost difference between the nuclear scenarios and the BPS-ref scenario. This highlights the importance of considering the full lifecycle costs of nuclear power, including decommissioning, when evaluating its competitiveness against other low-carbon technologies. The inclusion of decommissioning costs in the simulation would likely reinforce the conclusion that RE is a more cost-effective option for meeting energy demand, and that investments in nuclear power may not be the most economical choice for the energy transition. Decommissioning costs were omitted due to limited experience with full decommissioning [105], as only 25 reactors have been fully dismantled and decommissioned to date [135]. Many retired reactors are in various stages of decommissioning, such as defueling, safe storage, or awaiting full dismantlement.

### 5.1. Satisfying the surge in electricity demand

Electricity demand is set to surge in the coming decades due to rapid electrification of sectors including heating and transportation [97], on top of organic growth for energy with the growing economy [136]. Energy systems must rapidly invest in power generation capacities to meet this demand. Economically rational policymakers and energy consumers favour technologies that offer the lowest cost electricity, driving growth in RE capacity. If SMR development is delayed beyond the 2030s [127], their potential contribution to the energy transition will diminish as RE build-out will reduce the need for inflexible baseload generation capacities.

### 5.2. Indirect costs of nuclear power expansion

Large-scale variable RE integration is not only technically feasible, it also offers lower-cost $CO_2$ emission reduction, highlighting another opportunity cost of SMRs. The BPS-ref avoids environmental, societal, and economic risks associated with nuclear power. Historically, Finland has not produced or enriched uranium [137], so with high reliance on nuclear power it would remain an energy importer [138], exposed to swings in commodity markets [139], and import risks. However, with Terrafame's commencement of uranium recovery [140], some of this reliance is mitigated. The management of radioactive waste remains problematic, with many countries adopting a "wait-and-see" approach [141]. Despite the exploration of various long-term storage solutions, the sustainability of these approaches is subject to ongoing debate [142].

There is a prevailing emphasis on baseload power generation to hedge against windless and cloudy days, ignoring the cost advantages of RE-based solutions [143]. This emphasis requires a nuanced consideration of grid resiliency, particularly in the context of disruptions to nuclear power as well, when a tripping nuclear power facility takes out 1.6 GW of power supply from the Finnish national grid, about 16% of the average instantaneous power demand. The challenges posed by variable weather conditions can be addressed cost-effectively with better forecasting and through rapidly advancing batteries and sector coupling [144]. Meanwhile, the financial demands of baseload nuclear power plants divert resources from crucial societal needs such as healthcare [145,146], education [147,148], and social security [149,150], which are fundamental to maintaining high living standards.

Large-scale nuclear power plants would require a similar expansion of the transmission grid as RE-based solutions in Finland to deliver the power from remote generation sites to demand centres. The NP3 and NE3 scenarios require 18.7 and 18.9 GW of total transmission capacity, compared to 18.3 GW in the BPS-ref. The nuclear scenarios with more SMRs (NP2 and NE2) require lower transmission capacity (18.2 GW), contingent on the assumption that society will accept the placement of nuclear facilities close to or within urban areas, as 1.6 GW of SMRs would be installed in the capital region. The expansion of the transmission networks is seen as one of the major obstacles in the energy transition [151]. Transmission grid projects in Finland typically take around eight years to progress from initial planning to commissioning [152].

When these limitations are considered in light of socio-technical transition studies, system reconfiguration in both decarbonisation pathways requires infrastructure changes. However, the 100% RE pathway delivers a much more profound, system-wide reconfiguration of technology, society, markets, institutions, and culture. In contrast, the nuclear SMR pathway offers only limited technological substitution without significantly transforming the existing centralised energy regime, which may lead to delays in the phase-out of fossil fuels.

### 5.3. Advantages of nuclear power expansion

Although significantly more expensive and prone to reinforce current centralised energy infrastructures, baseload nuclear power may offer some advantages to the energy system. Nuclear scenarios reduce the need for electrolyser capacity, heating units, and power generation capacity compared to the variable RE heavy BPS-ref, potentially offering savings in construction materials, if there were a shortage [153]. Nuclear scenarios also minimise the need for energy storage, such as batteries and large-scale TES units. Additionally, nuclear power requires less land for operation than RE [154], although its overall life cycle land occupation is complicated by mining and nuclear waste management impacts [155].

Potentially, SMRs can also operate flexibly in a load-following mode [156]. Fig. 19 shows how nuclear power output decreases from 11.8 GW to 9.9 GW (16%) as wind power rises. However, this flexible operation results in lower SMR use, decreasing cost amortisation, and keeping the LCOE high.

### 5.4. Energy justice considerations on small modular reactors and renewable energy

The transition to a low-carbon energy system raises critical questions about energy justice, which emphasises the equitable distribution of benefits and burdens across society. It is particularly relevant when comparing the deployment of SMRs and RE technologies, as each pathway carries distinct social and economic implications.

#### 5.4.1. Distributive justice

The significantly higher costs of nuclear power, as demonstrated in this study, raise concerns about distributive justice. In Finland, cost overruns from past nuclear power projects such as Olkiluoto 3 have indirectly burdened consumers and taxpayers through increased electricity prices and legal disputes over cost-sharing [157]. In contrast, RE technologies like wind power and solar PV offer lower costs, with up to 53% lower LCOE and 46% lower LCOFE by 2050, and more decentralised benefits, enabling widespread participation and reducing energy poverty.

Municipalities hosting SMRs may see fewer benefits compared to traditional reactors. Early proposals for SMRs in Helsinki and Kuopio have raised concerns about who bears the risks versus who reaps the benefits [158]. SMRs require less labour, reducing their impact on local employment and tax revenues. Additionally, their high upfront costs often necessitate public subsidies, and the end-of-life costs and dismantling risks are transferred to taxpayers [159]. In contrast, RE technologies, such as wind power and solar PV, offer a more equitable distribution of benefits. Wind power plants, for instance, are a significant source of property tax revenue for many municipalities, generating over 46 m€ in 2024 [160]. This revenue supports local public services, such as healthcare, education, and social security, which are essential for maintaining high living standards. Additionally, the decentralised nature of RE systems allows for broader participation from diverse actors, including local communities and small businesses, promoting distributional justice and social acceptability.

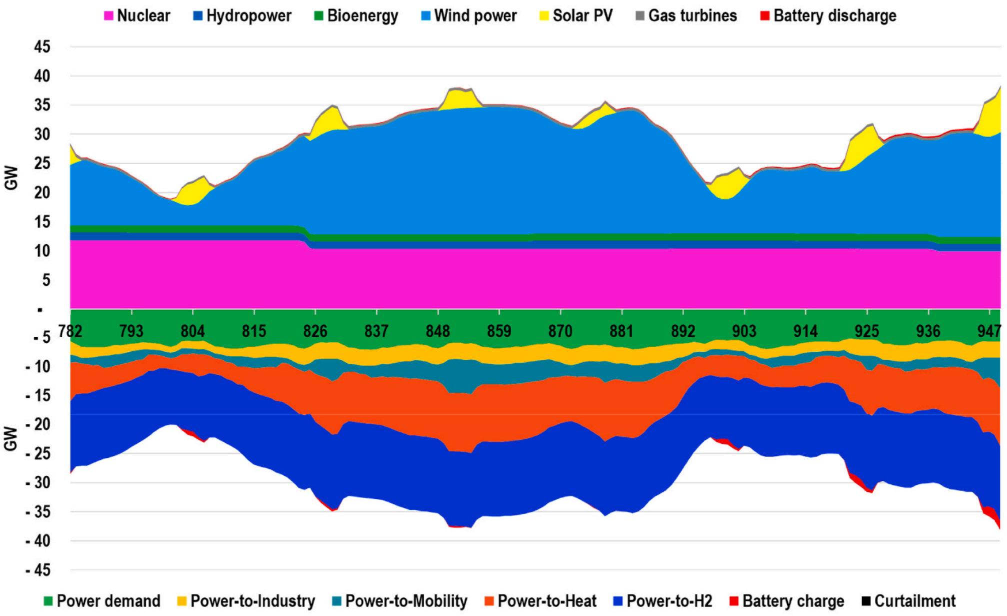

**Fig. 19.** Hourly system dynamics in an exemplary week in February in NE3 scenario.

### 5.4.2. *Procedural justice*

Procedural justice is another critical consideration in the comparison between SMRs and RE. The governance of nuclear power in Finland has been criticised for prioritising expert and industry perspectives over meaningful public participation [159]. While licensing processes involve public consultations, these mechanisms often lack substantive dialogue and fail to incorporate local concerns effectively. The licensing process for nuclear power facilities, such as Fennovoima's cancelled Hanhikivi-1 project, revealed shortcomings in procedural justice [161]. Protests in Pyhäjoki highlighted how formal consultation processes often fail to influence decision-making meaningfully [162]. For SMRs, procedural justice requires moving beyond formal consultations to ensure active and equitable participation by affected communities. Local acceptance is crucial, given the long-term social, ecological, and economic impacts of hosting these reactors. Strengthening participatory mechanisms, such as granting local veto rights and expanding stakeholder engagement in urban planning, could enhance the legitimacy and inclusivity of SMR-related decisions.

In contrast, RE technologies, particularly wind power and solar PV, are more conducive to decentralised innovation and participation. Current regulatory frameworks for RE are designed to attract a wide range of actors, including the general public and businesses outside the energy sector, increasing their potential for distributional justice and social acceptability. This inclusivity fosters a more equitable energy transition by empowering diverse stakeholders to contribute to and benefit from the system.

### 5.4.3. *Intergenerational justice*

Intergenerational justice highlights the ethical dilemmas posed by nuclear power, particularly the long-term management of radioactive waste. The hazardous nature of nuclear waste, which remains dangerous for millennia, imposes significant risks on future generations. While Finland's Onkalo facility addresses waste disposal from existing reactors, uncertainties remain about managing waste from SMRs. These responsibilities may impose additional burdens on host communities and future generations, exacerbating intergenerational injustices [159].

The intergenerational justice implications of SMRs are further compounded by their potential to create technological lock-in. Investing in SMRs risks committing societies to a centralised, inflexible energy system that may hinder the adoption of more innovative and cost-effective solutions in the future. This lock-in could delay the phase-out of fossil fuels and undermine efforts to meet urgent climate targets. In contrast, RE-based systems promote a decentralised energy transition that is more adaptable to future technological advancements and aligns with the urgency of addressing climate change. For example, the growth of distributed solar PV in Finland has been accelerated by investment subsidies [163], allowing households and all kinds of companies to take part in the transition [164] without committing society to a rigid, long-term infrastructure path, whereas feed-in tariffs or net-metering never existed in the country.

Despite the benefits of 100% RE systems, their development is not immune to social injustices [92,93], as in the specific case of the Sami population in Nordic countries [165]. However, as demonstrated in this study, the two decarbonisation pathways have considerably different cost implications for society as well as repercussions for system reconfiguration.

### 5.4.4. *Opportunity costs*

The opportunity costs of prioritising SMRs over RE are not merely economic but also societal and ethical. By choosing SMRs, society forgoes the opportunity to advance a more equitable, inclusive, and adaptable energy system. RE-based pathways offer a decentralised energy transition that empowers diverse stakeholders, reduces energy poverty, and promotes intergenerational justice by avoiding the long-term risks of nuclear waste. In contrast, SMRs reinforce existing centralised energy regimes, limit participation, and impose significant financial and environmental burdens on current and future generations.

## 5.5. *Limitations*

This study does not simulate unexpected nuclear power plant outages, which would require large backup solutions to guarantee power supply, such as utility-scale batteries [166] and thermal power capacities. In such a system, backup systems would remain out of operation for prolonged periods of time, making it harder to amortise their initial investments.

Finland was modelled as an isolated system, without considering the power interconnections with its neighbours. In theory, a simulation with electricity transmission would offer lower need for flexibility, as hours of excess and shortage could be satisfied with exports and imports, possibly further strengthening the case for the RE-based scenario. Moreover, the model did not include any social variable that could allow for a quantification of the impacts of energy injustices embedded in the analysed decarbonisation pathways.

The energy system modelling tool used in this study, LUT-ESTM, does not account for inter-annual storage [167,168] or consider the variability in inter-annual RE supply. Additionally, the tool lacks the capability to model transmission infrastructure for the transport of fuels such as methane, hydrogen, and carbon dioxide.

Furthermore, the analysis is based on long-term cost projections, which are inherently uncertain. For instance, battery CAPEX projections vary widely [169], due to uncertainties in advancements in materials science [170], the underestimated experience curve effects, or the potential in reutilising old EV batteries [171]. However, a preliminary sensitivity analysis shows that even if battery CAPEX were three times higher, the total annualised system cost would increase by just 0.2%. Importantly, the assumed projections are supported by literature and, given the substantial difference in system costs between the scenarios, the cost projections would need to be substantially off to alter the conclusions.

Another potential limitation is that this study assumes a high level of sustainable biomass availability, stemming from the pulp and paper industry. However, if that industry were to decline and bioenergy became less available, the Finnish energy system could increase onshore RE installations, as onshore wind power and solar PV would fill a potential bioenergy gap as for the rest of Europe [144,172]. If onshore land availability becomes constrained, Finland could consider offshore wind power [173,174]. One potential reason that could lead to lower availability of bioenergy is, for example, the potential legislative change that rewards forest owners to maintain growing trees, compensating them for the sequestered $CO_2$.

The generalisability of the findings in this study may be limited to energy systems with similar characteristics to Finland's, namely a high degree of flexibility from dispatchable bioenergy and sufficient land for RE. However, bioenergy is generally not essential for meeting the electricity demand, as it is not primarily used for balancing variable RE. Instead, its applications in heating, transport, and industry, complement both nuclear power and RE systems by providing flexibility and reducing reliance on fossil fuels. However, the literature on energy systems with high RE shares suggests that energy storage systems, such as batteries, vehicle-to-grid, and TES, can provide necessary flexibility in the absence of dispatchable RE sources [175]. The land area occupied by solar PV and onshore wind power in the BPS-ref would constitute less than 1.6% of the 292,000 $km^2$ unprotected land area of Finland, whereas the land area required for wind power is only 1% directly used [176]. Furthermore, energy systems with limited land availability can also explore offshore energy sources [177,178], such as offshore wind or wave power, which can help alleviate land constraints. Nonetheless, future studies on energy systems with limited dispatchable RE sources and strict land constraints would test the generalisability of this study.

## 6. Conclusion

Tripling nuclear energy capacity by 2050, as proposed by the COP28 declaration, would lead to significantly higher annualised costs and levelised costs of electricity compared to a cost-optimised system that prioritises renewable energy sources. The levelised cost of electricity and levelised cost of final energy and non-energy use in nuclear scenarios are 106–123% and 76–88%, respectively, higher compared to the cost-optimised scenario. The cost difference between the nuclear scenarios and the reference scenario would represent 2.3% of the Finnish gross domestic product in 2050. While hourly simulation results show that nuclear scenarios maintain lower installed capacity for electricity generation and energy storage, the reference scenario can meet energy demand more cost-effectively, while avoiding the environmental, societal, and economic risks associated with nuclear power. The renewables-based system achieves flexibility with 28% higher heat generation capacities, 48% higher electrolyser capacity, and 1700% more hydrogen storage capacity compared to nuclear scenarios, 2.1 GWh of utility-scale batteries, and 9 GWh of medium-temperature thermal energy storage.

The analysis did not consider power interconnections with neighbouring countries or unexpected nuclear power plant outages. Addressing these factors could potentially strengthen the case for the renewables-based system, as interconnections would reduce the need for flexibility in the renewables-based system, and sudden supply disruptions would require additional flexibility in nuclear scenarios.

Tripling nuclear power capacity would entail a substantial opportunity cost, as public resources could be allocated to more cost-effective renewable energy solutions. The financial savings from prioritising a highly renewable energy-based system could be used to address pressing social challenges in Finland, such as reducing health disparities, improving education, or strengthening social security. Therefore, opting for a nuclear power pathway raises ethical questions regarding the obligation of governments to optimise public resources to achieve the greatest societal benefit. Policymakers and energy consumers should prioritise investments in renewable energy sources and sector coupling technologies, as these strategies lower costs and promote a more just and inclusive energy transition.

## CRediT authorship contribution statement

**Rasul Satymov:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Salvatore Ruggiero:** Writing – original draft, Validation, Investigation. **Björn Steigerwald:** Writing – review & editing, Validation, Investigation, Conceptualization. **Jens Weibezahn:** Writing – review & editing, Validation, Investigation. **Neven Duić:** Writing – review & editing, Validation. **Jero Ahola:** Writing – review & editing, Validation, Funding acquisition, Conceptualization. **Dmitrii Bogdanov:** Writing – review & editing, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Christian Breyer:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

## Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the corresponding author used Llama 3.3 from Meta AI in order to improve the grammar and condense the text to enhance reading comprehension. After using this tool/service, the corresponding author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

## Declaration of competing interest

The authors declare no conflict of interest.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2025.138630.

## Data availability

Detailed data is available in the Supplementary Material.

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