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Key determinants of nuclear fission competitiveness and implications of its potential restart for the Italian power system

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ABSTRACT

This study introduces two key methodological enhancements to an open-source multi-regional model of the Italian power sector, namely a detailed representation of the nuclear fuel cycle and a discrete capacity formulation to capture the indivisible nature of reactor units and their systemic interactions, and applies them to assess the techno-economic feasibility and policy conditions under which nuclear fission could re-emerge as a competitive player within an Italian decarbonized power system by 2050. Through a structured scenario analysis, we examine both the combined influence of investment costs and hurdle rates on the competitiveness of nuclear power, comparing large light-water reactors and small modular reactors, and the potential implications of nuclear fission reintroduction for the Italian power system. A dedicated sensitivity analysis investigates the potential of Generation IV designs, such as lead-cooled fast reactors and high-temperature gas-cooled designs, under alternative cost assumptions. The results indicate that nuclear power would become economically viable in most scenarios with stable or moderately increasing capital costs, reaching up to the 8 GWe maximum constraint for the installed capacity by 2050 and reducing electricity imports by nearly 50%. Nuclear deployment would decrease the total system costs by up to €8 billion, while also reducing storage requirements (−42%), curtailed generation (−35%) and land use (−25%) compared to a non-nuclear decarbonization pathway. Overall, the study highlights the decisive role of financing conditions and policy frameworks in determining the future competitiveness of nuclear energy in Italy, emphasizing its potential contribution to energy security, system reliability, and cost-efficient decarbonization.

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Nomenclature

Acronyms	
C2N	Coal-to-Nuclear
CC	Carbon Capture
CNAI	National Map of Suitable Areas
CNEN	National Committee for Nuclear Energy
COP	Conference of the Parties
DU	Depleted Uranium
ENEA	National Agency for New Technologies, Energy and Sustainable Economic Development
EPR	European Pressurized Reactor
ESOM	Energy System Optimization Model
FOAK	First-of-a-Kind
GCR	Gas-Cooled Reactor
IAEA	International Atomic Energy Agency
IDC	Interests During Construction
IEA	International Energy Agency
L_LWR	Large size Light Water Reactor
LFR	Lead Cooled Fast Reactor
LWR	Light Water Reactor
Micro-CHP	Micro-Combined Heat and Power
MOX	Mixed Oxide
NPV	Net Present Value
OCC	Overnight Construction Cost
O&M	Operation and Maintenance
PWR	Pressurized Water Reactor
S_GCR	Small modular Gas-Cooled Reactor
S_LFR	Small modular Lead cooled Fast Reactor
S_LWR	Small modular Light Water Reactor
SMR	Small Modular Reactor
TEMOA	Tools for Energy Modeling Optimization and Analysis
TSO	Transmission System Operator
UCO	Uranium Carbide Oxide
UK	United Kingdom
UOX	Uranium Oxide
WACC	Weighted Average Cost of Capital

Region Labels	
ABR	Abruzzo
BAS	Basilicata
CAL	Calabria
CAM	Campania
EMR	Emilia-Romagna
FVG	Friuli-Venezia Giulia
LAZ	Lazio
LIG	Liguria
LOM	Lombardia
MAR	Marche
MOL	Molise
PIE	Piemonte
PUG	Puglia
SAR	Sardegna
SIC	Sicilia
TOS	Toscana
TAA	Trentino-Alto Adige
UMB	Umbria
VDA	Valle d’Aosta
VEN	Veneto

1. Introduction

Nuclear energy is the world's second largest source of low-carbon electricity, accounting for approximately 9% of global production in 2023 [1]. After strong expansion in the 1980s, driven mainly by energy security concerns following the oil crises – nuclear investment slowed significantly due to uncertainties related to high capital costs, long construction times, and increasingly stringent safety regulations, which intensified after the Chernobyl accident [2]. As a result, nuclear share of global electricity generation has gradually declined over the past 30–40 years [3], falling from around 18% in the late 1990s to below 10% today. However, rising energy demand and the need for dispatchable low-carbon power are renewing interest in nuclear energy. Global investments have more than doubled in the last 7 years [4]. At the Conference of the Parties (COP) 28 in 2023, more than 20 countries launched the Declaration to Triple Nuclear Energy, aiming to at least triple capacity by 2050 relative to 2020 levels [5]. In 2024, at COP 29, the US Government announced plans to at least triple domestic nuclear capacity by mid-century, while Google partnered with Kairos Power to deploy 500 MW of Small Modular Reactors (SMRs) capacity by 2035 [6]. In the same year, the European Commission established the European Industrial Alliance on Small Modular Reactors to support first deployments in the early 2030s [7]. According to the International Atomic Energy Agency (IAEA), the global nuclear capacity could increase by a factor of 2.5 by 2050 [8], reinforcing its potential role in decarbonization pathways [9].

Most operating nuclear power plants still belong to Generation II. Generation III/III + designs evolved from Generation II, by integrating passive safety systems, higher fuel burnup, and increased thermal efficiency [10]. In parallel, Generation IV concepts are under development [11]. These include both thermal and fast reactors, classified according to their neutron spectrum [12]. Thermal reactors, often operating at higher coolant temperatures, can achieve higher thermodynamic efficiency and supply heat for industrial uses [13]. Fast reactors enable fuel cycle closure through spent fuel recycling and the burning of long-lived actinides, significantly reducing the volume and long-term management challenges of high-level waste [14]. In parallel with large-scale systems, SMRs adopt a modular manufacturing approach, with factory-produced units transported and assembled on-site [15]. This can reduce capital costs, ease financing, shorten construction times, improve quality control, and enable deployment in remote areas [16]. However, SMRs typically exhibit lower net conversion efficiencies than large reactors of the same type [17]. This is due to scale effects, such as auxiliary power requirements not decreasing linearly and thus consuming a larger share of the gross output.

Italy was an early adopter of civil nuclear power, beginning construction of its first reactor in 1958 [18]. Following the 1986 Chernobyl accident and a national referendum reflecting strong public opposition, the government shut down all operating plants and halted new nuclear programs [18]. Today, Italy faces structural challenges in its energy system, particularly a strong spatial mismatch between electricity demand and renewable resources. In 2023, only 2% of wind generation and 43% of solar generation occurred in Northern regions [18], where 57% of electricity demand is concentrated, largely due to higher industrial activity (65% of national industrial electricity consumption) [19]. This imbalance increases transmission needs and highlights the strategic value of dispatchable low-carbon baseload generation. Moreover, Italy remains highly dependent on electricity imports: in 2023, it was the world's second largest net importer [18], covering 16.3% of domestic consumption [20]. In this context, new low-carbon power sources could support both decarbonization and energy security. Nuclear energy, with a median life-cycle carbon intensity of 12 gCO2/kWh [21], could contribute to this objective. Institutional signals of renewed interest have emerged, including the entry of National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) into the European Industrial Alliance on Small Modular Reactors in 2024 [22], and Italy's accession to the European Nuclear Alliance in 2025 [23]. Public acceptance has also improved [24]. Nevertheless, major barriers remain, including delays in decommissioning legacy reactors [25] and long-standing political and regulatory uncertainty, which increase investment risk and the cost of capital.

Assessing the potential future role of nuclear energy in Italy therefore requires analytical tools capable of addressing long-term technological, economic, and policy trade-offs. Energy System Optimization Models (ESOMs) are mathematical frameworks designed for this purpose [26]. They identify cost-optimal energy system configurations – typically assuming partial equilibrium, competitive markets, and perfect foresight – while meeting demand, technical constraints, and environmental targets [27]. Based on networks of technologies and energy carriers

Table 1
Heat and electricity demand taken from the net-zero scenario presented in Ref. [63].

Demand (PJ)	2025	2030	2035	2040	2045	2050
Heat	203.89	214.08	224.79	236.03	247.83	260.22
Electricity	984.13	1085.99	1191.04	1295.30	1393.12	1432.38

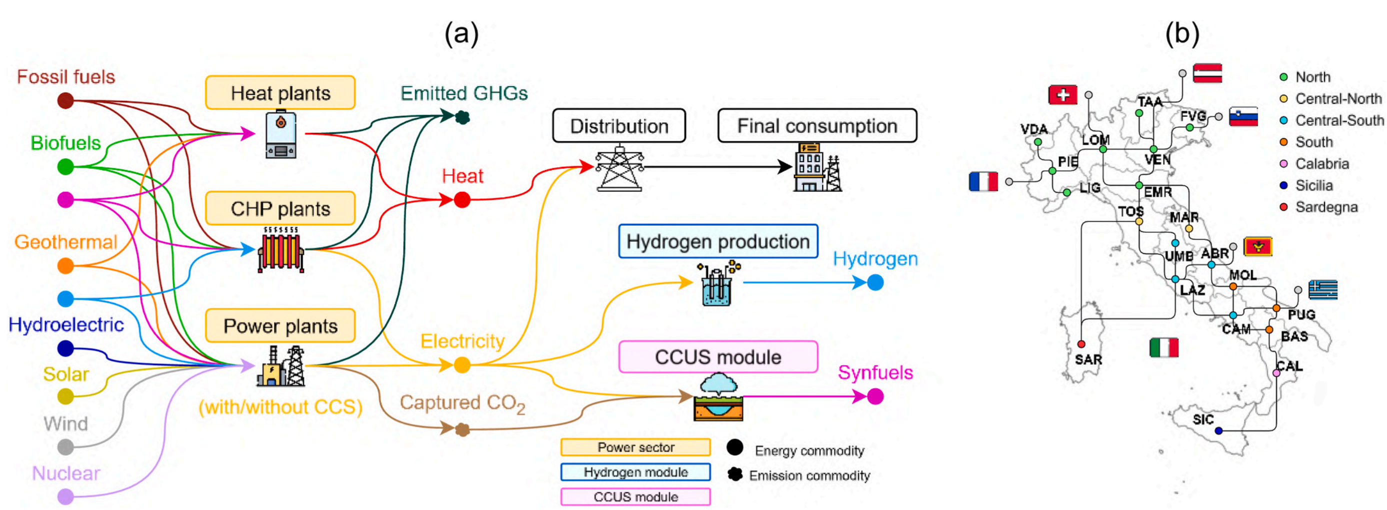

Fig. 1. Scheme of the multiregional power sector model instance highlighting (a) the main technology groups, input and output commodities, (b) representative nodes and transmission lines [55]. Acronyms are illustrated in the nomenclature alongside the extended names of regions.

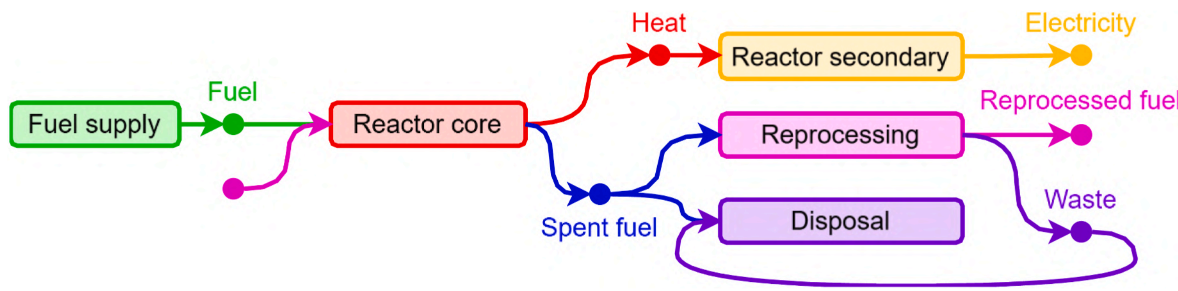

Fig. 2. Simplified nuclear chain. Technologies are represented by squares and commodities by circles.

characterized by techno-economic parameters, ESOMs support policy analysis, climate target assessment, and technology planning [28].

Despite their established role, the deployment of new nuclear units faces high First-Of-A-Kind (FOAK) costs and significant financial risks [29], alongside regulatory and supply chain hurdles [30]. To mitigate these challenges, the Coal-to-Nuclear (C2N) pathway proposes repurposing retiring coal-fired plants to leverage existing grid and cooling infrastructure [31], offering a strategic solution for system integration [32]. However, these complexities are often represented in a simplified manner within energy models. Key aspects such as the fuel cycle [33], material requirements [34], economic competitiveness thresholds [35], and risk-mitigation policies [36] are frequently overlooked. While acceptable for some applications, this simplification limits the ability to capture the diversity of reactor designs, costs, and operational characteristics. Moreover, few long-term planning studies systematically explore how nuclear competitiveness depends on macroeconomic parameters such as investment costs and interest rates. Although many assessments examine nuclear under specific assumptions [37], only a limited number analyze the sensitivity of deployment pathways to financial conditions [38], despite their strong influence on capital-intensive technologies like nuclear power [39]. Understanding these dependencies is essential to assess under which economic and policy conditions nuclear energy can become competitive [40], and to quantify the resulting implications for technology mix [41], sector-couplings [42], system reliability, environmental impacts [43] and overall transition costs.

To address these issues, this work pursues two objectives. First, it evaluates the economic conditions under which a potential restart of nuclear fission in Italy could be economically viable and assesses its contribution to long-term emission reduction in the power sector. This includes analyzing the combined effects of investment costs and hurdle rates on the competitiveness of Generation III+ and Generation IV reactors of different sizes relative to alternative technologies. Second, the study examines how siting policies and geographical constraints influence the spatial distribution of nuclear deployment, and the resulting impacts on backup capacity, storage requirements, curtailments, and land use at the regional level and under a net-zero constraint. To achieve these objectives, we conduct a set of targeted scenario experiments using a multiregional version of the TEMOA-Italy model [44], specifically enhanced with a detailed representation of the nuclear supply chain and a discrete capacity formulation.

The paper is organized as follows. Section 2 presents the adopted multiregional model instance and the techno-economic modeling of nuclear technologies. Moreover, it describes the scenarios related to nuclear economic competitiveness (Section 2.3) and alternative siting assumptions (Section 2.4). Section 3 discusses the results, analyzing nuclear competitiveness, the role of Generation IV SMRs, and the effects of a nuclear restart on deployment and system outcomes at national and regional scales. Section 4 addresses limitations and future research perspectives, while Section 5 summarizes the main findings and outlines the main policy implications.

2. Methodology

The methodology developed in this study relies on two main components. First, the Italian power system is represented in a multiregional model instance to provide a suitable optimization framework for exploring the competition between nuclear technologies and other electricity production options (Section 2.1). Second, the techno-economic characterization adopted to represent the selected fuel supply options, reactor types, temporary storage, reprocessing, and waste disposal facilities (Section 2.2).

2.1. Representation of the Italian power system

This section describes the Italian power sector model developed using the TEMOA (Tools for Energy Modeling Optimization and Analysis) framework, building on a validated full-scale national energy system model [53]. TEMOA is an open-source, bottom-up modeling platform based on linear optimization that minimizes total system costs over a defined time horizon, subject to technical and policy constraints and energy service demands. System costs include investment, fixed operation and maintenance (O&M) and variable O&M components, with the latter linked to technology activity and the former to installed capacity; all costs are discounted to the beginning of the time horizon. TEMOA's modular and transparent structure makes it well suited for academic and exploratory scenario analysis, including regional applications such as [45] for Piedmont and [46] for Pantelleria. Among similar tools for multi-sector energy system planning, such as TIMES [47] and OSeMOSYS [48], and tools for CLEW analyses such as GCAM [49], TEMOA was selected because it provides several built-in methodologies for uncertainty analysis, including modeling to generate alternatives [50], stochastic optimization [51], and global sensitivity analysis [52], while also benefiting from an existing Italian modeling platform that has been successfully benchmarked [53] against the TIMES framework used to support the Italian National Energy and Climate Plan [54].

The multiregional model instance [56] used here is derived from the power sector of TEMOA-Italy [44], an open-source national model calibrated using International Energy Agency (IEA) energy statistics for the base year 2006 and Eurostat Energy Balances up to 2022 [44]. Focusing on the power sector allows the analysis of competition between nuclear and alternative technologies under fixed electricity demand, avoiding cross-sectoral interactions and electrification dynamics. The model disaggregates the Italian power system into 20 nodes corresponding to administrative regions to capture spatial heterogeneity in demand, resources, and policy constraints (Fig. 1b). The model time scale consists of a time horizon spanning up to 2050 and 96 time slices per milestone year, corresponding to combinations of seasons (i.e., winter, spring, summer and fall) and 24 times of day per season (i.e., hourly resolution).

A scheme of the TEMOA-Italy power sector is illustrated in Fig. 1a. The technology portfolio includes coal and natural gas power plants with Carbon Capture (CC) and Micro-Combined Heat and Power (Micro-CHP) for residential, industrial, and commercial applications. The

Table 2
Reactor technologies techno-economic parameters.

Reactor	Fuel	Reprocessing	Efficiency (%)	Discrete Capacity (GWe)	Lifetime	Overnight Cost ($\$_{2022}$B/GWe)	Fixed O&M Cost ($\$_{2022}$M/GWe)	Capacity Factor (%)
L_LWR	UOX LWR or MOX	PUREX or	33	1.6	60	4.0	154	94
S_LWR	LWR	UREX		0.4		4.8		
S_LFR	MOX LFR	Pyro	42	0.2		-		
S_GCR	UCO GCR	-	41	0.1		-		

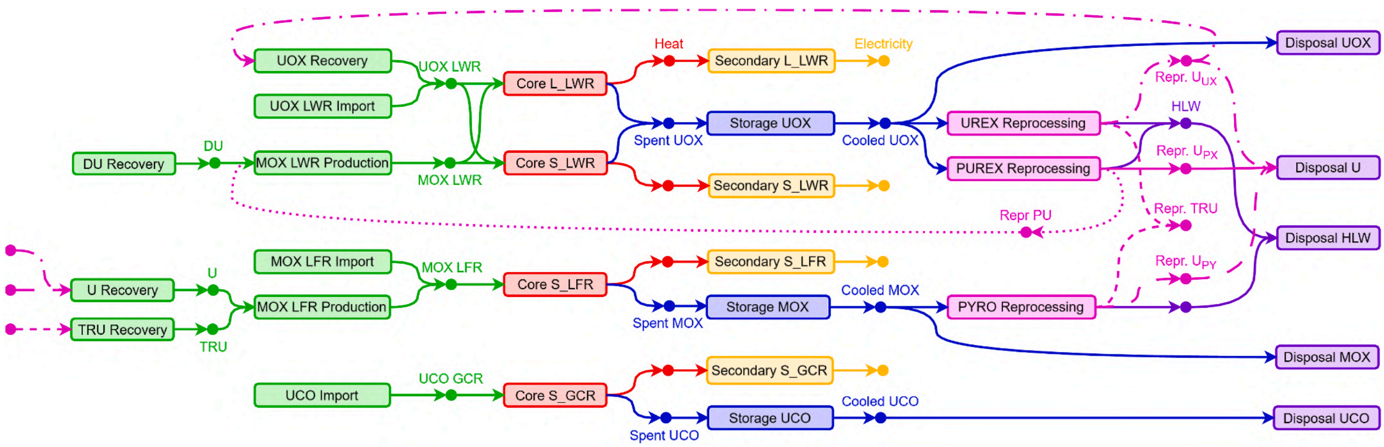

Fig. 3. Schematic representation of the nuclear technology chain represented in the model. The front-end section is represented with green blocks, cores and secondary circuits belonging to the reactor section are represented in red and yellow, respectively, while blue blocks represent temporary storage, pink reprocessing facilities and violet final disposal. Acronyms are illustrated in the nomenclature alongside the extended names of regions.

considered utility-scale energy storage options are lithium-ion batteries and pumped hydroelectric plants, while lithium-ion batteries are considered as distributed facilities [55]. Emissions are modeled following the dynamic approaches in Refs. [57], [58] for considering blending of renewable fuels, critical raw materials requirements for new capacity of energy technologies follow [59], [60] and technology-specific hurdle rates are taken from Refs. [61], [62].

Upstream fuel supply chains for coal, oil, natural gas, and biofuels are represented by dedicated technologies with associated variable costs. Electricity imports and exports are modeled through technologies reflecting average capacities and prices, as described in Ref. [63]. Electricity distribution, including conversion from centralized to distributed supply, is modeled with an assumed efficiency of 95% to account for grid losses. National heat and electricity demands are derived from a decarbonization scenario produced with the full TEMOA-Italy model (Table 1). These demands are then disaggregated across the 20 regions based on 2022 electricity demand shares and regional Gross Domestic Product for hydrogen, as detailed in Refs. [56], [64].

2.2. *Nuclear fission techno-economics*

The nuclear fuel cycle structure implemented into the Italian model is inspired by the JRC-EU-TIMES model approach [65]. Nuclear front-end and back-end stages are disaggregated more explicitly. Fig. 2 represents the connection between the most relevant technologies and commodities divided into three main sections: front-end (e.g. supply chain and fuel), reactors (e.g. core and secondary sides, producing heat

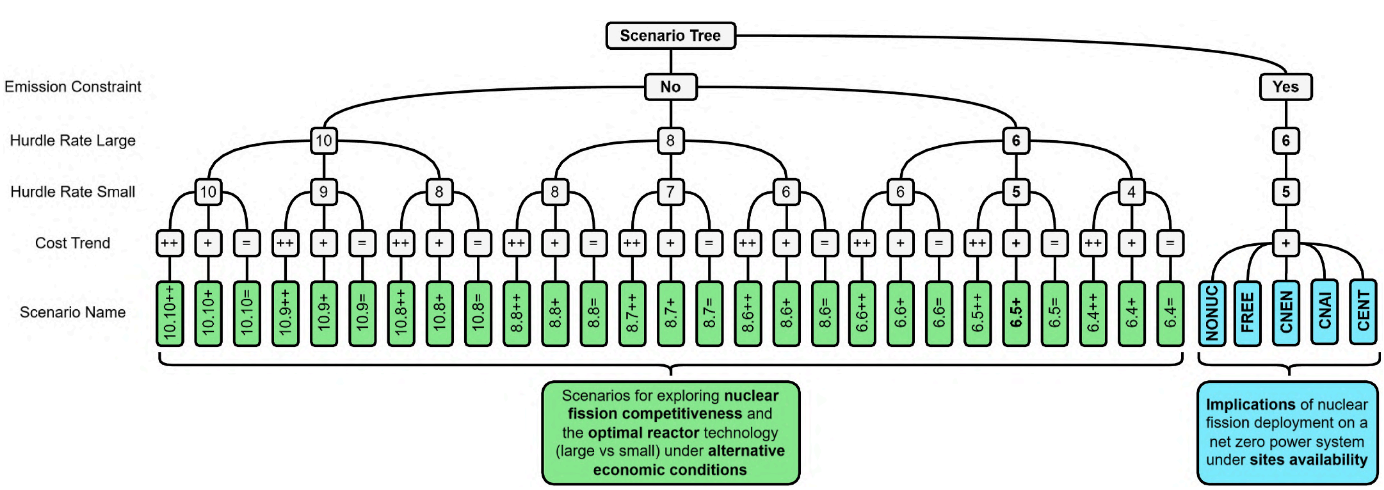

Fig. 4. Parameters combinations defining the investigated scenario tree in the present study. Scenarios presenting the same assumptions for hurdle rates and cost trend are highlighted in bold.

and electricity respectively) and back-end (e.g. temporary storage, spent fuel reprocessing and final disposal of waste). The complete modelling of the front-end and back-end is illustrated in Ref. [66], while this section focuses on the reactor segment.

Since modelling relies on real reactor designs, an overview of current and future concepts is required. The selection of the reactor type is based on a comprehensive overview of the current state of the art. Water reactors dominate nuclear power, accounting for over 95% of global net capacity, with Pressurized Water Reactors (PWRs) representing 78% in 2023 [67]. In Europe, all operating reactors in the European Union and the United Kingdom (UK) are Generation II water reactors except for Olkiluoto-3 (located in Finland), which is a European Pressurized Reactor (EPR), the first Generation III + unit and the first new European reactor since 2007 [67]. In December 2024, another EPR (Flamanville 3) entered operation in France [68]. Except for UK Gas-Cooled Reactors (GCRs), all European reactors are water-cooled, and all units under construction are PWRs, including EPR-1750 in the UK and VVER V-213 in Slovakia [67]. After prolonged stagnation, European new-build activity has thus converged on Generation III + PWRs. The EPR is therefore selected as the representative large reactor, given its maturity and regulatory compatibility within the European – and potential Italian – context.

To examine competition across reactor scales, SMRs are also considered. Among advanced SMRs designs listed in Ref. [2] (including AP300 SMR of Westinghouse, Aurora of Oklo, BWRX-300 of GE Hitachi Nuclear, 200-400 MW SMR of NUWARD, etc.), the UK SMR is chosen due to its advanced development status (Rolls-Royce SMR has been selected as the preferred bidder to partner with Great British Energy – Nuclear to develop SMRs [69]), its European manufacturer, and its reliance on PWR technology. Hereafter, the traditional large-scale EPR and its SMR version are referred to as Large-size Light Water Reactor (*L_LWR*) and Small-modular Light Water Reactor (*S_LWR*). To explore the potential role of alternative reactor designs – introducing new life-cycle options with possible relevant effect on fuel import and spent fuel management – two additional Generation IV SMRs are considered: a Lead Cooled Fast Reactor (LFR) and a very high temperature reactor. The choice of a fast reactor and a high temperature one makes it possible to exploit the advantages of these technologies in terms of spent fuel recycling and potential availability of high temperature heat for industrial uses different from electricity production, respectively. The two models from IEA nuclear projection research [2] are LFR-AS-200 (selected by the European Small Modular Reactor Industrial Alliance [70]), from this point onward referred to as Small modular Lead cooled Fast Reactor (*S_LFR*), and Xe-100 (X-Energy signed a joint development agreement for their deployment in the UK [71]), hereafter denoted as Small modular Gas-Cooled Reactor (*S_GCR*).

In terms of the economic characterization of reactors, the Overnight Construction Cost (OCC) includes pre-construction (owner's), construction (engineering, procurement, and construction) and contingency costs. The investment costs – i.e. OCC with the addition of interests during construction (IDC) – are computed from the overnight costs as reported, with *n* representing the construction time in years, *y* the year from 1 to *n* and *r* the discount rate as described by Equation (1), assuming payments occur at the end of each construction year.

$$CostInvest = \sum_{y=1}^{n} \left(\frac{OvernightCost}{n} \cdot (1+r)^{y-1} \right) \quad (1)$$

The reference overnight costs assumed here are \$4.0B/GWe for *L_LWR*, as per Table 3.4a from Ref. [72], which provides an overview of different LWR investment costs, and \$4.8B/GWe for *S_LWR* [17]. Due to lack of available data, fixed O&M costs for *S_LFR* and *S_GCR* are assumed to be equal to those of *S_LWR*. This simplification balances potential operational advantages (e.g., online refueling) against the reduced economies of scale and higher technical complexity of non-water-cooled designs. Their investment costs – which are still highly uncertain [39] – will be subject to further analysis in the following sections. For these reasons, the two innovative SMRs are excluded from the core scenario framework and are available exclusively within the dedicated sensitivity analysis presented in Section 3.3.

Regarding construction time, the highest values included in the 90% probability interval of Monte Carlo simulation from Ref. [17] are conservatively selected, corresponding to 10 years for *L_LWR* and 6 years for *S_LWR*. These values are also aligned with the conservative scenario discussed in Ref. [73] corresponding to 125 and 71 months, respectively. Decommissioning costs [74], [75] are not considered, as the long operational lifetime of nuclear plants makes their present value negligible when discounted at the installation year [72]. Fixed O&M costs for all the reactors is \$154M/GWe, corresponding to the optimistic value for USA in Ref. [76].

Technical parameters listed in Table 2 are taken from Ref. [77]. EPR has a burnup (measured in gigawatt-days per ton (GWd/t), representing the total thermal energy extracted from a unit of fuel before its discharge from the reactor) of 60 GWd/t, leading to 5.18 PJ/ton for the *L_LWR*, while the UK SMR burnup is 55 GWd/t, corresponding to 4.75 PJ/ton for *S_LWR*. LFR-200-AS and Xe-100 have burnup of 100 GWd/t and 165 GWd/t, respectively, corresponding to 8.64 PJ/ton for *S_LFR* and 14.26 PJ/ton for *S_GCR*. The lifetime is assumed at 60 years, and the maximum capacity factor is set to 0.94 for all reactors, as confirmed in Ref. [78] for new plants, while the actual capacity factor is a result of the optimization process performed by the model. All nuclear technologies are assumed to be available no sooner than 2040, taking into account the necessary preparation of the regulatory framework, as well as the construction time of new facilities. While this timeline is ambitious when considering recent European construction experiences and delays, it represents a conservative assumption relative to the Italian government's current scenarios, which expect operational reactors as early as 2035 [79]. The 2040 horizon serves not as a predictive forecast, but as an analytical baseline to examine the systemic implications of a nuclear restart by 2050. Previous sensitivity tests [66] indicate that shifting the startup date does not significantly alter fission's competitiveness by 2050. A delay would primarily affect the transition path and the temporary mix required to meet emission targets, without altering the final optimal capacity.

The complete nuclear supply chain represented in TEMOA-Italy, including fuel supply, reactors, temporary storage, reprocessing facilities and final disposal of waste, is shown in Fig. 3. The *L_LWR* and *S_LWR* share the same supply chain, based on Uranium Oxide (UOX) and Mixed Oxide (MOX) fuels, with MOX accounting for up to 33% of the total input. UOX can be either imported or partially recovered – after temporary storage – from spent fuel though the UREX + reprocessing, which also separates transuranic elements. Alternatively, the PUREX reprocessing allows to recover plutonium from the spent fuel, to be blended with Depleted Uranium (DU) for new MOX fabrication. The same configuration is applied to the *S_LFR*, whose front-end is based on MOX fuel, either imported or produced with uranium and transuranic elements recovered through pyroprocessing or the abovementioned reprocessing paths for LWRs spent fuel. All reprocessing techniques separate high level waste, and each waste commodity has a dedicated final disposal technology. The *S_GCR* is the only reactor type with no reprocessing options and, consequently, it follows a one-through fuel cycle based on Uranium Carbide and Oxide (UCO). The techno-economic modelling of the nuclear chain is discussed in detail in

Table 3
Current investment costs in $\$_{2022}$B/GWe including IDC depending on Hurdle Rate.

Investment Cost ($\$_{2022}$B/GWe)	Hurdle Rate						
	10%	9%	8%	7%	6%	5%	4%
L_LWR	6.4		5.8		5.3		
S_LWR	6.2	6.1	5.9	5.8	5.6	5.5	5.4

Table 4
Normalized reactors investment costs (€M/€M) future trends (for scenarios ++, + and =).

Scenario	2035	2040	2045	2050
++	1.00	1.61	1.96	1.96
+	1.00	1.28	1.41	1.41
=	1.00	1.00	1.00	1.00

Ref. [66]. The detailed nuclear chain techno-economic characterization described in Fig. 3 is innovative compared to the traditional and simplified ESOMs' approach for nuclear technologies, enabling analysis of fuel import dependence and waste reduction through reprocessing.

To better represent real-world constraints, the TEMOA formulation is extended with a new modeling feature that enables discrete capacity additions. Unlike standard energy planning tools that allow continuous capacity expansion, this approach constrains new installations to multiples of a user-defined "DiscreteCapacity." This is particularly relevant for technologies characterized by large, indivisible units, such as nuclear power plants, whereas continuous approximations are more suitable for modular renewables. The distinction is especially important in a multiregional setting, where regions may favor SMRs or large reactors depending on local demand. To avoid numerical issues, discrete values are rounded to realistic sizes, ensuring that the maximum capacity constraint defined in Section 2.3 is an exact multiple of these units. The adopted DiscreteCapacity values and the main techno-economic parameters of the modeled reactors are reported in Table 2, focusing on their electricity generation performance.

2.3. Economics determining nuclear fission competitiveness

Regarding the first objective of the paper (assessing nuclear competitiveness under varying economic conditions), this section defines the scenarios aimed at investigating the implications of a nuclear fission restart in Italy and how variations in certain parameters, such as hurdle rates and investment cost trends, affect nuclear plants' competitiveness. It begins with an overview of nuclear capacity expansion across the 27 scenarios (Fig. 4), all developed under the CNEN regional siting constraints (described in Section 2.4). Finally, the potential contribution of *S_GCR* and *S_LFR* is explored under alternative investment cost assumptions, due to the lack of reliable data emerged for the capital costs of such innovative reactors [80].

The OCC typically accounts for roughly 55% of nuclear total levelized cost. In this regard, some approaches aimed at reducing upfront investment costs – such as C2N conversions, which involve reusing existing coal plant infrastructure for new nuclear installations – are receiving growing attention [81], although they are not considered in this study. Other life-cycle costs have lower contributions – approximately 15% for IDC, 15% for O&M and decommissioning provision, and 15% for fuel and provisions for spent fuel – and have shown minimal variation over time and across countries [82]. For this reason, the analysis focuses on two economic parameters that influence OCC reflecting different drivers: hurdle rates and future investment cost trends. Hurdle rates, mainly driven by government policy and regulation, are supposed to remain stable across the scenarios' time periods. On the contrary, OCC varies across time periods reflecting different assumptions for future cost trends.

Hurdle rates are calculated using the WACC formula, as discussed by Ref. [61]. As shown by Ref. [2], hurdle rates for both *L_LWR* and *S_LWR* (the only reactors considered in this study) are generally between 6% and 8% depending on the role of nuclear energy production in company portfolios. Given the historical political instability of Italy and the expected opposition from at least part of the population to the restart of the Italian nuclear sector, scenarios explored in this analysis implement three different hurdle rate levels for the *L_LWR* technology, ranging from an optimistic base of 6% to 8% and 10%, conservatively. Such assumptions are also aligned to those made by Ref. [83] for the Netherlands. Quantifying the benefit in the hurdle rate of SMRs compared to large reactors is not trivial, as it involves competing factors: while the FOAK status, regulatory uncertainty, and supply chain immaturity could increase risk, the lower capital requirements and modularity of SMRs might appeal to a broader range of investors. Since the goal is to identify the economic conditions under which SMRs could reach competitiveness, and considering their higher investment cost disadvantage, scenarios with SMR hurdle rates higher than those of *L_LWR* are not explored. As a result, alongside assuming the same hurdle rate of large reactors, we also consider hurdle rates levels 1% and 2% lower in specific scenarios for this technology. For other technologies, including intermittent renewables, the hurdle rate is assumed to remain unchanged across the scenarios. Indeed, their shorter operational lifetimes, lower capital intensity, and future projections for cost reductions reduce the relevance of the cost of capital in determining their competitiveness.

Coming to reactor cost variation, historical cost trends for nuclear investments in different countries have been taken from Ref. [82], where the first decade of nuclear installations emerges to be typically characterized by a decreasing annualized rate of change ranging from −6%/yr to −17%/yr. The subsequent decade generally shows the opposite pattern, with annual increases between +2% and +12%. Some considerations should be made about the data mentioned. Firstly, there are no recent data for the American and European regions, as the investigated

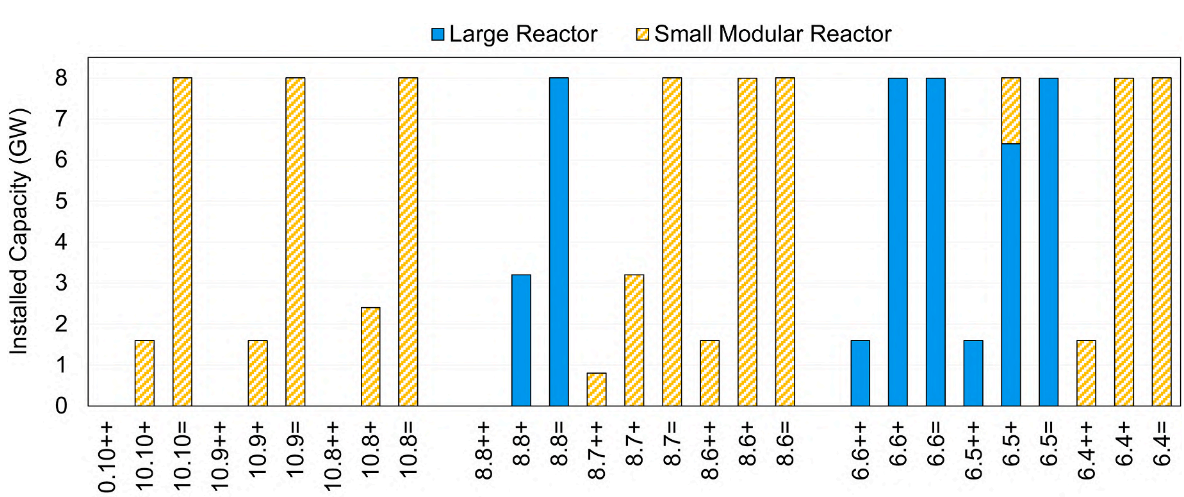

Fig. 5. Total installed nuclear reactors capacity in each scenario.

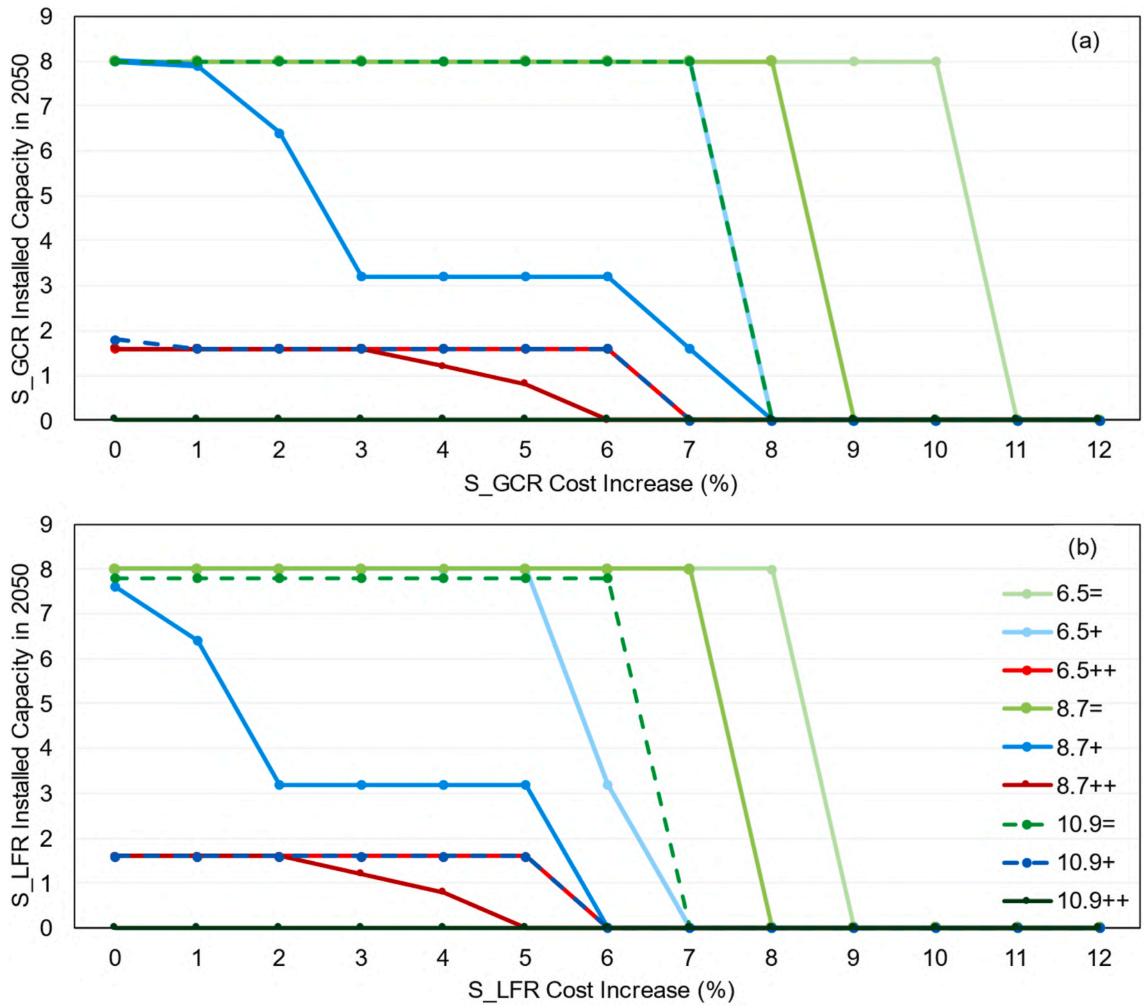

Fig. 6. *S_GCR* (a) and *S_LFR* (b) installed capacity depending on investment costs increase.

period spans from 1954 to 1991. The most recent data concern Asia and shows stable costs between 1980 and 2008. South Korea is the only country to present stable costs throughout the entire period, suggesting that the political context can heavily determine these trends through different policies and regulatory frameworks. Given that, three different pathways are investigated for the scenarios:

- stable investment costs for the entire time horizon (=);
- +5% annualized rate of change between 2035 and 2040 followed by +2%/yr up to 2045 and constant costs afterward (+);
- +10% annual increase from 2035 to 2040 followed by +4%/yr up to 2045 (++). This choice is very conservative compared to the National Renewable Energy Laboratory conservative, moderate, and advanced scenarios for the USA, which consider only decreasing cost trends [73].

All the possible combinations of assumptions made for hurdle rates and cost trends result in 27 scenarios reported in the scenario tree shown in Fig. 4. For easier visualization, the name of each scenario is labelled in the format L.S, where L and S correspond to the hurdle rates for large reactors and SMRs, respectively, followed by the symbols =, +, or ++ depending on the assumed cost trend in each case (for example, scenario 6.4 = assumes 6% hurdle rate for large reactors, 4% hurdle rate for SMRs, and a stable cost trend). The investment costs obtained with

Table 5
Nuclear installed capacity by region and type of reactor in each scenario.

Region	Installed Capacity (GWe)							
	FREE		CNEN		CNAI		CENT	
	L_LWR	S_LWR	L_LWR	S_LWR	L_LWR	S_LWR	L_LWR	S_LWR
EMR					-	-	1.60	0.80
FVG		0.80		0.80	-	-	-	-
LAZ					1.60	1.20	1.60	0.80
LOM	4.80		4.80	0.80	-	-	-	-
PIE					1.60	2.00	3.20	
TAA		0.40	-	-	-	-	-	-
TOS	1.60	0.40	1.60		-	-	-	-
Italy	6.40	1.60	6.40	1.60	3.20	3.20	6.40	1.60

Equation (1) based on hurdle rates are reported in Table 3, illustrating the high sensitivity of total capital requirements to financing conditions and IDC. The impact of cost trends on these investment costs is shown in Table 4 represented by the resulting multiplication factors. Notably, these factors allow the model to test the robustness of nuclear competitiveness against potential cost escalation, considering scenarios where investment costs could nearly double by 2050 (e.g., reaching a 1.96 factor in scenario ++).

Maximum potential nuclear capacity is fixed at 8 GWe in 2050, assuming the political target stated in Ref. [79] as the maximum achievable deployment of nuclear facilities in Italy. Additionally, we assume that no nuclear installations will occur before 2040, also based on [84]. As a result, the maximum installable nuclear capacity is 1.6 GWe in 2040, 3.2 GWe in 2045 and 8.0 GWe in 2050.

The sensitivity analysis on economic inputs is carried out assuming all the regions, presenting at least one site identified as suitable for hosting nuclear power plants by Ref. [85], are available for new installations. This assumption corresponds to scenario CNEN among those more extensively discussed in Section 2.4 and represented in Figure A1 (see the Appendix).

The sensitivity analysis on the investment cost of Generation IV reactors (*S_LFR* and *S_GCR*) explores their economic competitiveness against other designs. From the 27 scenarios illustrated, the sensitivity analysis involves the 9 in which SMRs hurdle rate is 1% lower than *L_LWR* one, selected because they consider a potential financing facilitation due to the smaller size of SMRs, while excluding the very ambitious scenarios assuming −2% reduction. Starting at *S_LWR* costs level, *S_GCR* and *S_LFR* investment costs are progressively increased by 1% increments until they become fully uncompetitive (i.e., no capacity deployed) against the water-cooled SMRs. This approach does not imply cost parity between mature water-cooled designs and FOAK Generation IV concepts; rather, it serves as a reverse-benchmarking exercise to identify the maximum cost threshold at which these advanced reactors remain competitive.

2.4. Policies determining available sites for nuclear fission in Italy

This section addresses the second objective of the paper stated in Section 1, examining various combinations of potential sites available for nuclear plants in Italy, with the aim of analyzing the optimal configuration depending on alternative geographical constraints. This analysis is conducted with a net-zero emission constraint for the power system, following the emission reduction trajectory proposed in Ref. [56]. The reference economic conditions used in this part of the paper are those of scenario 6.5+, selected as the most probable among all of them: it assumes an hurdle rate for the *L_LWR* similar to the global average for nuclear investments; the 1% difference between large reactors and SMRs considers the possibility of slightly favorable financing conditions for the latter, while increasing costs follow the historical growth rates for developed countries. Note that the following four scenarios presented should not be intended as technically viable configurations, but rather as an analysis on the response of the model to a set of different geographical constraints.

Article 23 of Italian Law No. 393 of 2 August 1975 entrusted the National Committee for Nuclear Energy (CNEN) with the task of drafting a map of sites suitable for the construction of nuclear power plants [85]. The map, published in 1979, was made overlapping four other maps, each of them excluding areas that did not satisfy specific constraints: geology, demography, cooling water availability, land slope [86]. While the siting criteria have inevitably evolved over the decades, potentially rendering this map obsolete by modern standards, it remains the only official document produced for this specific purpose in Italy. This result is used as a constraint for regions in which the model is allowed to install nuclear plants in the first scenario, named CNEN.

The second configuration – CNAI – takes as reference the National Map of Suitable Areas (Carta Nazionale delle Aree Idonee, CNAI). Published in 2023 by the Ministry of Environment and Energy Security, this map lists all the suitable sites for the construction of the national radioactive waste repository [87]. This analysis is considerably more recent than the previous one. Although the siting requirements for a waste repository differ significantly from those of a power plant, the investigation of this scenario is done to explore how the model outcomes vary with different assumptions concerning available regions for nuclear deployment, which in any case involve a subset of regions with respect to the CNEN scenario.

Another scenario – CENT – restricts the installation of nuclear capacity to the four regions which hosted a nuclear plant in the past [18]. In the context of a potential nuclear energy restart, these former sites may represent the most politically and socially feasible locations, as they are the only areas with prior experience, existing infrastructure legacies, or established institutional familiarity with nuclear activities. This scenario is designed to explore the implications of prioritizing such locations. The last configuration – FREE – imposes no geographical constraints aiming to identify the purely cost-optimal regional allocation, providing a benchmark for comparison with the other scenarios' results. The regional constraints for the four scenarios are reported in

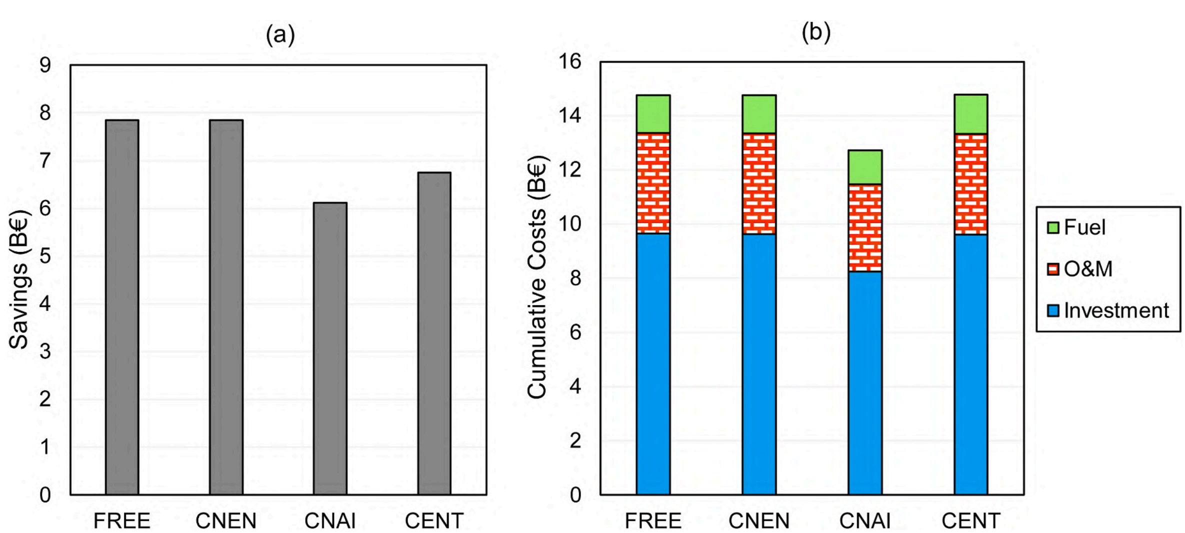

Fig. 7. Total system savings (a) and nuclear cumulative costs (b) in each of the scenarios assuming different sites availability (FREE, CNEN, CNAI and CENT) compared to NONUC.

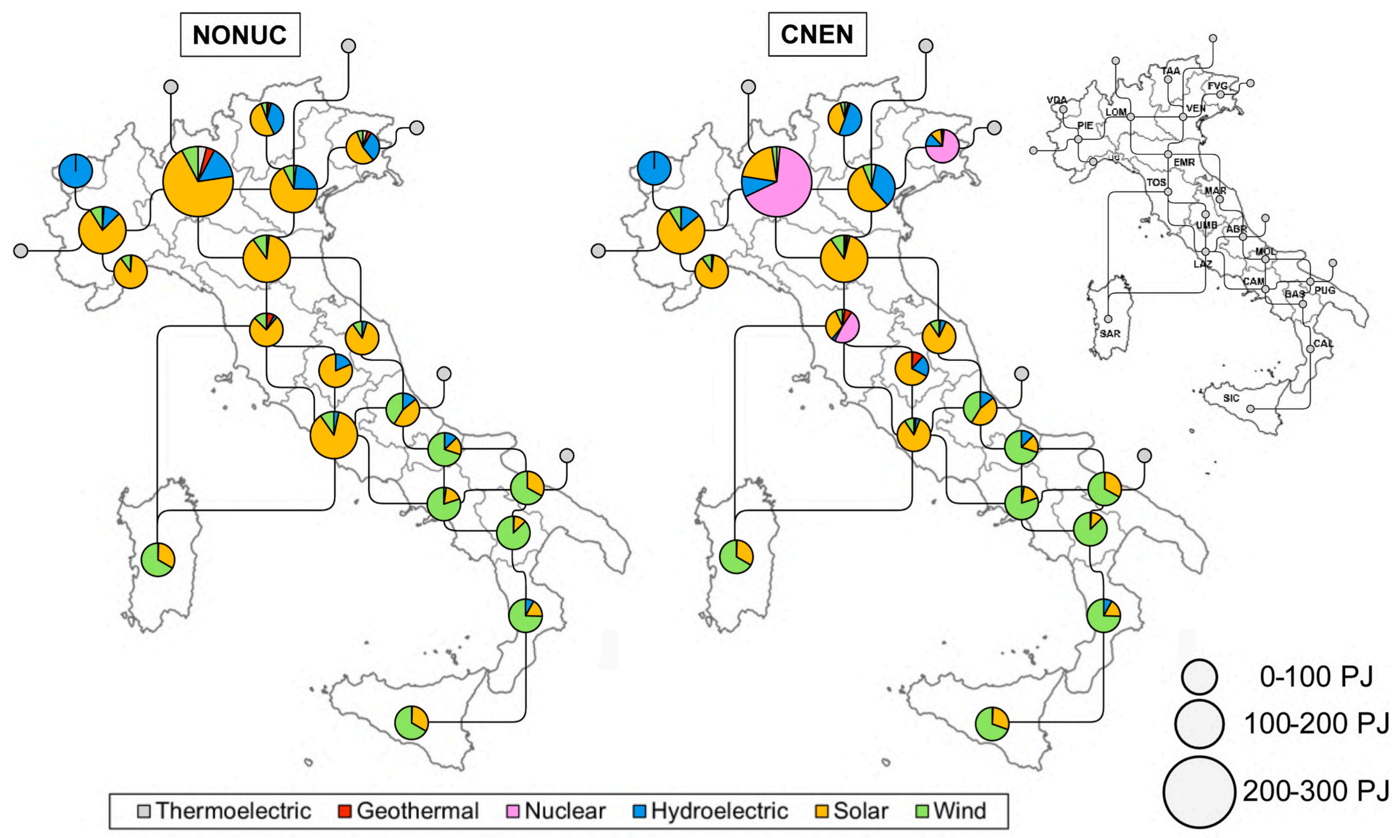

Fig. 8. Regional 2050 electricity generation mix in NONUC and CNEN scenarios. Acronyms are illustrated in the nomenclature alongside the extended names of regions.

Figure A1 (see the Appendix).

3. Results

This section presents and discusses the results of the modeling simulations, identifying the key factors that influence the role of nuclear fission in the Italian energy transition. The findings are organized as follows. Section 3.1 evaluates the economic determinants of nuclear competitiveness, including the potential role of Generation IV SMRs under cost uncertainty. Section 3.2 examines the results of the siting analysis, focusing on the implications of a nuclear restart for the national and regional power systems in terms of backup requirements, land use, and hourly operational patterns.

3.1. Resulting key determinants of nuclear fission competitiveness

Installed capacities by reactor type are presented in Fig. 5. Scenarios are ordered by decreasing *L_LWR* hurdle rates, decreasing *S_LWR* hurdle rates, and cost trends from ++ to = . Nuclear technologies are deployed in 23 of the 27 scenarios. In stable cost scenarios (=), the 8 GWe nuclear capacity constraint is always saturated. Conversely, in scenarios with increasing costs (+), installed capacity decreases as hurdle rates rise, while four of the ++ scenarios show no nuclear deployment, highlighting the strong influence of this parameter on nuclear competitiveness.

Because of their different construction times and (consequently) interests during construction, hurdle rates influence the economic competitiveness between *L_LWR* and *S_LWR*. Large units leverage economies of scale, but their higher IDC causes a sharp loss in competitiveness as hurdle rates increase; conversely, the shorter construction periods of SMRs mitigate their sensitivity to rising hurdle rates. Specifically, *L_LWR* emerges as the cost-optimal choice when the hurdle rate equals 8% for both *L_LWR* and *S_LWR*. At 6% *L_LWR* hurdle rate, these reactors are preferred unless significant facilitation for *S_LWR* financing (4% hurdle rate). Notably, scenario 6.5+ is the only configuration in which both *L_LWR* and *S_LWR* technologies are deployed simultaneously.

The introduction of nuclear power significantly affects the energy mix. As shown in Figure A2 (see the Appendix) and focusing on Lombardia (LOM in Figure A1, see the Appendix), the region with the highest electricity demand and the most consistent installation of nuclear capacity, electricity imports drop from 41% of the regional supply to a negligible share with nuclear deployment.

Regarding the potential role of Generation IV SMRs, Fig. 6 shows that *S_GCR* is always preferred to *S_LFR* at equal investment cost. Moreover, when *S_GCR* investment cost equals that of *S_LWR*, it completely replaces any other reactor type and, in some cases, even increases the total installed nuclear capacity. In the most favorable economic scenario for SMRs (6.5 =), 8 GWe of *S_GCR* are installed provided its investment cost stays within +10% compared to *S_LWR*. The only configuration with no deployment of this design is scenario 10.9++ (highest cost trend and assumed hurdle rate levels). Regarding deployment trends, the three constant-cost (=) scenarios and scenario 6.5+ maintain the maximum installed capacity before dropping to zero. In the remaining cases, capacity varies more gradually as costs increase, highlighting different sensitivity to capital expenditure and financing assumptions. Fig. 6b represents the case in which *S_GCR* is excluded to explore the behavior of *S_LFR*. The resulting trends are very similar to the ones in Fig. 6a, with an average difference in the investment cost assumption of approximately 1% between the two Generation IV reactor types to get similar results in terms of deployed capacity. Overall, results suggest that the typically higher efficiency of Generation IV SMRs may determine economic competitiveness against water-cooled SMRs if their construction costs don't exceed 10% higher with respect to the latter ones. This value

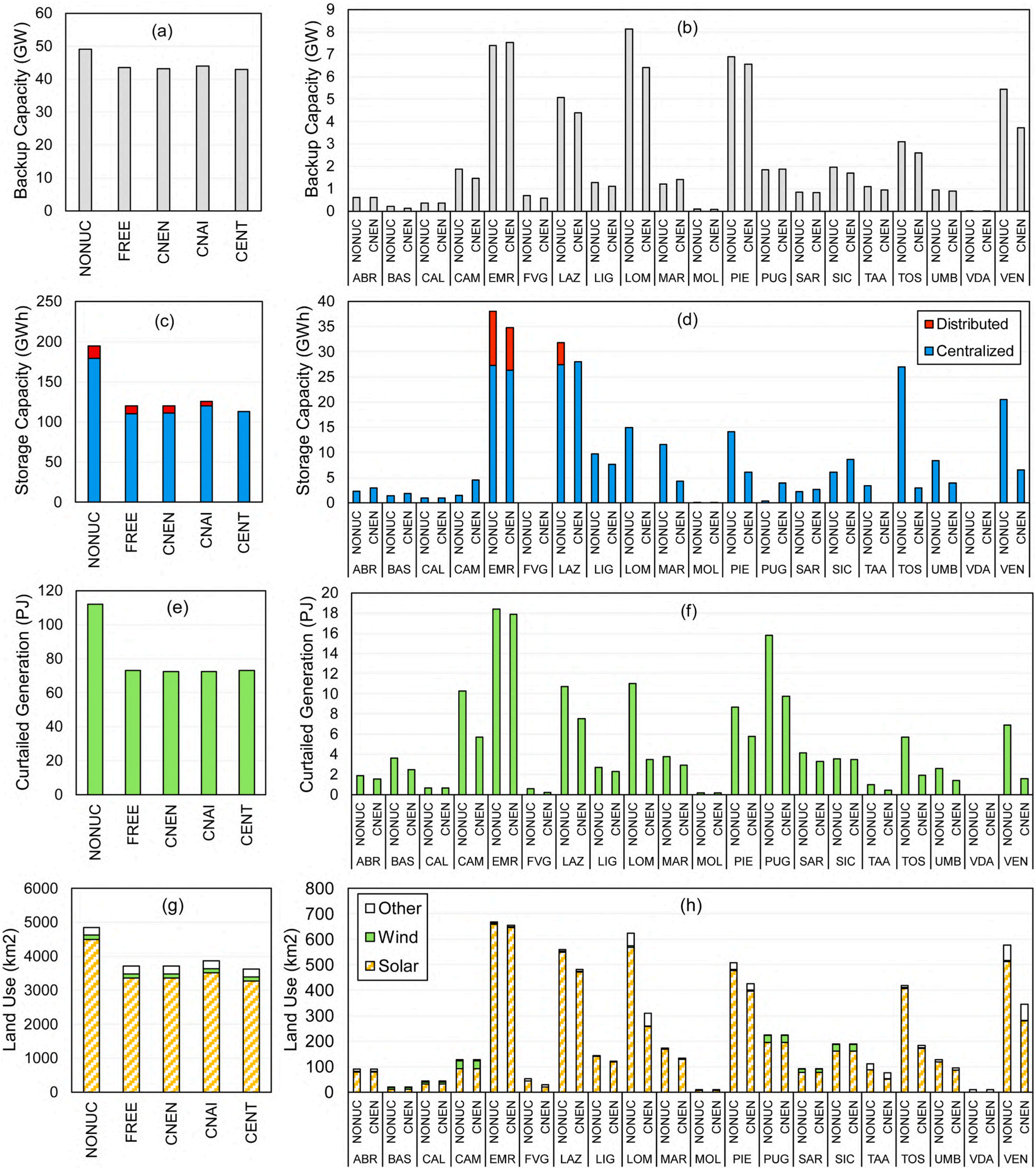

Fig. 9. Implication of nuclear deployment for backup thermoelectric generation capacity (national (a) and regional (b)), storage capacity (national (c) and regional (d)), curtailed electricity generation (national (e) and regional (f)) and land use for power plants (national (g) and regional (h)). Acronyms are illustrated in the nomenclature alongside the extended names of regions.

is consistent with the 2040 cost uncertainty ranges projected in Ref. [2], falling between the Announced Pledges Scenario and Net Zero Emissions by 2050 Scenario. This alignment highlights the critical role of both technological learning and policy support in determining the future economic landscape of advanced reactor designs.

3.2. Implications of nuclear fission restart under different sites availability

Table 5 summarizes the regional distribution of nuclear installations across all scenarios. The first observation is that CNAI is the only scenario which does not reach the maximum capacity constraint of 8 GWe,

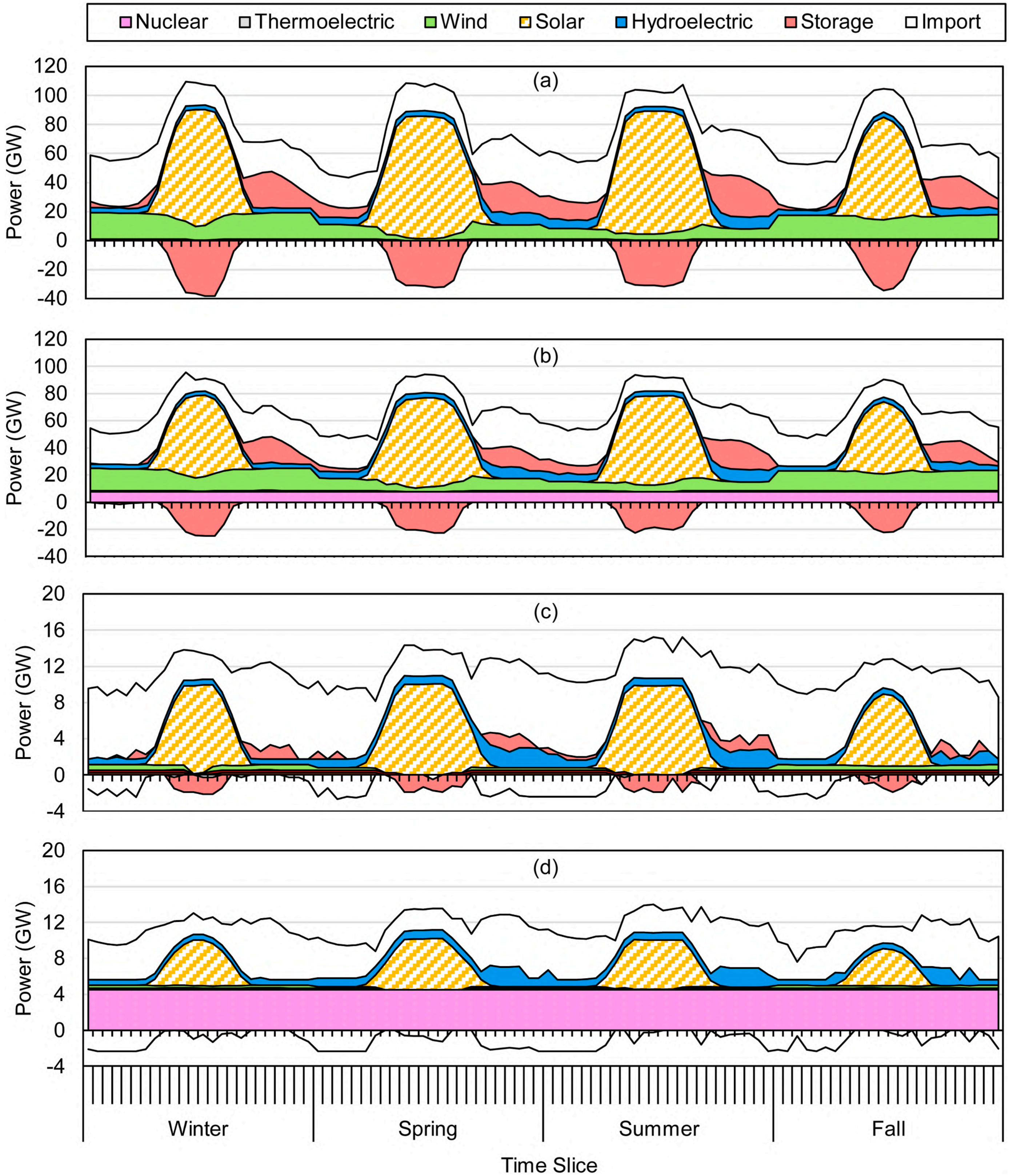

Fig. 10. Hourly power generation by technology: at national level in NONUC (a) and CNEN (b), and in LOM in NONUC (c) and CNEN (d). Ticks of the horizontal axes represent the 24 times of day used to represent time-dependent input and decision variables in each season, corresponding to hourly resolution.

and remains at 6.4 GWe. The cost-optimal configuration – FREE – has the highest nuclear deployment in LOM, the highest-demand region, with three *L_LWR*, while one *L_LWR* and one *S_LWR* are in TOS, and three additional *S_LWR* are distributed among other northern regions. CNEN results differ from FREE mainly by the siting of two SMR in LOM. In CNAI and CENT, where siting constraints do not allow for the construction of nuclear plants in LOM and TOS, the plant installation shifts to neighboring regions, such as PIE, EMR, and LAZ, enabling the possibility of transmitting electricity through the transmission grid.

Figure A3a (see the Appendix) compares national energy generation mix of scenarios allowing nuclear deployment, compared to NONUC. Meeting the emission constraint requires satisfying rising demand while almost eliminating all the thermoelectric capacity. In the NONUC scenario – with no nuclear deployment – this demand is primarily met by solar (+550 PJ) and wind (+280 PJ) generation, with the addition of a significant import (+130 PJ). The introduction of nuclear power reduces imported electricity by up to 22% compared to NONUC. Figure A3b (see the Appendix) illustrates the evolution of available capacity of the power sector. In this case, nuclear plants reduce the total installed capacity due to their higher capacity factor with respect to renewable technologies. Specifically, solar available capacity (+110 GWe in NONUC in addition to 50 GWe of wind) is reduced by up to 20%.

The primary takeaway from Fig. 7 is that nuclear integration provides substantial and robust net system savings across all scenarios, ranging from €6B to €8B across all scenarios. Fig. 7a presents the Net Present Value (NPV) of total system cost savings in each scenario relative to the NONUC baseline. All costs are discounted to the 2022 reference year using a 5% social discount rate, consistent with the model's objective function. They are very similar in terms of FREE and CNEN – almost €8B –, as expected, given the soft geographical limitations introduced in the second one. This value represents the net system cost reduction, accounting for all cost components in the optimization, including the savings resulting from reduced requirements for storage, backup capacity, and fuel use. CNAI savings decrease to about €6B, suggesting a direct correlation between nuclear deployment levels and total system costs reduction. Conversely, the intermediate value of less than €7B observed in CENT highlights the effect of stricter geographical constraints, making it approximately €1B more expensive than the optimal configuration.

Cumulative costs of the nuclear chain are illustrated in Fig. 7b. As expected, investment costs are the most impacting component (about 65%), followed by O&M (25%) and fuel (10%), aligning with values reported in Ref. [82]. Comparing these two graphs, it results that the ratio between overall system savings and investments in nuclear generation is about 0.5, underscoring the economic relevance of nuclear integration under favorable conditions. However, as the model's temporal horizon is limited to 2050, these results only capture the first 10 years of operation for reactors commissioned in 2040. The remaining 50 years of nuclear plants' lifetime and their consequent system benefits are not accounted for in this calculation. Conversely, the investment costs are entirely loaded at the time of installation. This temporal truncation leads to a significant underestimation of the long-term NPV of nuclear integration, as the reported 0.5 savings-to-investment ratio reflects only a fraction of the total life-cycle benefits against the full capital expenditure.

3.3. *Regional and operational implications for the power system*

Focusing now on NONUC and CNEN for a more comprehensive comparison of the nuclear deployment implications for the entire system, Fig. 8 shows the regional electricity generation mix in 2050 under such scenarios, highlighting that nuclear primarily acts as a regional substitute for northern solar capacity. The main effect of introducing nuclear capacity is the substitution of part of the solar generation in the northern regions with nuclear power. This shift is particularly relevant in areas where renewable technologies operate with lower capacity factors. Conversely, the southern regions – where most of the renewable capacity is concentrated – experience only marginal changes in their generation mix. From a geographical perspective, this configuration reflects the spatial distribution of both demand and renewable resources in Italy, with demand concentrated in the North and higher renewable potentials in the South. In principle, such a mismatch could lead to significant transmission requirements and associated costs, as electricity needs to be transported over long distances. However, the introduction of nuclear capacity in northern regions only partially alters these dynamics. Given the relatively limited nuclear capacity allowed (up to 8 GWe) and its preferential siting in high-demand areas, the resulting reduction in long-distance electricity flows is not sufficient to substantially modify the overall transmission expansion needs. As a result, the overall requirements for transmission capacity remain largely unaffected, even with the inclusion of northern nuclear facilities. This result is also confirmed in scenarios FREE, CNAI and CENT, regardless of the specific assumptions on regional availability. While nuclear deployment slightly reduces the need for northward electricity transfers from renewable-rich southern regions, the persistence of high shares of variable renewables and the existing geographical distribution of resources continue to drive similar transmission requirements across scenarios. Furthermore, since the model's 20-node resolution is significantly finer than the 7 official electricity market bidding zones currently used by Terna – the Italian Transmission System Operator (TSO) – [88], the approximations induced by the regional copper-plate assumption are likely to be contained within an acceptable range. Therefore, differences in grid-related costs associated with geographical factors remain limited in this modelling framework.

Fig. 9a illustrates the total thermoelectric backup capacity across all scenarios, showing a reduction up to 6 GWe (−12%) in cases with nuclear deployment. Fig. 9b highlights regional variations between NONUC and CNEN, with the most pronounced decreases observed in regions hosting nuclear plants – especially in LOM –, although similar trends are evident across almost all regions. Fig. 9c and d present analogous results for storage capacity. At national level, nuclear deployment strongly reduce storage requirements (up to 42%), with the CNEN scenario showing largest impacts in LOM, MAR, PIE, TOS, and VEN. Similar, the presence of nuclear baseload reduces the curtailed intermittent renewable generation approximately by 35% at national level in all scenarios with nuclear available compared to NONUC, as well as for regional curtailments both in regions with and without nuclear power plants in the CNEN scenario compared with NONUC (see Fig. 9f). Such benefits in terms of reduced investments in grid assets, similar to the findings of [9], are particularly relevant considering that recently the Italian TSO projected dramatically high marginal costs for the integration of renewable electricity production for near-100% renewable targets for 2050 [89].

Differences in the land use between scenarios, obtained considering direct soil occupation for wind and PV and also fuel processing spacing for nuclear (no upstream manufacturing of materials [90], are mainly driven by variations in solar capacity, with reductions of approximately 25% in those with nuclear deployment (see Fig. 9g). Notably, regions where nuclear power plants are deployed in CNEN are not the only ones with significant changes, as represented in Fig. 9h.

Fig. 10a and b compare total hourly power generation at the national level in the NONUC and CNEN scenarios, respectively. The baseload contribution of nuclear power is evident, reducing both the need for storage during solar peak hours and electricity imports by other countries. This effect is much more evident in LOM, where the relevant demand fraction covered by the constant nuclear generation in CNEN (Fig. 10d) allows to strongly decrease both import and the storage of solar production observed in NONUC (Fig. 10b).

4. Limitations and perspectives

This study has several limitations. The analysis focuses exclusively on the Italian power sector, neglecting interactions with heating, industry, and transport. Regional siting assumptions were defined in the absence of an official siting document, introducing uncertainty regarding the feasibility and location of new plants. The electricity grid is represented in a simplified manner, adopting a copper-plate assumption at the regional level, which may affect estimates of interregional power flows and makes the model overlook local grid effects [91]. In addition, the analysis addresses primarily techno-economic aspects and does not explicitly capture political, regulatory, or social factors – such as licensing delays or public acceptance – that could significantly affect deployment timelines and costs. Furthermore, the assumption of perfect foresight may favor capital-intensive technologies with long lead times by mitigating risks associated with future market and policy uncertainties.

Cost assumptions are based on literature and remain uncertain, particularly with respect to learning effects and financing conditions [52]. Sensitivity analyses focus on nuclear investment costs and hurdle rates, while financing conditions for other technologies are kept constant. The uniform O&M cost assumption is a limitation, as it does not capture the specific trade-offs between the technical innovations and the reduced economies of scale of SMR and Generation IV reactors. The representation of nuclear technologies is limited to a small set of reactor designs, and the model horizon extends only to 2050, excluding longer-term effects related to reactor lifetimes, decommissioning, and waste management.

Future research could extend the framework to a multi-sectoral setting, capturing interactions between electricity, hydrogen, and other end-use sectors, and the broader role of nuclear in decarbonization pathways [92]. Additional scenario dimensions could include nuclear supply-chain constraints, fuel recycling strategies, or policy responses to crises and geopolitical disruptions. A more detailed representation of transmission networks and cross-border electricity exchanges would further improve spatial accuracy. Methodological improvements could also involve stochastic programming to better represent investment decision-making under deep uncertainty. The binary geographical constraints for the siting used in this study could be overcome by incorporating probabilistic social acceptance mapping, complemented by analyses aimed at quantifying the risks of project delays and the cost premiums triggered by social barriers.

The analysis also covers a limited subset of nuclear technologies. Future work could include additional fission concepts – such as fast breeder, molten salt, or high-temperature gas-cooled reactors – which may offer improved fuel utilization, operational flexibility, or reduced waste volumes [93], [94]. Extending the time horizon beyond 2050 would allow assessment of long-term impacts related to decommissioning, reinvestment, and system evolution.

Finally, the methodological framework can be applied to other regions, such as the European Union or the United States, enabling comparative assessments of nuclear competitiveness across different policy and market contexts.

5. Conclusions and policy implications

This study assesses the potential role of nuclear fission in decarbonizing the Italian power sector under alternative assumptions on technology costs, financing conditions, and siting constraints. Both large light water reactors and small modular reactors of Generation III+ and IV are considered, allowing for a comprehensive evaluation of their economic and system-level impacts.

The results show that nuclear competitiveness in Italy is primarily driven by capital costs and financing conditions. Nuclear is competitive in most scenarios, but not when high investment costs coincide with hurdle rates of 8% or above. When financing conditions are favorable (hurdle rates below 8%), the maximum capacity constraint of 8 GWe is reached even under increasing cost trends, highlighting the central role of the cost of capital. Large reactors remain the least-cost option under similar financing conditions, while SMRs become relatively more competitive at high hurdle rates due to shorter construction times and lower exposure to investment risk. These findings indicate that access to low-cost capital can be as decisive as technological learning in enabling nuclear deployment.

At the system level, deploying up to 8 GWe of nuclear capacity could substantially reduce electricity imports (by up to about 50%), lower exposure to external market volatility, and reduce the need for renewable capacity, land use, storage, and backup generation. These effects are strongest in northern regions, where nuclear substitutes imports and part of solar deployment, while impacts in the south are more limited. Transmission requirements remain largely unchanged. Overall, combining nuclear with renewables leads to a more compact, reliable, and cost-efficient power system, underscoring the importance of stable regulatory frameworks, predictable licensing, and transparent siting processes to reduce financing risk. In the Italian context, recognizing nuclear projects as essential public utility infrastructures could foster better coordination between central and local authorities, providing a clearer framework to manage siting and enhance community engagement.

In conclusion, the analysis shows that nuclear power – if supported by favorable financing conditions and coherent policy frameworks – can meaningfully contribute to Italy's decarbonization objectives while alleviating some technical and spatial challenges of a renewable-dominated system. Policies that reduce capital barriers, integrate nuclear within clean energy support mechanisms, and foster social acceptance through inclusive processes could enable nuclear to play a complementary role in Italy's energy transition.

CRediT authorship contribution statement

Andrea Mastrantuono: Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Matteo Nicoli:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Formal analysis, Conceptualization. **Valeria Di Cosmo:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Daniele Mosso:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Anderson Rodrigo de Queiroz:** Writing – review & editing, Validation. **Laura Savoldi:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

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

During the preparation of this work the authors used ChatGPT® in order to revise the text grammar and readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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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.

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Appendix

The appendix provides supplementary material to support the interpretation of scenario results. Figure A1 illustrates the regional availability assumptions for nuclear power plant installation across the considered scenarios, highlighting the regions where deployment is permitted. Figure A2 reports the electricity supply mix for Lombardy in 2050, with scenarios ordered according to the increasing contribution of nuclear fission to total generation. Finally, Figure A3 presents the resulting electricity production and installed capacity by technology under the alternative site-availability assumptions, providing further insight into how regional siting constraints influence the evolution of the power system.

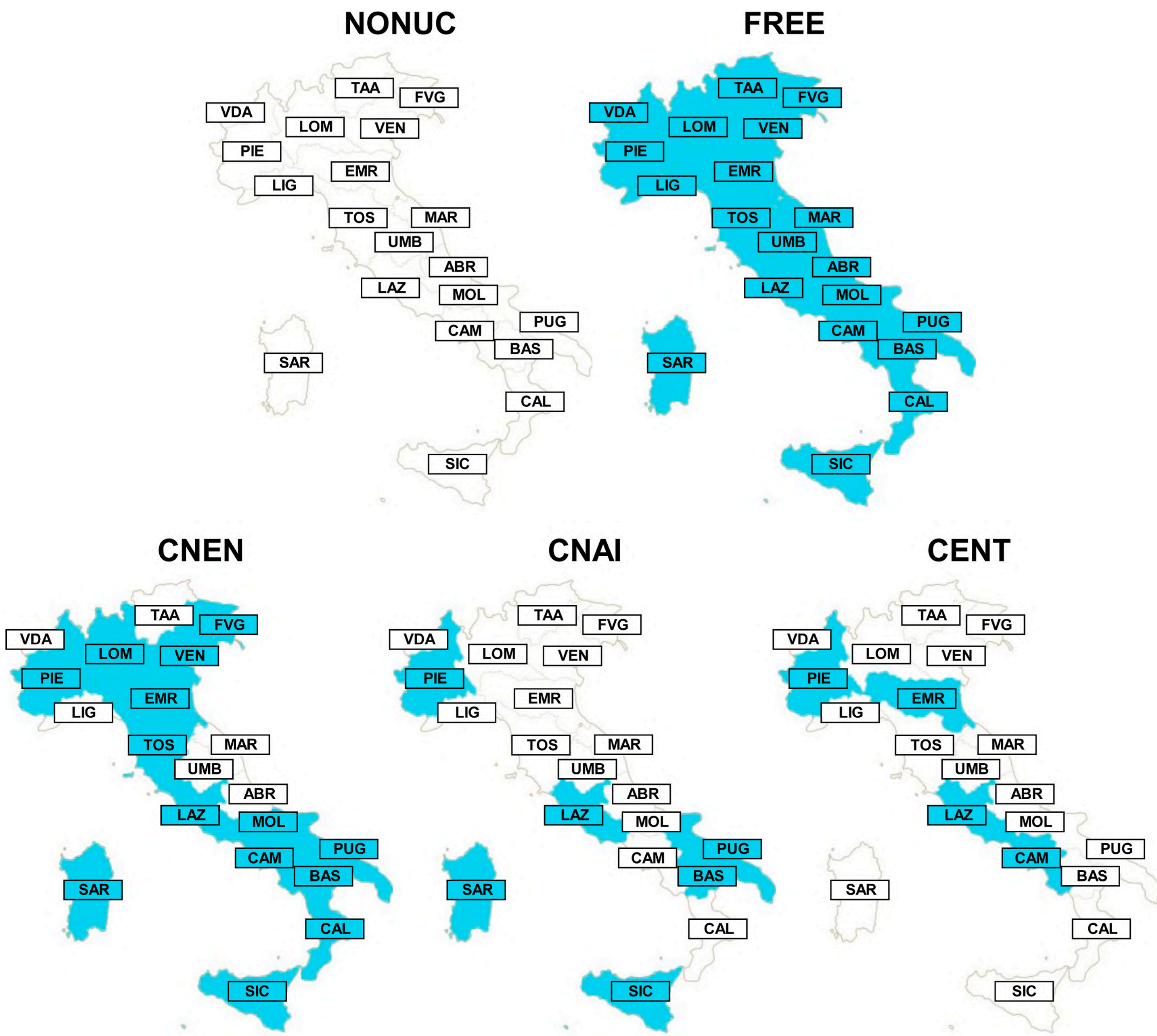

Fig. A1. Regions where nuclear plant installation is allowed in each scenario (blue stands for available regions, white for unavailable). Acronyms are illustrated in the nomenclature alongside the extended names of regions.

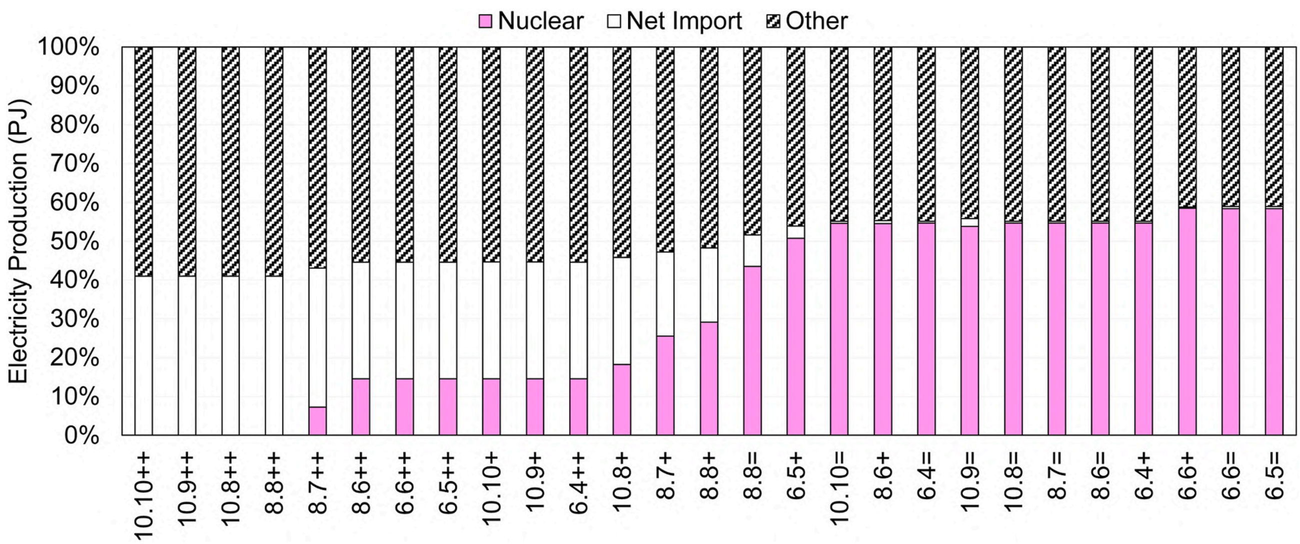

Fig. A2. Electricity supply to LOM in 2050 by source, with scenarios sorted by increasing generation shares by nuclear fission.

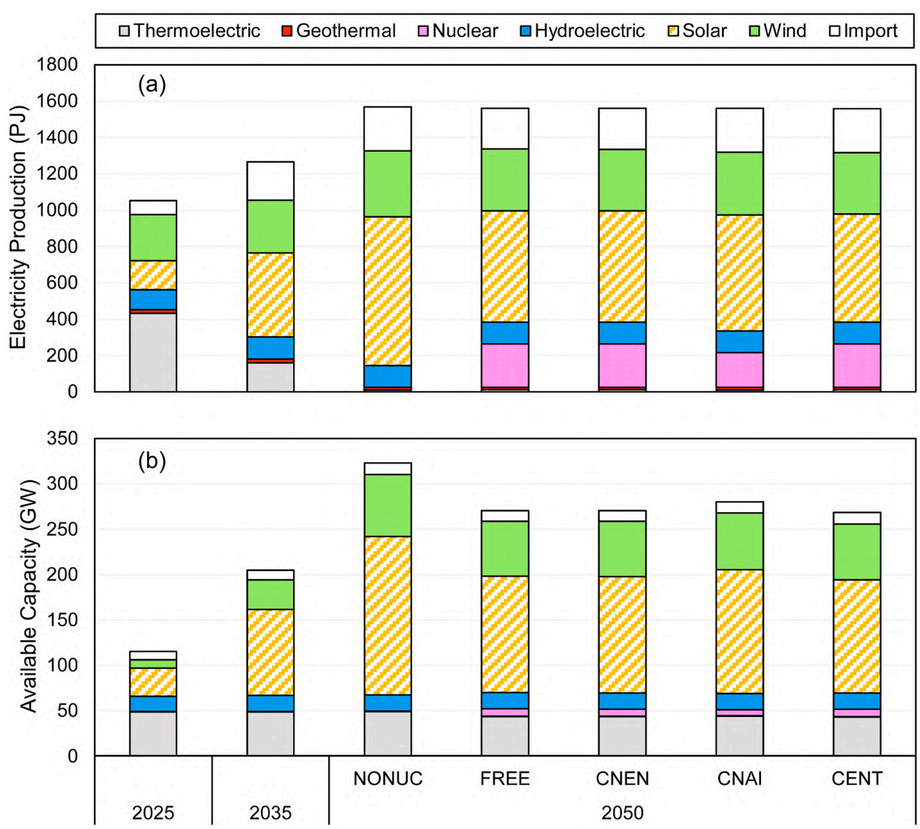

Fig. A3. Electricity production (a) and available capacity (b) by technology in each of the scenarios assuming different site availability.

Data availability

The TEMOA model version used for the analysis presented in this paper is available at [95], while the TEMOA-Italy model instance version adopted is available at [44]

References

[1] International Energy Agency (IEA). "World Energy Outlook 2024," [Online]. Available: https://www.iea.org/reports/world-energy-outlook-2024. [Accessed 7 January 2025].

[2] International Energy Agency (IEA). The path to a new era for nuclear energy [Online]. Available: https://www.iea.org/reports/the-path-to-a-new-era-for-nuclear-energy. [Accessed 21 November 2025].
[3] World Bank Group. Electricity production from nuclear sources (% of total) | data [Online]. Available: https://data.worldbank.org/indicator/EG.ELC.NUCL.ZS. [Accessed 24 October 2025].
[4] W. Energy Investment and th Edition. World energy investment 2025 [Online]. Available:. tenth ed. 2025. www.iea.org.
[5] Nuclear Energy Agency (NEA) - COP28 recognises the critical role of nuclear energy for reducing the effects of climate change [Online]. Available: https://www.oecd-nea.org/jcms/pl_89153/cop28-recognises-the-critical-role-of-nuclear-energy-for-reducing-the-effects-of-climate-change. [Accessed 22 January 2025].
[6] "Nuclear Power in the COP29 Spotlight as Countries and Companies Eye Climate Solutions | IAEA." [Online]. Available: https://www.iaea.org/newscenter/news/nuclear-power-in-the-cop29-spotlight-as-countries-and-companies-eye-climate-solutions. [Accessed 22 January 2025].
[7] "European Industrial Alliance on Small Modular Reactors - european Commission." [Online]. Available: https://single-market-economy.ec.europa.eu/industry/industrial-alliances/european-industrial-alliance-small-modular-reactors_en. [Accessed 22 January 2025].
[8] "IAEA Outlook for Nuclear Power Increases for Fourth Straight Year, Adding to Global Momentum for Nuclear Expansion | IAEA." [Online]. Available: https://www.iaea.org/newscenter/pressreleases/iaea-outlook-for-nuclear-power-increases-for-fourth-straight-year-adding-to-global-momentum-for-nuclear-expansion. [Accessed 22 January 2025].
[9] Aszódi A, et al. The effect of the future of nuclear energy on the decarbonization pathways and continuous supply of electricity in the European Union. Nucl Eng Des Dec. 2023;415:112688. https://doi.org/10.1016/J.NUCENGDES.2023.112688.
[10] Reinberger D, Ajanovic A, Haas R. The technological development of different generations and reactor concepts. 2019. p. 243–58. https://doi.org/10.1007/978-3-658-25987-7_11.
[11] Bamshad A, Safarzadeh O. Effects of the move towards Gen IV reactors in capacity expansion planning by total generation cost and environmental impact optimization. Nucl Eng Technol Apr. 2021;53(4):1369–77. https://doi.org/10.1016/j.net.2020.09.005.
[12] Cheng H, Cheng S, Chen S. Sodium fast reactors. Nuclear power reactor designs: from history to advances. Jan. 2024. p. 185–208. https://doi.org/10.1016/B978-0-323-99880-2.00010-2.
[13] World Nuclear Association. Generation IV nuclear reactors [Online]. Available: https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/generation-iv-nuclear-reactors. [Accessed 22 January 2025].
[14] Locatelli G, Mancini M, Todeschini N. Generation IV nuclear reactors: current status and future prospects. Energy Policy Oct. 2013;61:1503–20. https://doi.org/10.1016/j.enpol.2013.06.101.
[15] Locatelli G, Bingham C, Mancini M. Small modular reactors: a comprehensive overview of their economics and strategic aspects. Prog Nucl Energy May 2014;73:75–85. https://doi.org/10.1016/J.PNUCENE.2014.01.010.
[16] Ingersoll DT. Improving nuclear affordability. Small modular reactors. Jan. 2016. p. 91–109. https://doi.org/10.1016/B978-0-08-100252-0.00006-9.
[17] Asuega A, Limb BJ, Quinn JC. Techno-Economic analysis of advanced small modular nuclear reactors. 2023.
[18] "Nuclear Power in Italy - world Nuclear Association." [Online]. Available: https://world-nuclear.org/information-library/country-profiles/countries-g-n/italy. [Accessed 26 June 2025].
[19] Terna SPA. Dati statistici sull'energia elettrica in Italia 2023. 2023.
[20] Terna: electricity consumption increases by 2.2% in 2024 - terna spa [Online]. Available: https://www.terna.it/en/media/press-releases/detail/electricity-consumption-2024. [Accessed 21 November 2025].
[21] Edenhofer Ottmar. Climate change 2014 : mitigation of climate change : Working Group III contribution to the Fifth assessment report of the Intergovernmental Panel on climate Change. Cambridge University Press; 2015.
[22] Energy: Nuclear. ENEA joins European alliance for small reactors - media." [Online]. Available: https://www.media.enea.it/en/press-releases-and-news/years-archive/year-2024/energy-nuclear-enea-joins-european-alliance-for-small-reactors.html. [Accessed 26 June 2025].
[23] European Nuclear Alliance grows as Italy also formally joins [Online]. Available: https://www.eunews.it/en/2025/06/16/european-nuclear-alliance-grows-as-italy-also-formally-joins/. [Accessed 26 June 2025].
[24] Bohdanowicz Z, Łopaciuk-Gonczaryk B, Kowalski J. Europe becomes pro-nuclear? Drivers of public support for nuclear energy in six EU countries after the energy crisis of 2022. Energy Policy May 2025;200. https://doi.org/10.1016/j.enpol.2025.114528.
[25] Piattaforma Nazionale per un Nucleare Sostenibile - GdL5 "Rifiuti e Decommissioning," [Online]. Available:. Rapporto finale. 2024. https://www.mase.gov.it/portale/-/piattaforma-nazionale-per-un-nucleare-sostenibile-pubblicazione-rapporti-conclusivi. [Accessed 4 November 2025].
[26] Yue X, Pye S, DeCarolis J, Li F, Rogan F, Gallachóir B. A review of approaches to uncertainty assessment in energy system optimization models. Energy Strategy Rev Aug. 2018;21:204–17. https://doi.org/10.1016/J.ESR.2018.06.003.
[27] Hunter K, Sreepathi S, DeCarolis JF. Modeling for insight using tools for energy model optimization and analysis (Temoa). Energy Econ Nov. 2013;40:339–49. https://doi.org/10.1016/j.eneco.2013.07.014.
[28] Nicoli M. An energy planning perspective about the multi-sectorial synergies and implications of the energy transition. Politecnico di Torino, Turin: PhD Thesis; 2025 [Online]. Available: https://iris.polito.it/handle/11583/3001281. [Accessed 7 July 2025].
[29] Vanatta M, Patel D, Allen T, Cooper D, Craig MT. Technoeconomic analysis of small modular reactors decarbonizing industrial process heat. Joule Apr. 2023;7(4):713–37. https://doi.org/10.1016/j.joule.2023.03.009.
[30] Abdussami MR, Daley K, Hoelzle G, Verma A. Investigation of potential sites for coal-to-nuclear energy transitions in the United States. Energy Rep Jun. 2024;11:5383–99. https://doi.org/10.1016/J.EGYR.2024.05.020.
[31] Hansen J, et al. Investigating benefits and challenges of converting retiring coal plants into nuclear plants [Online]. Available: https://doi.org/10.2172/1886660. [Accessed 26 April 2026].
[32] Bin Cho S, Root SJ, Saeed RM, Olowu TO, Shigrekar A, Westover TL. Microreactor-liquid metal battery system in energy markets: an evaluation of potential costs, technology, and policy impacts. Appl Energy Nov. 2025;398:126403. https://doi.org/10.1016/J.APENERGY.2025.126403.
[33] Han D, Huang G, Zhang X, Chen J, Gao S. A multi-stochastic SMR siting model applied to the province of Saskatchewan, Canada: emphasis on technological competition and policy impacts. Resour Conserv Recycl Mar. 2022;178:106059. https://doi.org/10.1016/J.RESCONREC.2021.106059.
[34] Olkkonen V, Ekström J, Hast A, Syri S. Utilising demand response in the future Finnish energy system with increased shares of baseload nuclear power and variable renewable energy. Energy Dec. 2018;164:204–17. https://doi.org/10.1016/J.ENERGY.2018.08.210.
[35] Pattupara R, Kannan R. Alternative low-carbon electricity pathways in Switzerland and it's neighbouring countries under a nuclear phase-out scenario. Appl Energy Jun. 2016;172:152–68. https://doi.org/10.1016/J.APENERGY.2016.03.084.
[36] Pfenninger S, Keirstead J. Renewables, nuclear, or fossil fuels? Scenarios for great Britain's power system considering costs, emissions and energy security. Appl Energy Aug. 2015;152:83–93. https://doi.org/10.1016/J.APENERGY.2015.04.102.
[37] Thellufsen JZ, et al. Cost and system effects of nuclear power in carbon-neutral energy systems. Appl Energy Oct. 2024;371:123705. https://doi.org/10.1016/J.APENERGY.2024.123705.
[38] Duan L, Petroski R, Wood L, Caldeira K. Stylized least-cost analysis of flexible nuclear power in deeply decarbonized electricity systems considering wind and solar resources worldwide. Nat Energy Feb. 2022;7(3):260–9. https://doi.org/10.1038/s41560-022-00979-x. 2022 7:3.
[39] Steigerwald B, Weibezahn J, Slowik M, von Hirschhausen C. Uncertainties in estimating production costs of future nuclear technologies: a model-based analysis of small modular reactors. Energy 2023;281(Oct). https://doi.org/10.1016/j.energy.2023.128204.
[40] Wang C, et al. Annual capacity analysis and multi-objective optimization of a nuclear-renewable integrated energy system. Energy Jan. 2026:140002. https://doi.org/10.1016/j.energy.2026.140002.
[41] Wang C, Raza SA, Adebayo TS, Yi S, Shah MI. The roles of hydro, nuclear and biomass energy towards carbon neutrality target in China: a policy-based analysis. Energy Jan. 2023;262:125303. https://doi.org/10.1016/j.energy.2022.125303.
[42] Lee J, Kim J. Balancing hydrogen and nuclear: how nuclear expansion reshapes power-to-gas and hydrogen storage in a carbon neutral energy system. Energy Nov. 2025;336:138437. https://doi.org/10.1016/j.energy.2025.138437.
[43] Yasir Mehboob M, Ma B, Sadiq M, Mehboob MB. How do nuclear energy consumption, environmental taxes, and trade globalization impact ecological footprints? Novel policy insight from nuclear power countries. Energy Dec. 2024;313:133661. https://doi.org/10.1016/j.energy.2024.133661.
[44] MAHTEP Group, "MAHTEP/TEMOA-Italy - release 3.3," GitHub. Accessed: January. 15, 2026. [Online]. Available: https://github.com/MAHTEP/TEMOA-Italy/releases/tag/3.3.
[45] Amir Kavei F, Nicoli M, Quatraro F, Savoldi L. Enhancing energy transition with open-source regional energy system optimization models: TEMOA-Piedmont. Energy Convers Manag Mar. 2025;327:119536. https://doi.org/10.1016/J.ENCONMAN.2025.119536.
[46] Amir Kavei F, Alfano ME, Nicoli M, Quatraro F, Savoldi L. Integrated water-energy modeling in TEMOA energy system optimization model: pantelleria case study. Energy Nexus 2025;18:100461. https://doi.org/10.1016/J.NEXUS.2025.100461.
[47] Energy technology systems analysis program, "TIMES." Accessed: January. 4, 2025. [Online]. Available: https://iea-etsap.org/index.php/etsap-tools/model-generators/times..
[48] Howells M, et al. OSeMOSYS: the open source energy modeling system: an introduction to its ethos, structure and development. Energy Policy Oct. 2011;39(10):5850–70. https://doi.org/10.1016/J.ENPOL.2011.06.033.
[49] GCAM: global change analysis model | global change intersectoral modeling system." Accessed: April. 20, 2026. [Online]. Available: https://gcims.pnnl.gov/modeling/gcam-global-change-analysis-model..
[50] DeCarolis JF. Using modeling to generate alternatives (MGA) to expand our thinking on energy futures. Energy Econ Mar. 2011;33(2):145–52. https://doi.org/10.1016/J.ENECO.2010.05.002.
[51] de Faria VAD, de Queiroz AR, DeCarolis JF. Optimizing offshore renewable portfolios under resource variability. Appl Energy Nov. 2022;326:120012. https://doi.org/10.1016/J.APENERGY.2022.120012.
[52] Nicoli M, et al. A framework for global sensitivity analysis in long-term energy systems planning using optimal transport. Energy Nov. 2025;338:138788. https://doi.org/10.1016/J.ENERGY.2025.138788.
[53] Nicoli M, Gracceva F, Lerede D, Savoldi L. Can we rely on open-source energy system optimization models? The TEMOA-Italy case study. Energies Sep. 2022;15(18):6505. https://doi.org/10.3390/en15186505.

[54] Ministry of Economic Development, Ministry of the Environment and Land and Sea Protection, Ministry of Infrastructure and Transport. Integrated national energy and climate plan 2019. 2019 [Online]. Available: https://commission.europa.eu/energy-climate-change-environment/implementation-eu-countries/energy-and-climate-governance-and-reporting/national-energy-and-climate-plans_en. [Accessed 19 August 2022].
[55] Nicoli M, Faria VAD, de Queiroz AR, Savoldi L. Modeling energy storage in long-term capacity expansion energy planning: an analysis of the Italian system. J Energy Storage 2024;101PA:113814. https://doi.org/10.1016/j.est.2024.113814.
[56] Cais M, et al. Hybrid superconducting energy pipelines: key cost thresholds and system implications for Italy. Int J Hydrogen Energy 2026;210:153627. https://doi.org/10.1016/j.ijhydene.2026.153627.
[57] Colucci G, Lerede D, Nicoli M, Savoldi L. A dynamic accounting method for CO2 emissions to assess the penetration of low-carbon fuels: application to the TEMOA-Italy energy system optimization model. Appl Energy Dec. 2023;352:121951. https://doi.org/10.1016/j.apenergy.2023.121951.
[58] Colucci G, Lerede D, Nicoli M, Savoldi L. Dynamic accounting for end-use CO2 emissions from low-carbon fuels in energy system optimization models. Energy Proceedings 2022;29. https://doi.org/10.46855/energy-proceedings-10294.
[59] Vai A, Colucci G, Nicoli M, Savoldi L. May the availability of critical raw materials affect the security of energy systems? An analysis for risk-aware energy planning with TEMOA-Italy. Mater Today Energy 2025;48:101805. https://doi.org/10.1016/j.mtener.2025.101805.
[60] Vai A, Colucci G, Nicoli M, Savoldi L. A comprehensive metric to assess the security of future energy systems through energy system optimization models. Energy Proceedings 2024;47. https://doi.org/10.46855/energy-proceedings-11292.
[61] Nicoli M, Colucci G, Di Cosmo V, Lerede D, Savoldi L. Evaluating the impact of hurdle rates on the Italian energy transition through TEMOA. Appl Energy 2024; 377PC:124633. https://doi.org/10.1016/j.apenergy.2024.124633.
[62] Laera S, Colucci G, Di Cosmo V, Lerede D, Nicoli M, Savoldi L. Technology-specific hurdle rates for energy system optimization models. Energy Proceedings 2024;39. https://doi.org/10.46855/energy-proceedings-10911.
[63] Nicoli M, et al. Enabling coherence between energy policies and SDGs through open energy models: the TEMOA-Italy example. In: Labriet M, Espegren K, Giannakidis G, O'Gallachoir B, editors. Aligning the energy transition with the sustainable development goals: key insights from energy system modelling. Springer; 2024. p. 97–118. https://doi.org/10.1007/978-3-031-58897-6_5.
[64] Cais M. Exploring the potential future role of superconducting energy pipelines in the Italian electricity and hydrogen transmission systems. Jul. 2025.
[65] European Commission. Joint research centre data catalogue - the JRC European TIMES energy system model [Online]. Available: https://data.jrc.ec.europa.eu/collection/id-00287. [Accessed 24 October 2025].
[66] Mastrantuono A. Nuclear fission techno-economic characterization for energy system models and scenario analysis for Italy [Online]. Available: https://webthesis.biblio.polito.it/35852/. [Accessed 9 September 2025].
[67] International Atomic Energy Agency (IAEA). Nuclear power reactors in the world – 2024 edition. 2024 [Online]. Available: https://www.iaea.org/publications/15748/nuclear-power-reactors-in-the-world. [Accessed 22 January 2025].
[68] World Nuclear Association, "Flamanville 3 - world Nuclear Association." Accessed: September. 9, 2025. [Online]. Available: https://world-nuclear.org/nuclear-reactor-database/details/flamanville-3.
[69] GOV:UK. "Rolls-Royce SMR selected to build small modular nuclear reactors - GOV.UK." [Online]. Available: https://www.gov.uk/government/news/rolls-royce-smr-selected-to-build-small-modular-nuclear-reactors. [Accessed 23 October 2025].
[70] Alessandro Pulcini - Fortune Italia, "Nucleare, newcleo e Ansaldo tra le aziende supportate dall'alleanza Ue sugli Smr." Accessed: November. 6, 2025. [Online]. Available: https://www.fortuneita.com/2024/10/11/nucleare-newcleo-e-ansaldo-tra-le-aziende-supportate-dallalleanza-ue-sugli-smr/.
[71] Centrica, "Centrica and X-energy agree to deploy UK's First Advanced Modular Reactors." Accessed: October. 23, 2025. [Online]. Available: https://www.centrica.com/media-centre/news/2025/centrica-and-x-energy-agree-to-deploy-uk-s-first-advanced-modular-reactors/.
[72] International Energy Agency (IEA). Nuclear Energy Agency (NEA), and Organisation for Economic Co-operation and Development (OECD). In: Projected costs of generating electricity – 2020 edition; 2020 [Online]. Available: https://www.oecd-nea.org/upload/docs/application/pdf/2020-12/egc-2020_2020-12-09_18-26-46_781.pdf. [Accessed 20 January 2025].
[73] "Nuclear | Electricity | 2024 | ATB | NREL." Accessed: March. 29, 2025. [Online]. Available: https://atb.nrel.gov/electricity/2024/nuclear..
[74] Pabitra L De. Costs of decommissioning nuclear power plants - a report on recent international estimates. IAEA Bulletin; 1990 [Online]. Available: https://www.iaea.org/sites/default/files/publications/magazines/bulletin/bull32-3/32304783942.pdf. [Accessed 22 August 2023].
[75] Nuclear Energy Agency (NEA) and Organisation for Economic Co-operation and Development (OECD). Costs of decommissioning nuclear power plants. 2016 [Online]. Available: https://www.oecd-nea.org/jcms/pl_14910/costs-of-decommissioning-nuclear-power-plants?details=true. [Accessed 22 August 2023].
[76] L. M. Larsen, A. Abou-Jaoude, N. Guaita, and N. Stauff, "Nuclear energy cost estimates for net zero world initiative.".
[77] Advanced reactor information system | Aris [Online]. Available: https://aris.iaea.org/TechnicalData/. [Accessed 20 January 2025].
[78] World Nuclear Association (WNA), "World nuclear performance report 2025," 2025..
[79] Ministry of the Environment and Energy Security. Integrated national plan for energy and climate 2024. 2024 [Online]. Available: https://www.mase.gov.it/portale/documents/d/guest/pniec_2024_revfin_01072024-pdf. [Accessed 30 March 2025].
[80] Carelli MD, et al. Economic features of integral, modular, small-to-medium size reactors. Prog Nucl Energy May 2010;52(4):403–14. https://doi.org/10.1016/j.pnucene.2009.09.003.
[81] Haneklaus N, Qvist S, Gładysz P, Bartela Ł. Why coal-fired power plants should get nuclear-ready. Energy 2023;280(Oct). https://doi.org/10.1016/j.energy.2023.128169.
[82] Lovering JR, Yip A, Nordhaus T. Historical construction costs of global nuclear power reactors. Energy Policy Apr. 2016;91:371–82. https://doi.org/10.1016/J.ENPOL.2016.01.011.
[83] Fattahi A, Sijm J, Van den Broek M, Gordón RM, Dieguez MS, Faaij A. Analyzing the techno-economic role of nuclear power in the Dutch net-zero energy system transition. Adv Appl Energy Sep. 2022;7:100103. https://doi.org/10.1016/j.adapen.2022.100103.
[84] Ibrahim JK. Nuclear power plant development. In: Nuclear reactor technology development and utilization; Jan. 2020. p. 363–405. https://doi.org/10.1016/B978-0-12-818483-7.00012-3.
[85] "Gazzetta Ufficiale." [Online]. Available: https://www.gazzettaufficiale.it/eli/id/1975/08/23/075U0393/sg. [Accessed 12 September 2025].
[86] CNEN - Carta dei siti (aree suscettibili di insediamento di impianti nucleari) | Archivio Nucleare [Online]. Available: http://www.archivionucleare.com/index.php/2009/07/09/cnen-carta-siti/. [Accessed 12 September 2025].
[87] Ministero dell'Ambiente e della Sicurezza Energetica. "Nucleare, pubblicato l'elenco delle 51 aree idonee alla localizzazione del Deposito nazionale - ministero dell'Ambiente e della Sicurezza energetica." [Online]. Available: https://www.mase.gov.it/portale/-/nucleare-pubblicato-l-elenco-delle-51-aree-idonee-alla-localizzazione-del-deposito-nazionale. [Accessed 12 September 2025].
[88] The new electricity market zones: what you need to know | lightbox [Online]. Available: https://lightbox.terna.it/en/insight/new-electricity-market-zones. [Accessed 24 March 2026].
[89] Terna. "Prospettive di Sviluppo del Sistema Energetico 2050," [Online]. Available: https://download.terna.it/terna/Terna_Prospettive_Sviluppo_Sistema_Energetico_2050_Copertura_domanda_elettrica_8de15802728e7d1.pdf. [Accessed 21 November 2025].
[90] Lovering J, Swain M, Blomqvist L, Hernandez RR. Land-use intensity of electricity production and tomorrow's energy landscape. PLoS One Jul. 2022;17(7): e0270155. https://doi.org/10.1371/journal.pone.0270155.
[91] Nicholas TEGG, et al. Re-examining the role of nuclear fusion in a renewables-based energy mix. Energy Policy 2021;149:112043 [Online]. Available: http://arxiv.org/abs/2101.05727. [Accessed 15 February 2024].
[92] Vaccaro A, Rosen MA, Agelin-Chaab M, Santarelli M. Techno-economic analysis of future clean hydrogen potential from the five-step copper–chlorine cycle powered by nuclear energy. Int J Hydrogen Energy Oct. 2025;176:151471. https://doi.org/10.1016/J.IJHYDENE.2025.151471.
[93] Moore M, Pencer J, Leung LKH, Sadhankar R. Knowledge gaps in economic analyses of advanced reactor concepts. 2014 [Online]. Available: https://www.gen-4.org/gif/upload/docs/application/pdf/2014-09/pbnc_paper-aecl.pdf. [Accessed 22 August 2023].
[94] Stewart WR, Shirvan K. Capital cost estimation for advanced nuclear power plants. Renew Sustain Energy Rev Mar. 2022;155:111880. https://doi.org/10.1016/J.RSER.2021.111880.
[95] MAHTEP Group, "MAHTEP/TEMOA - release 2.1," GitHub. Accessed: October. 9, 2025. [Online]. Available: https://github.com/MAHTEP/TEMOA/releases/tag/2.1.