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Nuclear fission techno-economic characterization for energy system models and scenario analysis for Italy

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Abstract

The progressive urgency to mitigate climate change, driven by the increasing concentration of greenhouse gases in the atmosphere and the accelerating global temperature rise, is reshaping energy policies and research priorities worldwide. In this context, nuclear energy is gaining renewed interest as a dispatchable, low-carbon source capable of contributing to the decarbonization of energy systems. This thesis focuses on the possible role of nuclear fission in the future Italian power sector, where nuclear power has been absent since 1987, but is now re-emerging in public and political debate. The work aims at investigating under which economic, technical, and policy conditions nuclear power could become a viable option in Italy. The first step is the detailed modeling of the nuclear fuel cycle, including front-end processes (e.g. uranium import, enrichment, and fuel fabrication), reactor operation, and back-end processes (e.g. spent fuel management and reprocessing). These elements are integrated into a power-sector model instance of the TEMOA (Tools for Energy Modelling Optimization and Analysis) open-source energy system optimization framework, enabling a transparent and reproducible techno-economic assessment. A set of scenarios is constructed to evaluate how variations in key parameters such as investment costs, hurdle rates, and capacity constraints affect the competitiveness of different nuclear technologies, including Generation III+ and Generation IV reactors. In particular, large reactors are the optimal choice when their hurdle rate is 6% or 8%. Conversely, SMRs are generally preferred when their hurdle rate is lower than that of large reactors. The results provide policy-relevant insights into the economic and environmental implications of reintroducing nuclear energy in Italy, quantifying its potential impact on system costs, greenhouse gases emissions, and critical material use. In the most favorable scenario, nuclear technologies provide 15% of electricity demand by 2050, reducing greenhouse gases emissions by up to 17%, while saving approximately 300,000 tons of critical raw materials like Aluminum, Copper, Chromium and Nickel. A sensitivity analysis is performed for advanced SMRs costs to identify relevant thresholds for their competitiveness. By doing so, the thesis contributes to filling key research gaps regarding nuclear energy modelling within open-source energy system tools and supports an informed discussion on the feasibility of nuclear deployment in Italy's energy transition.

Keywords

Nuclear Fission; Small Modular Reactor; Energy Policy; Scenario Analysis; TEMOA.

List of Acronyms

ADS	Accelerator Driven System
BWR	Boiling Water Reactor
CCGT	Combined-Cycle Gas Turbine
CCUS	Carbon Capture Utilization and Storage
CGE	Computable General Equilibrium
COP	Conference of the Parties
CRM	Critical Raw Material
DU	Depleted Uranium
EU	European Union
GCR	Gas-Cooled Reactor
GDP	Gross Domestic Product
GFR	Gas-Cooled Fast Reactor
GWP	Global Warming Potential
HLW	High Level Wastes
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IDC	Interests During Construction
L_LWR	Large size Light Water Reactor
LFR	Lead Cooled Fast Reactor
LWR	Light Water Reactor
Micro-CHP	Micro-Combined Heat and Power
MoU	Memorandum of understanding
MOX	Mixed Oxide
MSR	Molten Salt Reactor
O&M	Operation and Maintenance
OCC	Overnight Construction Cost
OECD	Organization for Economic Co-operation and Development
PHWR	Pressurized Heavy Water Reactor
PUREX	Plutonium and Uranium Recovery by Extraction
PWR	Pressurized Water Reactor
PyPSA-Earth	Python for Power System Analysis – Earth extension
S_GCR	Small modular Gas-Cooled Reactor
S_LFR	Small modular Lead cooled Fast Reactor
S_LWR	Small modular Light Water Reactor
SCWR	Supercritical Water-Cooled Reactor
SFR	Sodium-cooled Fast Reactor
SMR	Small Modular Reactor
SWU	Separative Work Units
TEMOA	Tools for Energy Modeling Optimization and Analysis
TIMES	The Integrated MARKAL-EFOM System
TRISO	TRi-structural ISOtropic
UCO	Uranium Carbide and Oxide
UK	United Kingdom
UOX	Uranium Oxide
USA	United States of America
VHTR	Very High Temperature Reactor
WACC	Weighted Average Cost of Capital

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Chapter 1

Introduction

1.1 Nuclear energy

Nuclear energy is the second largest source of low carbon electricity on a global scale, contributing for approximately 9% of electricity production in 2023 [1]. After a surge of investments in the 1980s – mainly driven by energy security concerns following the oil crises – high capital costs, increasing construction times and more stringent safety regulations after Chernobyl accident determined a lack of investments [2]. As a consequence, its share has declined gradually over the past 30–40 years, dropping from its peak of ~18% in the late 1990s to below 10% today. The increasing energy demand and the need for a reliable low carbon source could lead to an increasing interest in this technology. Global investments in nuclear power have more than doubled in the last 7 years (see Figure 1) [3]. In 2023, at the Conference of the Parties (COP) 28, more than 20 countries launched the Declaration to Triple Nuclear Energy, with the goal to triple their nuclear capacity from 2020 to 2050 [4]. In 2024 at COP 29 also the US Government shared its plan for at least tripling its US nuclear power capacity by mid-century, while Google signed a deal with Kairos Power to deploy 500 MW of Small Modular Reactors (SMRs) capacity by 2035 [5]. In the same year the European Commission launched the European Industrial Alliance on Small Modular Reactors, which aims to facilitate and accelerate the development, demonstration and deployment of the first SMRs projects in Europe in the early 2030s [6]. According to the International Atomic Energy Agency (IAEA), overall nuclear capacity is now projected to increase by 2.5 times by 2050 [7], reinforcing its critical role in the path toward decarbonization.

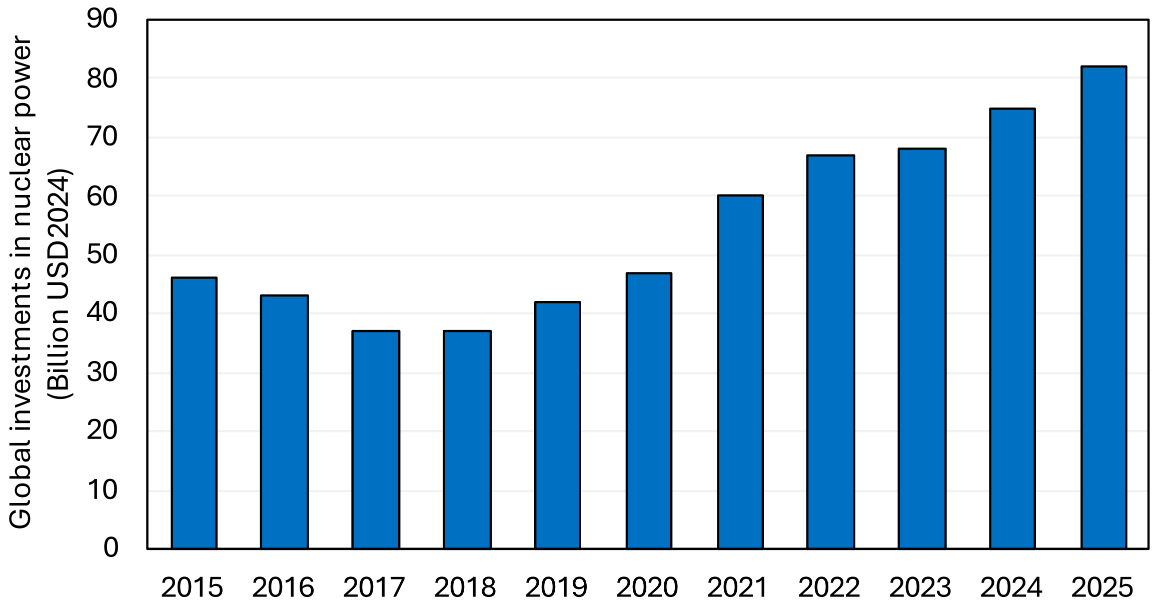

Figure 1. Global investments in nuclear power from 2015 to 2025 [3].

In the 21st century, most of the operating nuclear power plants belongs to **Generation III**. Their fuel is typically UO_2 powder in the shape of pellets contained in zircalloy claddings and can have different levels of fissile material enrichment. **Generation III+** can be considered an evolution of Generation III, with improvements regarding safety (introducing passive safety systems), lifetime, design, and efficiency. At the same time, **Generation IV** new concepts are under development. This category includes 6 reactor types, considered as the most promising: Supercritical Water-Cooled Reactor (SCWR), Very High Temperature Reactor (VHTR), Molten Salt Reactor (MSR), Gas-Cooled Fast Reactor (GFR), Lead Cooled Fast Reactor (LFR), Sodium-cooled Fast Reactor (SFR) [8]. According to the type of neutrons they use, they can be classified in two categories:

- **Thermal reactors**: SCWR, VHTR and MSR work with thermal neutrons. Their coolants typically are heated up to higher temperatures, allowing them to reach higher thermodynamic efficiency and giving the possibility of exploiting the produced heat for industrial applications.
- **Fast reactors**: GFR, LFR and SFR work with fast neutrons. The biggest advantage of this type of reactor is the capacity of recycling spent fuel in them and burn long lived actinides. In this way the amount of high-level waste is reduced and its management strongly simplified.

Another promising concept is the Accelerator Driven System (ADS) which is a subcritical LFR, meaning that the nuclear chain reaction is not self-sustained once the criticality is reached, but it is fed by a particle accelerator. This one makes protons hit a target, called spallation source, with the consequential production of neutrons. In this way, in case of an accident, the accelerator is turned off and the chain reaction will stop, making the reactor intrinsically safer. [9]

For what regards **SMRs**, the idea behind this kind of reactor is changing the manufacturing method: instead of building a single big power plant, a series of small reactors can be produced in factory and then installed module by module. This implies several advantages, like the reduction of capital costs, easier financing, lower construction times, the possibility to build in a controlled factory, provide power away from large grid systems. On the other hand, they have lower efficiencies for the same amount of energy produced with respect to bigger size power plants of the same category. [2], [10]

Italy was a pioneer of civil nuclear power, starting the construction of its first reactor in 1958 [11]. However, following the 1986 Chernobyl accident and a subsequent referendum – despite none of questions regarded the banning of nuclear energy –, the Italian government decided to shut down all their four nuclear plants and to terminate programs for new investments [11]. Italy's current energy mix is insufficient to fully meet domestic electricity demand. As a result, the country ranks as the world's second largest net importer of electricity [11], with 16.3% of its internal consumption covered by net imports [12]. Interest in nuclear energy seems growing in the last period, as ENEA joined European Industrial Alliance on Small Modular Reactors in June 2024 [13] and Italy joined European Nuclear Alliance one year later [14]. These actions, together with global climate goals and the geopolitical drive for energy sovereignty, are signal for a potential trend shift. However, regulatory uncertainty, social acceptance, and long planning horizons remain critical barriers.

1.2 Modeling tools for the energy transition

The global energy transition is fundamentally reshaping energy systems toward sustainability, with a growing emphasis on decarbonization, electrification, and diversification of supply. While renewables such as wind and solar have become central to national strategies due to cost reductions and climate targets, they introduce new challenges in terms of system reliability, flexibility, and land use. As a dispatchable and low-carbon option, nuclear power can contribute to solving these issues, especially in systems with high penetration of intermittent renewables. Nuclear energy has avoided 72 Gt of CO_2 since 1971 [2], thanks to its median life-cycle carbon intensity of 12 gCO_2/kWh [15]. In the energy transition context, these characteristics make it a critical component of many decarbonization pathways.

Energy System Optimization Models (ESOMs) are mathematical frameworks designed to support long-term planning of energy systems under uncertainty [16]. By relying on linear programming (or other optimization techniques), ESOMs solve for the least-cost configuration of technologies and resources that satisfy energy demands across sectors (e.g., electricity, heating, transport) and regions. They typically operate under assumptions like partial equilibrium in competitive markets with perfect foresight [17]. This means that prices are computed in such a way that suppliers produce exactly the amounts the consumers want to buy, they are equal to the marginal cost, and markets behave in an ideal way – buyers know the quantities of goods they require during all the time horizon, allowing to impose a fixed demand value. They guide decisions on infrastructure investments, technology deployment, and energy flows over time horizons – usually several decades –, accounting for policy goals and technical constraints. These models typically adopt a **bottom-up** approach, explicitly representing individual technologies and their characteristics [18]. Each process or device – e.g., a fuel production or a wind turbine – is characterized by techno-economic parameters such as efficiency, cost, emissions, and availability. On the contrary, **top-down** models represent the energy system through aggregated economic variables and are often used to assess macroeconomic impacts – e.g., Gross Domestic Product (GDP) – of energy policies [19]. Top-down models include Computable General Equilibrium (CGE) models [20], Input-Output models, and System Dynamics models, and are frequently used in economic forecasting. While top-down models are better at capturing economic feedback and structural shifts across the economy, bottom-up models like ESOMs are more appropriate for detailed technology assessments and policy scenario development in the energy domain.

Within ESOMs, the structure is built around a Reference Energy System (RES): a network of technologies that transform primary resources into final energy services through defined commodity flows. Technologies are modeled in terms of input and output commodities, investment costs, O&M costs, technical lifetimes, and constraints such as capacity factors or ramping limits. Optimization aims to minimize total system cost while satisfying constraints on energy balance, emissions, policy targets, and technology availability. One of the key strengths of ESOMs is their ability to represent entire energy supply chains and their interactions across sectors (e.g., electricity, heating, transport). This makes them especially powerful for evaluating systemic impacts of deploying new technologies, such as nuclear reactors or renewable resources, and for identifying trade-offs among competing objectives like cost, emissions, and resource use. ESOMs are used by governments, international organizations, and academic institutions to inform policy decisions, assess climate goals, and guide technology roadmaps. [21]

Several families of ESOMs exist. One of the most widely used in national and regional planning contexts TIMES (The Integrated MARKAL-EFOM System), developed under the IEA-ETSAP initiative [22]. It is accessed through the VEDA interface, which facilitates input data handling and output visualization [23]. In this thesis, the selected framework is TEMOA, a fully open-source ESOM implemented in Python [17]. TEMOA is built upon the Pyomo optimization library and designed to solve large-scale linear programming problems. Its modular, transparent, and reproducible structure makes it ideal for academic and exploratory scenario modeling (including regional instances like [24] and [25]), and it allows for easy extension of model structure and logic. The model developed in this thesis is based on TEMOA-Italy [26], [27], an open-source national-scale model of the Italian energy system built with historical energy statistics from International Energy Agency (IEA) for the base year 2006 and Eurostat Energy Balance for calibration up to 2022 [28]. From this foundation, a specialized power-sector-only version called TEMOA-Italy-Power was developed to explore techno-economic conditions for nuclear fission deployment in Italy. This model focuses exclusively on the power sector to enable high-resolution analysis of electricity generation technologies, investment strategies, and fuel cycle processes. However, the detailed structure of the nuclear fuel cycle used in this thesis takes direct inspiration from the approach adopted in TEMOA-Europe, a single-region model that covers OECD Europe using 2005 as base year [29]. Within it the nuclear front-end and back-end stages are disaggregated more explicitly. This structure was adapted and expanded to fit the national context of Italy, as TEMOA-Italy originally lacked such fuel cycle detail.

Although nuclear technologies are often included in national energy plans, their modeling within energy models is typically simplified. Most of the available models neglect key elements such as the full nuclear fuel cycle, the material footprint, the economic thresholds required for competitiveness and the policy frameworks needed to reduce investment risk. In the abovementioned models, TIMES and TEMOA-Italy completely lack the spent fuel management, not considering crucial aspects like reprocessing options or temporary storage and final disposal. Other open-source ESOMs, like PyPSA-Earth (Python for Power System Analysis – Earth extension), use a single generic fuel commodity and a single reactor technology. This oversimplified configuration fails to capture the variety of reactors in terms of capacity, fuel cycles, costs, technical characteristics, resulting in a limited and less realistic representation of nuclear power within the energy system.

1.3 Aim and structure of the thesis

The aim of the thesis is to investigate under which economic, technical, and policy conditions nuclear fission – in particular Generation III+, Generation IV and SMRs – could become a viable option for decarbonizing the Italian power sector. To this end, a detailed representation of nuclear technologies – including front-end and back-end fuel cycle stages – is developed and implemented in TEMOA. A power-sector-only version of TEMOA-Italy is developed to isolate the effects of nuclear technology deployment from broader cross-sectoral dynamics. The model integrates the nuclear fuel cycle, cost components, emissions and material requirements. A scenario-based approach is used to investigate the influence of investment costs, financing assumptions and capacity targets. The study identifies conditions under which nuclear technologies become competitive – special attention is given to the comparison between large reactors and SMRs – and explores impacts of its deployment on total system costs, emissions and demand of critical raw materials.

The work is structured as follows. Chapter 2 presents the methodology and the nuclear techno-economic modeling framework, describing how front-end, reactor core and back-end stages are shaped in detail and data assumptions. Chapter 3 outlines the implementation in TEMOA-Italy-Power and validation strategy adopted. Chapter 4 describes the policy and economic scenarios explored. Chapter 5 discusses results regarding nuclear deployment, system costs, greenhouse gases emissions, and critical material consumption. Chapter 6 concludes with key findings, policy implications, and suggestions for future research directions.

Chapter 2

Methodology

This chapter highlights the techno-economic modeling approach adopted to represent nuclear fission within the energy system framework Two main sources of methodological inspiration were adopted. TEMOA-Europe includes a detailed structure of the nuclear fuel chain, encompassing front-end processes, different reactors, and back-end stages such as reprocessing and disposal [29]. The configuration used in this thesis replicates this logic, especially in terms of the flow between technologies and commodities, the separation of the reactor core and secondary electricity generation loop, and the inclusion of spent fuel treatment pathways. However, TEMOA-Europe does not provide sufficient disaggregation in the modeling of front-end processes. On the contrary, in many TIMES implementations, the nuclear front-end is modeled through a sequential chain that includes U_3O_8 import, UF_6 conversion, enrichment, UOX fuel fabrication, and loading into reactors. This structure enables a modular representation of the front-end fuel cycle, where techno-economic parameters (e.g., costs, capacity limits, import dependencies) can be attributed to each step. The structure also facilitates the tracking of material flows and the representation of alternative pathways such as MOX fabrication and reprocessing. In this work, the overall architecture of the nuclear modeling was taken from TEMOA-Europe, while the front-end structure is inspired from the JRC-EU-TIMES model [30]. This hybrid approach allows for both structural coherence with previous TEMOA models and a richer techno-economic detail in the front-end stages, where supply chain costs, capacities, and import options can significantly influence scenario results.

The following subsections describe each stage of the nuclear chain in detail, highlighting the assumptions, input data, and parameterization choices applied in the TEMOA-Italy-Power model. It details the structure of the nuclear fuel cycle and describes the assumptions and data sources used for the techno-economic characterization of each stage, including the representation of power plants reactors (Section 2.1), front-end (fuel supply, Section 2.2) and back-end (spent fuel managing, Section 2.3). A list of the technologies and commodities included in each stage is shown in Table 1, while a schematic view of the nuclear fission technology chain is presented in Figure 2, showing the connection between technologies and commodities.

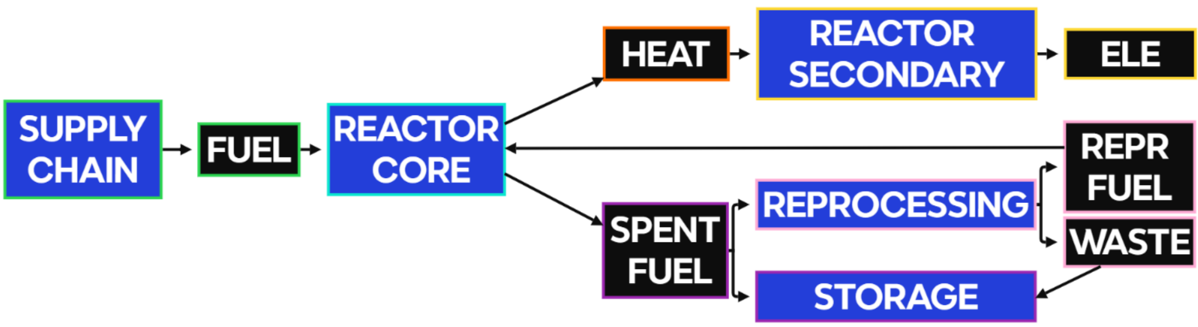

Figure 2. Simplified nuclear chain. Technologies are represented by blue squares, commodities by black ones.

Table 1. Front-end, reactor and back-end subdivision.

Section	Technologies	Commodities
Front-end	Supply chain	Fuel
Reactor	Reactor core	Heat
	Reactor secondary	Electricity
Back-end	Reprocessing	Spent fuel
	Storage	Reprocessed fuel
		Waste

2.1 Reactors

Currently, the most widespread technologies for nuclear reactors are Pressurized Water Reactors (PWRs), representing 78% of net electrical nuclear available capacity in the world. On the contrary, 11% is made by Boiling Water Reactors (BWRs), while Pressurized Heavy Water Reactors (PHWRs) cover 6% of the total. Thus, more than 95% of the global nuclear power is characterized by water reactors. [31]

Table 2. Operating reactors in the European Union [31].

Category	Reactor	Net Capacity (GWe)	Country
BWR	BWR-25	3.94	Finland, Sweden
	BWR-6	1.06	Spain
	BWR-300	2.57	Sweden
PWR	WH 2LP	2.19	Belgium, Slovenia
	WH 3LP	9.32	Belgium, Spain, Sweden
	Framatome 3 loops	0.96	Belgium
	VVER-V-320	4.06	Bulgaria, Czech Republic
	VVER-V-213	7.12	Czech Republic, Finland, Hungary, Slovakia
	CP0	3.58	France
	CP1	16.32	France
	CP2	1.81	France
	P4 REP 1300	26.40	France
	N4 REP 1450	5.99	France
	KWU 2LP	0.48	Netherlands
	PWR 3 loops	1.00	Spain
	SNUPPS	1.20	UK
	EPR	1.60	Finland
PHWR	CANDU 6	1.30	Romania
GCR	AGR	4.69	UK

Table 3. Leading SMR companies plan and technology [2].

Company - Country	Category	Reactor	Net Power (MWe)	Development plan
NuScale – USA	PWR	VOYGR SMR	77	Romania: 6-module plant (462 MW) planned operation by 2029 Memorandum of understanding (MoU)/agreement in Bulgaria, Canada, Czechia, Ghana, Indonesia, Korea, Poland, Ukraine and US
Westinghouse Electric Company - USA	PWR	AP300 SMR	330	UK: advanced approval stage for the AP300 (1st reactor online in early 2030s) MoU/agreement in Canada, Czechia, Romania and Ukraine
Terrapower - USA	SFR	Natrium	345	US: Natrium reactor planned for Wyoming, US, with operation target 2030
GE Hitachi Nuclear - USA	BWR	BWRX-300	300	Canada: contract for building the first SMR with OPG by 2029 MoU/agreement in Czechia, Estonia, Poland, Sweden and UK
Rolls-Royce SMR - UK	PWR	UK SMR	470	UK: government funding for SMR development, deployment in early 2030s MoU/agreement in Czechia, Netherlands, Poland and Sweden
NUWARD - France	PWR	NUWARD	200-400	France: 200-400 MW SMR, with the construction start planned around 2030 MoU/agreement in Finland, India, Italy, Poland, Slovakia and Slovenia
X-energy - USA	GCR	Xe-100	80	US: selected for Advanced Reactor Demonstration Program with 320 MW SMRs online by 2030. MoU in Canada
Oklo – USA	SFR	Aurora	15	US: Aurora SMR first lab-plant to be ready by 2027
Moltex Energy – Canada	MSR	SSR-W	300	Canada: agreement with New Brunswick Power for first reactor by early 2030s
CNNC - China	PWR	ACP100	125	China: ACP100 SMR under construction in Hainan, operation expected by 2026
Kairos Power – USA	MSR	Hermes Low-Power Demonstration Reactor	35	US: first Generation IV SMR online by 2027
Newcleo – France	LFR	LFR-AS-200	200	UK: developing LFR design. First 200 MW commercial unit expected in the UK by 2033
Korea Hydro & Nuclear Power – South Korea	PWR	i-SMR	170	Korea: simulator reactor completed by the second half of 2027 and SDA by 2028

Focusing on the European situation, given the Italian case study being investigated, the operational reactors in the European Union (EU), including UK, are shown in Table 2 by categories [31]. They are all Generation II reactors apart from OLKILUOTO-3, the EPR built in Finland with commercial operation start in 2023, which is the first Generation III+ reactor operating in Europe. Moreover, Gas-Cooled Reactors (GCRs) in the UK are the only ones in the list which are not water reactors. Looking at reactors under construction in Europe, they are all PWRs and, specifically, EPR in France, EPR-1750 in the UK, and VVER V-213 in Slovakia [31]. The current situation for SMRs development, presented in Table 3 [2], shows reactors that should be available by the end of 2020s and 2030s.

Four reactors have operated in Italy (2 BWRs, 1 PWR and 1 GCR), with the last shutdown in 1990 [31]. To select reactor categories available for new potential installations, some considerations must be made:

- **Nuclear industry stagnation**: in the 20 years between the last grid connection in Czech Republic (2002, even if not already in European Union) and Olkiluoto in Finland (2022), there was only one other nuclear reactor grid connection, in Romania (2007) [31]. For a potential restart the Italian government is likely to opt for constructing new-generation reactors (III+ and IV), following the Finnish example or taking inspiration by the list of reactors currently under construction.
- **Geopolitical factors**: the current geopolitical situation – in particular following the Ukrainian conflict – could favor specific markets (e.g. the European one), producers (e.g. historical allies like USA) and reactor models while disadvantaging others identified as less reliable over the long run (e.g. Russia or China).

Based on these points, only Generation III+ and IV reactors produced by European countries, USA, Japan, and Canada will be considered as potential options for new power plants deployment in Italy. Table 4 presents the candidate technologies.

Table 4. List of new technologies and relative reactors.

Category	Reactors	Producer	Nominal Power
BWR	ABWR	Japan	1315 MWe
	ESBWR	USA	1520 MWe
PWR	EPR	France	1650 MWe
	Rolls-Royce SMR	UK	470 MWe
PHWR	EC6	Canada	690 MWe
SCWR	JSCWR	Japan	1620 MWe
VHTR	Xe-100	USA	82.5 MWe
	GTHTR300c	Japan	300 MWe
MSR	IMSR400	USA	390 MWe
	Thorcon 500	USA	250 MWe
GFR	EM2	USA	1060 MWe
LFR	ALFRED	European Union	125 MWe
	ELFR	European Union	630 MWe
	LFR-AS-200	UK	200 MWe
SFR	PRISM	USA	311 MWe
ADS	MYRRHA	Belgium	100 MWt

Being the most widespread technology, the PWR is selected as first type of reactor, including a large size Light Water Reactor (L_LWR) – e.g. EPR – and a Small modular Light Water Reactor (S_LWR) – e.g. Rolls-Royce SMR–. The reactor section is represented by technologies listed in Table 5 and commodities in Table 6.

Table 5. Reactor section technologies of LWR nuclear chain in TEMOA-Italy-Power.

Technology	Description
CORE L_LWR	Large size Light Water Reactor core
CORE S_LWR	Small Modular Light Water Reactor core
SECONDARY L_LWR	Large size Light Water Reactor secondary
SECONDARY S_LWR	Small Modular Light Water Reactor secondary

Table 6. Reactor section commodities of LWR nuclear chain in TEMOA-Italy-Power.

Commodity	Description
HEAT L_LWR	Nuclear heat from large size Light Water Reactor core
HEAT S_LWR	Nuclear heat from Small Modular Light Water Reactor core
ELE	Centralized electricity produced

The overnight and investment costs at a discount rate of 3%, 7%, and 10% are presented in Table 7 [32]. While the overnight cost includes pre-construction (owner's), construction (engineering, procurement, and construction) and contingency costs, it does not include interests during construction (IDC). The latter are instead accounted in the investment costs. This aspect can be particularly relevant for technologies with high investments costs and high construction time, like nuclear reactors. The overnight cost for the S_SMR is taken from [10] and equals $4,844/kW, higher with respect to L_LWR due to economies of scale related phenomena.

Table 7. LWRs investment costs. [32]

Nuclear generating technologies – New build							
Country		Technology	Net capacity (MWe)	Overnight costs (USD_{2018}/kWe)	Investment costs (USD_{2018}/kWe) 3%	7%	10%
OECD Countries	France	EPR	1650	4013	4459	5132	5705
	Japan	ALWR	1152	3963	4402	5068	5633
	Korea	ALWR	1377	2157	2396	2759	3066
	Russia	VVER	1122	2271	2523	2904	3228
	Slovak Republic	Other nuclear	1004	6920	7688	8850	9837
	United States	LWR	1100	4250	4721	5435	6041
Non-OECD Countries	China	LWR	950	2500	2777	3197	3554
	India	LWR	950	2778	3086	3552	3949

The investment costs are computed from the overnight costs as reported, where *n* is the construction time in years, *y* is the year from 1 to *n* and *r* is the discount rate, see Equation 1.

As construction time, 10 and 6 years are chosen for large reactors and SMRs respectively. They are the highest values included in the 90%-probability interval of Monte Carlo simulation from [10]. Additionally, these values are in line with the conservative scenario in [33], where construction time is 125 months for large reactors and 71 for SMRs.

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

For fixed costs, referring to operation and maintenance (O&M) costs, the values in Table 8 are considered. These costs present a significant variability, from few dollars per kWe to some hundreds. The big difference between USA and the other countries can be attributed to the different manpower cost. Being Italy a developed economy, the optimistic USA value of 154 $/kWe is assumed for both the reactors.

Table 8. Country-specific nuclear fixed O&M cost ranges (USD_{2022}/kWe). [34]

Country	Optimistic	Base	Conservative
United States	$154	$179	$223
Chile	$28	$35	$43
Indonesia	$4	$6	$6
Egypt	$6	$6	$8
Nigeria	$4	$4	$6
Argentina	$18	$20	$24
Thailand	$14	$18	$22
India	$6	$6	$8
Ukraine	$14	$16	$22
South Africa	$24	$28	$37

The efficiency and the lifetime of the two reactors are from [35]. EPR presents a burnup of 60 GWd/ton, corresponding to 5.184 PJ/ton for the L_LWR, while Rolls-Royce SMR 55 GWd/ton, leading to 4.752 PJ/ton for S_LWR. The lifetime is 60 years for both reactors. The capacity factor is supposed to be 0.94 for both reactors. All nuclear technologies are available starting from 2035.

2.2 Front-end modeling

The aim of this section is providing the techno-economic description of the nuclear fission front-end for European countries and for the Italian case study. The modeling of the nuclear fuel supply chain – including uranium processing, enrichment, and fuel fabrication – follows the structure typically adopted in TIMES implementations, allowing a more granular representation of upstream processes. In 2023, no natural Uranium was delivered to EU utilities coming from internal EU production [36]. For this reason, technologies simulating internal mining are not available in the model inventory. Usually, the imported raw material is not natural Uranium but U_3O_8, commonly referred to as "yellowcake". The three main stages of fuel production are: conversion of U_3O_8 to UF; enrichment, e.g. increasing the concentration of fissile material up to that needed by the reactor; fuel fabrication, with the fuel in the form requested by each type of reactor as final product. For each of these three processes, the possibilities of developing an internal facility or importing the final product are considered. For example, in 2023 EU internal providers contributed to satisfy 28.69% of conversion services and 54.88% of enrichment demand [36]. The different import and preprocessing options are reported in Figure 3.

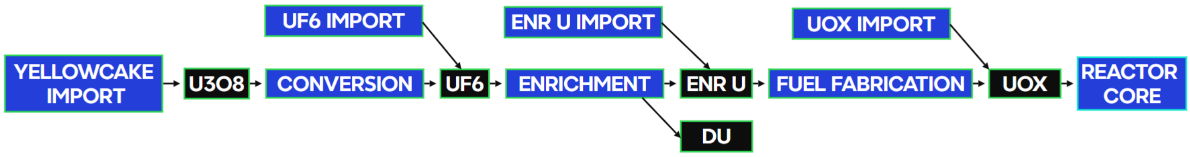

Figure 3. Possible import and preprocessing options considered.

In Table 9 the costs to produce 1 kg of UO_2 fuel in September 2021 are reported, taken from [36], [37]. From [36], it can be noticed that fuel prices have increased in the following two years. In particular, the average price of conversion services was 40 \$/kgU in both the EU and North American markets, the enrichment cost was \$137/SWU (Separative Work Units), and natural uranium had an average spot price of 62 \$/(lb U_3O_8) and an average long-term price of 58 \$/(lb U_3O_8). The average price between spot and long-term has been selected as representative of the fuel production cost, resulting in \$132/kg U_3O_8. For what regards fuel fabrication, there are not available data for 2023. Since they are all industrial processes, its percentage growth with respect to the 2021 value is supposed to be similar to conversion and enrichment ones. Being both about +160%, applying this increase results in a cost of 543/\$(kg UO_2). An overview of the mentioned costs implemented in the model is provided in Table 10.

Table 9. Front-end fuel cycle costs of 1 kg of Uranium as UO_2 fuel in September 2021 [37].

Process	Amount required × prices	Cost	Proportion of total
Uranium	8.9 kg U_3O_8 × 94.6 \$/(kg U_3O_8)	\$842	51%
Conversion	7.5 kg UF_6 × 16 \$/(kg UF_6)	\$120	7%
Enrichment	7.3 SWU × 55 \$/SWU	\$401	24%
Fuel fabrication	per kg UO_2	\$300	18%
Total		\$1663	

Table 10. Front-end fuel cycle costs of 1 kg of Uranium as UO_2 fuel in 2023.

Process	Amount required × prices	Cost	Proportion of total
Uranium	8.9 kg U_3O_8 × 132 \$/(kg U_3O_8)	\$1175	51%
Conversion	7.5 kg U × 40 \$/(kg UF_6)	\$300	7%
Enrichment	7.3 SWU × 137 \$/SWU	\$1000	24%
Fuel fabrication	per kg UO_2	\$543	18%
Total		\$3018	

For prospective new nuclear plants, the front-end nuclear fuel cost is typically only 15-20% of the total lifecycle costs, as opposed to 30-40% for operating nuclear plants [37]. As shown in [32], the levelized cost of electricity (LCOE) by nuclear plants is only marginally determined by the fuel cost, while it mostly depends on investment and fixed costs. The available data concerning the investment cost of conversion, enrichment and fuel fabrication processes are very poor, but estimations can be attempted. Indeed, Orano group invested a total of 1.150 B€ in the project implemented at the Malvési (Aude, France) and Tricastin (Drôme, France) sites [38].

The Philippe Coste conversion plant (Tricastin) was commissioned in 2018 and has a production capacity of 15,000 tU/year [39]. Thus, it can be computed an investment cost of 77 k€ for an installed conversion capacity of 1 tU/y. Since 7.5 kg of converted Uranium are needed to produce 1 kg of fuel, the investment cost implemented is 0.575 $M€_{2018}$/(tU/y). Using the 2022 values in Table 11, an average capacity factor of 0.677 can be computed for **primary conversion** facilities. It must be remembered that these values are heavily affected by the market (for example ConverDyn in USA had a zero-production due to absence of demand) [40].

Table 11. Estimated world primary conversion capacity and UF_6 production in 2022 [40].

Company	Country	Location	Licensed capacity (tU)	UF_6 production (tU)
Cameco	Canada	Port Hope	12500	10600
CNCC (estimated)	China	Lanzhou & Hengyang	15000	10500
ConverDyn	USA	Metropolis	7000	0
Orano	France	Pierrelatte, Malvesi	15000	8900
Rosatom (estimated)	Russia	Seversk	12500	12000
Total			62000	42000

The Georges Besse II **enrichment** plant was commissioned in 2004 and inaugurated on December 14, 2010. The investment was about 3 B€ for an enrichment capacity of 7.5 SWU every year [41], leading to an investment cost of 400 €/SWU. On October 19, 2023, the Board of Directors of Orano has approved the investment in the project to extend the production capacity of the Georges Besse II uranium enrichment plant on the Tricastin site (Drôme et Vaucluse). With a forecast investment amount of 1.7 B€, this plan will enable to increase its production capacities by 2.5 million SWUs [42]. Here, the investment cost is 680 €/SWU and since it is a more recent data it is the one chosen for the model. To convert it in M€/(tU/y), this value must be multiplied by the number of SWU required to produce 1 ton of enriched Uranium (7300). Assuming the enrichment for feed material, product and waste equal to 0.72%, 4.40% and 0.02%, respectively, the corresponding separation potential V_i can be computed as in Equation 2. This leads to product material for each kg of feed material P=0.12kg and waste W=0.88, obtaining a final value equal to 4.964 M€/(tU/y), evaluated according to Equation 3.

$$V_i = (2i - 1) ln\left(\frac{i}{1-i}\right) \tag{2}$$

$$CostInvest\left(\frac{\frac{M€}{tU}}{y}\right)=\frac{\frac{PlantCost}{SW}}{V_P+W\frac{V_W}{P}-F\frac{V_F}{P}} \tag{3}$$

Since it is difficult to find data for **fuel fabrication** facilities, the same investment cost with respect to enrichment plants is assumed for them. Supporting this choice, [43] says that "Currently, fuel fabrication capacity for all types of LWR fuel throughout the world considerably exceeds the demand. It is evident that fuel fabrication will not become a bottleneck in the foreseeable supply chain for any nuclear renaissance.".

2.3 Back-end modeling

This section refers to the modeling of reactors downstream. Most of the depleted fuel by nuclear fission power plants (more than 90%) is unused Uranium with a small amount of Plutonium and it can be recycled [44]. The current means of doing this is by separating the plutonium and recycling that, mixed with depleted uranium, as mixed oxide (MOX) fuel. Very little recovered uranium is recycled at present. Fission products and minor actinides are separated as high-level waste when the used fuel is processed [45].

An available technology for fuel **reprocessing** is Plutonium and Uranium Recovery by Extraction (PUREX). The features of this method are presented in [46]: nuclear spent fuel is reprocessed by the separating Uranium (92.8%), Plutonium (1.2%) and High-Level Wastes (HLW) (6%). Pu is then mixed with Depleted Uranium (DU) to produce MOX. Existing and possible future reprocessing technologies are considered and listed in Table 12, with the relative spent fuel they work with. The association between each reprocessing technology and its output commodities is presented in Figure 4, alongside with the produced reprocessed fuel.

Table 12. Reprocessing technologies with relative spent fuel they reprocess.

Reprocessing techniques	Spent fuel
DUPIC	UOX
PUREX	UOX
COEX	UOX
UREX	UOX
UREX+	UOX
GANEX	UOX
DIAMEX-SANEX	MA+HLW
PYROPROCESSING	MOX
ONLINE REPROCESSING	UF4

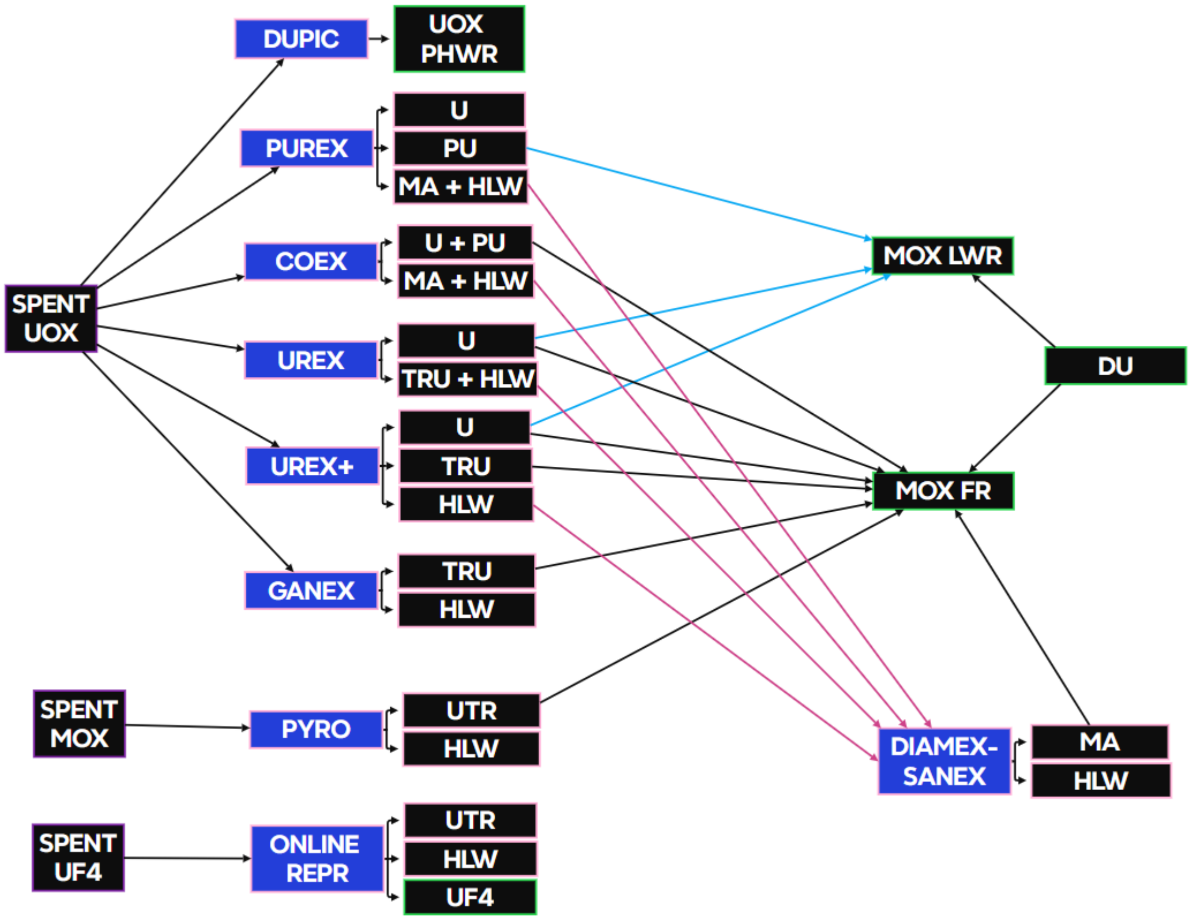

Figure 4. Postprocessing technologies with output commodities.

PUREX reprocessing and MOX fuel production have no investment costs, as both processes are assumed to be imported, similarly to UOX fuel. Although modeled as two separate technologies, MOX fuel imports depend on PUREX reprocessing, ensuring that imported MOX fuel exclusively uses recycled plutonium from spent fuel. A fictitious technology is considered to represent DU used in MOX production, with no costs DU is treated as a waste of the enrichment process. In this way, an internal production and a fuel import can be modeled simply by adjusting costs.

The other process involved in the back-end is **storage**. Indeed, nuclear spent fuel is typically subject to interim pool storage and dry storage, followed by reprocessing or final disposal. The new technologies and commodities considered are listed in Table 13 and Table 14, respectively. Some assumptions are necessary to model this chain. Even if advanced light water reactors such as the EPR or AP1000 can accept complete fuel loadings of MOX if required, these reactors generally use MOX fuel as about one-third of their core [45]. So, the maximum input of MOX in the core is imposed to 33%. Efficiencies in terms of material quantities are the ones reported in [46], while all the costs are given by [47].

Interim and dry storage are put aggregated into a single technology for simplicity, whose cost is the sum of the two steps. In particular, for the interim cost (50 \$/kgHM + 5 \$/kgHM for each year [47]) the cost is computed supposing it is paid all at the beginning of the process and with a storage period of 5 years, giving a value of 0.075 M\$/tHM. Summing this one to the dry storage one (150 \$/kgHM [47]), the total value is 0.225 M\$/tHM.

For what regards the **final disposal**, the cost is divided between packaging and disposal costs. In this case, UOX spent fuel and HLW separated with PUREX are considered, while Pu separated through PUREX is only recycled in MOX. Separated Uranium disposal cost is assumed equal to its storage one because for the moment it is not put in the final disposal, waiting for technologies to recycle it. To convert the waste disposal unit costs from $/m^3 to $/tHM, a density of 3tHM/m^3 is assumed for spent UOX and 0.2 tHM/m^3 for HLW. The obtained values are negligible with respect to packaging costs, so the overall variable cost is assumed equal to the packaging one.

Table 13. Back-end technologies of LWR nuclear chain.

Technology	Description	Variable cost (M$_{2009}$/tHM)
STORAGE UOX	Interim storage of UOX spent fuel	0.225
PUREX REPROC	PUREX reprocessing of UOX spent fuel	1.000
DISPOSAL UOX	Spent UOX disposal	0.250
DISPOSAL U	Separated Uranium disposal	0.225
DISPOSAL HLW	Separated HLW disposal	1.000
PRODUCTION MOX LWR	Production of MOX fuel assemblies for LWR	1.250
DU RECOVERY	Depleted Uranium recovery	0

Table 14. Back-end commodities of LWR nuclear chain.

Commodity	Description
SPENT UOX	Nuclear UOX spent fuel
COOLED UOX	Nuclear cooled UOX spent fuel
PUREX SEPARATED U	Uranium separated with PUREX
PUREX SEPARATED HLW	HLW separated with PUREX
PUREX SEPARATED PU	Pu separated with PUREX
DU	Depleted Uranium
MOX LWR	Nuclear MOX fuel assemblies for LWR

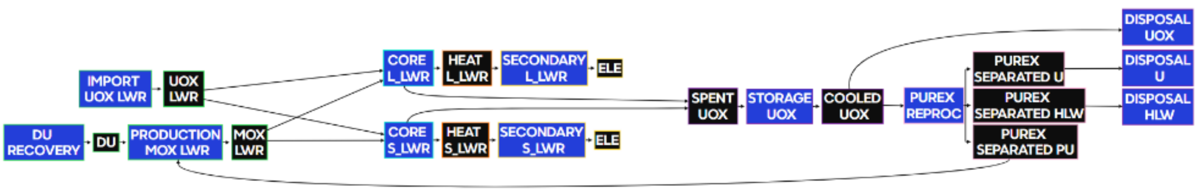

Figure 5. LWR nuclear chain in TEMOA-Italy-Power.

2.4 Alternative reactors and reprocessing options

To enrich the inventory of available reactors, other two SMRs are considered: a Small modular Lead cooled Fast Reactor (S_LFR) and a Small modular Gas-Cooled Reactor (S_GCR).

The **S_LFR** is modelled with LFR-AS-200 as reference reactor. Being an LFR, it needs a different kind of reprocessing at the back-end, e.g., pyroprocessing. This reprocessing technique separates Transuranic (TRU) elements, formed by Pu and Minor Actinides (MA), instead of only Pu, increasing the recycling efficiency with respect to PUREX, decreasing disposal costs thanks to lower quantities of HLW and limiting proliferation risks [46]. It must be noticed that even if this reactor uses MOX as fuel, it has a different composition with respect to the one used by LWRs. Indeed, a big advantage of fast reactors is the possibility of burning also TRU as fuel, allowing a higher fuel efficiency and lower HLW. Costs and efficiency are taken from [47], except for S_LFR fixed and investment costs, for which there are no available data, and they have been assumed to be equal to the S_LWR ones.

The **S_GCR** is modelled with parameters referred to the Xe-100 reactor. The Xe-100 core comprises ~220 000 graphite pebbles fuel elements each containing ~18 000 UCO (Uranium Carbide and Oxide) TRISO (TRi-structural ISOtropic) coated particles. The big advantages of this reactor are the high burnup (165 GWd/tHM) and a coolant outlet temperature of 750°C [35]. This last characteristic, together with its 200 MW thermal capacity, makes it potentially interesting for industrial applications. The UCO fuel cost of 4000 $/kgU is suggested by [48]. The other costs are equalized to S_LFR since there is no available data, with the exception of storage and disposal costs which are hypothesized to be 5 times bigger than UOX ones due to the lower density of the fuel. In this chain there is no reprocessing because of the different structure of the fuel that would require particular treatments, and front-end is composed by the only fuel import.

Additionally, **UREX+ reprocessing** is added as alternative to the PUREX one for LWR spent fuel. This process introduces the possibility of recycling TRU to produce new MOX, but also Uranium to produce new UOX, after a new enrichment, or MOX. The big advantage with respect to PUREX is that, as pyroprocessing, Pu is not completely separated, but it is linked to other TRU. Even if in [47] the nominal value of costs is equal to PUREX one, it is preferred to use the same ratio between their upper bound values, increasing it by a 33%. For what regards UOX recovery after UREX+, the cost is the sum of enrichment and fuel production (Table 10).

The technologies for both S_LFR and S_GCR front-end and back-end with relative costs are reported in Table 15, while commodities are listed in Table 16. The same assumptions made for UOX storage are valid for MOX and UCO. The reactor section of S_LFR and S_GCR is equivalent to the LWRs one, with efficiencies taken from [35].

Table 15. Front-end and back-end technologies of S_LFR and S_GCR nuclear chain.

Technology	Description	Variable Cost
UOX RECOVERY	Enrichment and fuel production of UOX from U separated through UREX+ reprocessing	1.543 $M\$_{2009}$/tHM
UREX REPROC	UREX+ reprocessing of UOX spent fuel	1.330 $M\$_{2009}$/tHM
U RECOVERY	U separation for MOX production	0
PRODUCTION MOX LFR	Production of MOX fuel assemblies for LFR	1.250 $M\$_{2009}$/tHM
IMPORT MOX LFR	Import of MOX fuel assemblies for LFR	4.000 $M\$_{2009}$/tHM
TRU RECOVERY	TRU separation for MOX production	0
STORAGE MOX	Interim storage of MOX spent fuel	0.472 $M\$_{2009}$/tHM
PYRO REPROC	Pyroprocessing of MOX spent fuel	2.750 $M\$_{2009}$/tHM
DISPOSAL MOX	Spent MOX disposal	0.525 $M\$_{2009}$/tHM
IMPORT UCO	Import of UCO fuel for GCR	4.000 $M\$_{2020}$/tHM
STORAGE UCO	Interim storage of UCO spent fuel	1.125 $M\$_{2009}$/tHM
DISPOSAL UCO	Spent UCO disposal	1.250 $M\$_{2009}$/tHM

Table 16. Front-end and back-end commodities of S_LFR and S_GCR nuclear chain.

Commodity	Description
UREX SEPARATED U	Uranium separated with UREX+
UREX SEPARATED HLW	HLW separated with UREX+
UREX SEPARATED TRU	TRU separated with UREX+
RECOVERED U MOX	U separated for MOX production
RECOVERED TRU MOX	TRU separated for MOX production
MOX LFR	Nuclear MOX fuel assemblies for LFR
SPENT MOX	Nuclear MOX spent fuel
COOLED MOX	Nuclear cooled MOX spent fuel
PYRO SEPARATED U	Uranium separated with PYRO
PYRO SEPARATED HLW	HLW separated with PYRO
PYRO SEPARATED TRU	TRU separated with PYRO
UCO GCR	Nuclear UCO fuel for GCR
SPENT UCO	Nuclear UCO spent fuel
COOLED UCO	Nuclear cooled UCO spent fuel

For each technology, ESOMs typically deploy new capacity corresponding to the optimal configuration aiming at minimizing the total cost of the system. The capacity decision variable typically assumes continuous values in real numbers. However, this could represent a significant simplification when dealing with nuclear power plants, due to their rated capacity being constrained to specific and discrete commercially available sizes. For this reason, a new parameter called "DiscreteCapacity" is introduced in the model. When a discrete capacity is associated with a technology, the new capacity deployed in each vintage must be a multiple of that value. The DiscreteCapacity values slightly differ from the actual commercial size of the different reactors [35], as they are selected such that the imposed maximum capacity constraint is an exact multiple of each reactor type's discrete investment size. This modeling choice is intended to avoid numerical issues or infeasibilities related to the saturation of the maximum capacity constraint, ensuring that the model can allocate reactor units without exceeding the cap due to rounding or granularity mismatches. The DiscreteCapacity value for each nuclear reactor technology is reported in Table 17. In Table 18 all techno-economic parameters for reactor technologies are summarized.

Table 17. DiscreteCapacity associated with each reactor technology.

Technology	**Reactor model**	**DiscreteCapacity (GW)**
L_LWR	EPR	1.6
S_LWR	Rolls-Royce SMR	0.4
S_LFR	LFR-AS-200	0.2
S_GCR	Xe-100	0.1

Table 18. Reactor technologies techno-economic parameters.

<table>
<tr><th>Reactor</th><th>Fuel</th><th>Reprocessing</th><th>Efficiency (%)</th><th>Discrete Capacity (GW)</th><th>Lifetime</th><th>Investment Cost in 2035 ($M\$_{2022}$/GW)</th><th>Fixed O&M Cost ($M\$_{2022}$/GW)</th><th>Capacity Factor (%)</th></tr>
<tr><td>L_LWR</td><td rowspan="2">UOX LWR or MOX LWR</td><td rowspan="2">PUREX or UREX</td><td rowspan="2">33</td><td>1.6</td><td rowspan="4">60</td><td>5289</td><td rowspan="4">154</td><td rowspan="4">94</td></tr>
<tr><td>S_LWR</td><td>0.4</td><td rowspan="3">5631</td></tr>
<tr><td>S_LFR</td><td>MOX LFR</td><td>Pyro</td><td>42</td><td>0.2</td></tr>
<tr><td>S_GCR</td><td>UCO GCR</td><td>-</td><td>41</td><td>0.1</td></tr>
</table>

Chapter 3

Implementation in TEMOA

This chapter describes the implementation of the aforementioned methodology on a power sector model instance for Italy. The focus on the power sector only is justified by the intention of analyzing the effects of selected parameters on the competitiveness of nuclear fission technologies in electricity generation, without interference from cross-sectoral interactions and variations in the end-uses electrification between the studied scenarios. In this context, the TEMOA (Tools for Energy Modeling Optimization and Analysis) has been chosen, due to the existence of a validate full-scale Italian energy system model [49]. TEMOA is an open-source, bottom-up energy system modeling framework solving linear optimization problems. It is designed to minimize the total cost of the energy system over the given time horizon, under technical and policy constraints and satisfying energy service demands. The three main components of the total costs are investment cost, fixed operation and maintenance (O&M) cost and variable O&M cost. The latter is related to the technology activity, while the other two are linked to the technology's capacity. All costs in the model are discounted at the beginning of the time horizon. The main techno-economic parameters involved into technology characterization and the connection between physical, demand and emission commodities are shown in Figure 6.

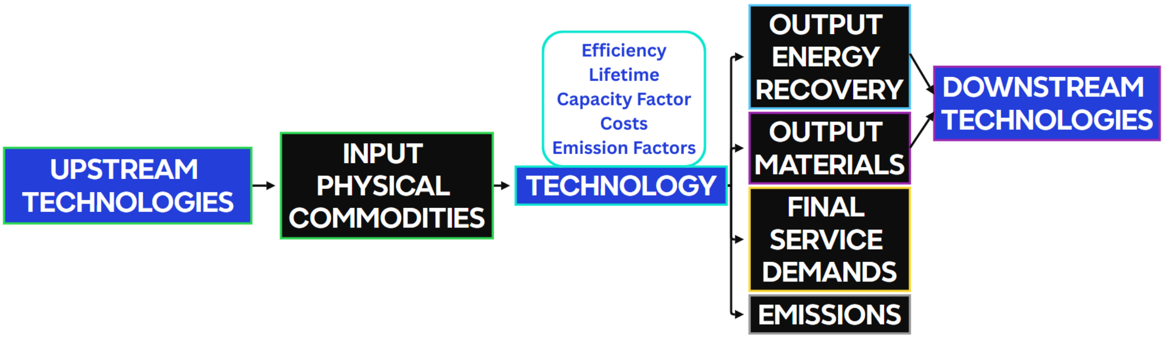

Figure 6. The main techno-economic parameters and connection between commodities in TEMOA.

The techno-economic characterization of nuclear fission technology options illustrated in Chapter 2 and the scenarios presented in Chapter 4 have been implemented into a TEMOA-compliant model instance representing the Italian power system based on the power sector of TEMOA-Italy [50]. TEMOA-Italy is a model that simulates the Italian energy system. The time horizon goes from 2006 (base year) to 2050, and it is fully calibrated up to 2020. Each time period is divided into four seasons (winter, spring, summer and fall) and four times of day (night, morning, noon and afternoon). This choice, alternative to the use of the integrated multi-sectorial version of TEMOA-Italy resides in the necessity of studying the competition of fission power plants with alternative power generation technologies at constant electricity demand levels.

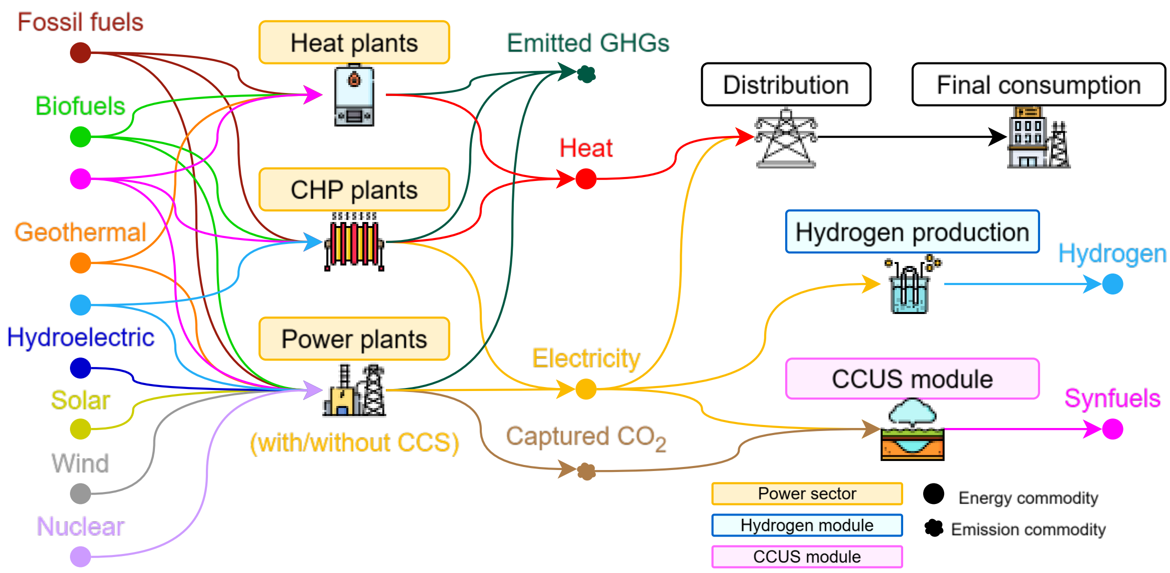

Figure 7. Scheme of the TEMOA-Italy power sector [50].

The available technologies produce distributed electricity, centralized electricity and heat, and include coal and natural gas power plants with Carbon Capture (CC) and Micro-Combined Heat and Power (Micro-CHP) for residential, industrial and commercial applications. Lithium-ion batteries and pumping hydroelectric plants are the available storage technologies for centralized electricity, while for distributed electricity only lithium-ion batteries are considered [50]. Emissions are modeled following the approach detailed in [51], [52], while technology-specific hurdle rates are from [53].

For what concerns the upstream, the supply chain of coal, oil, natural gas and biofuels is represented by technologies producing the energy commodities delivered to the power sector and accounting for the commodity variable cost. Electricity imports and exports are also considered by introducing devoted technologies to represent the average import and export capacities and prices. The distribution of electricity and conversion from centralized electricity to the distributed one is represented by considering an efficiency of 95% to simulate grid losses. Heat and electricity demands are modelled using results from a decarbonization scenario using TEMOA-Italy and they are listed in Table 19.

Table 19. Heat and electricity demand taken from the Net0 scenario presented in [54].

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

Once made these considerations, the nuclear chain as represented in Figure 8 can be introduced. Since this case study is focused on the Italian model, without existing fuel supply facilities available, it is assumed that reactor-ready fuel will be supplied by other European countries. The effects of this assumption, expected to have a minor impact on the results given the limited sensitivity of the cost of the electricity produced by nuclear power plants on the fuel cost, may be subject to future investigations which are beyond the scope of this analysis. For such a reason, the front-end will be represented by UOX importation only. The complete nuclear fission chain is shown in Figure 8, where the clear separation between the three main sections - front-end, reactor and back-end - can be noticed.

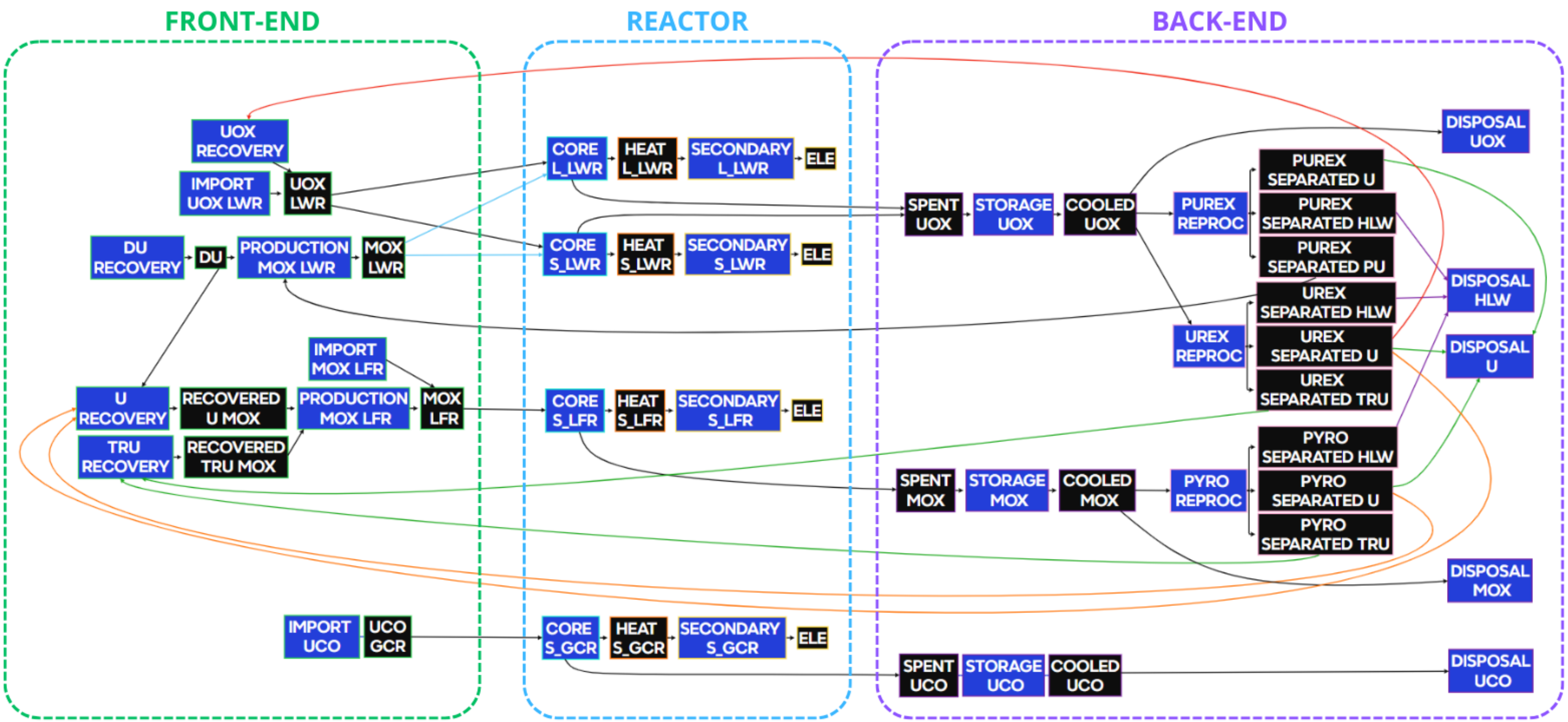

Figure 8. Complete nuclear chain configuration in TEMOA-Italy-Power.

Chapter 4

Scenarios definition

The scenarios defined in this chapter firstly aim at investigating how the variation of some parameters can affect the system optimization. Since the economic data describing S_LFR and S_GCR are affected by significant uncertainties, they are excluded by this step of the analysis. Only L_LWR and S_LWR are available, allowing competition between large size and small modular reactors of the same type.

4.1 Conditions determining the nuclear fission cost-competitiveness

To analyze the competition of nuclear technologies, three parameters are selected and for each of them different values are considered. Normalized costs and hurdle rate are selected as economic parameters, significantly determining the LCOE for nuclear fission [32], while different maximum capacity thresholds are inserted to include factors limiting nuclear penetration (e.g., licensing, permitting, labor force, infrastructure). The former refers to investment costs for reactors technologies and variable costs for reprocessing ones. The choice of investigating these costs in particular is supported by the fact that the OCC (Overnight Construction Cost) represents the single largest component of the total levelized cost of generating electricity with nuclear power, typically accounting for roughly 55%, while other lifecycle costs - approximately 15% for IDC, 15% for O&M and decommissioning provision, and 15% for fuel and provisions for used fuel - are more predictable and have had far less variation over time and country [55]. Both the selected economic parameters affect the OCC but reflecting different drivers: hurdle rates are mainly influenced by government policy and regulatory conditions, while normalized costs are determined by technology suppliers and cost trends on the supply side. Each value of these three parameters is identified with a letter (H = hurdle rate, N = normalized cost, C = maximum capacity) and a number (depending on the value assumed by the parameter). Some considerations must be made about how these values are chosen.

Looking at [56], depending on the role nuclear energy production has in companies value, WACC (Weighted Average Cost of Capital) is included between 6% and 8%. Supposing that Italy could have higher WACC with respect to the global average, the optimistic value for L_LWR **hurdle rate** is 6%, the medium one is 8% and the pessimistic one is 10%. Assuming that SMRs could be seen as less risky investments, giving some factors like their higher acceptability from the population, S_LWR discount rates are supposed to be equal or lower than L_LWR values, with a difference of 1% or 2% in the case it is lower, as reported in Figure 9. The hurdle rate of other technologies, including intermittent renewables, does not vary in the investigated scenarios since their shorter lifetime and the lower capital cost combined with the future projections for cost reductions makes the cost of capital a less critical issue in determining their cost-competitiveness.

For the normalized costs of reactors, [55] presents an analysis on nuclear **investment costs** historical trends in different countries, summarized in Table 20. In the first era of commercial deployment of a specific reactor, which typically lasts around 10 years, there has always been a decreasing annualized rate of change in OCC, going from -6%/yr to -17%/yr. This initial period is usually followed by an inversion in the trend, with a rising in costs before stabilization. The only exception is represented by South Korea, which has a different behavior with respect to all the other countries, maybe due to its particularly stable political situation, having a low but constant decrease in OCC for all the time. Given that, in N- costs have a rate of -5%/yr with respect to the 2035 reference up to 2040, other 5 years with a -2%/yr rate and a constant cost from 2045. The result is a reduction of 30% in 10 years, which seems to be acceptable looking at values in Table 21, Table 22 and Table 23 representing conservative, moderate and advanced scenario in [33]. To explore conservative scenarios as well, N+ assumes a symmetric increasing trend, with a +5%/yr from 2035 to 2040, +2%/yr up to 2045 and constant costs afterward, while N= assumes constant values for the whole time horizon.

Table 20. Summary of costs trends by country [55].

Country	Era (defined by time period in which reactors began construction)	Annualized rate of change in OCC (%/yr)	Total change in OCC by era (%)
USA	1954–1968, 18 demonstration reactors	-14%	-81%
	1964–1967, 14 turnkey reactors	-13%	-33%
	1967–1972, 48 reactors completed pre-TMI	+23%	+190%
	1968–1978, 51 reactors completed post-TMI	+5 to +10%	+50 to +200%
France	1957–1966, 7 gas-cooled reactors	-17%	-77%
	1971–1991, 59 light-water reactors	+2 to +4%	+50 to +100%
Canada	1957–1974, 6 reactors	-8%	-77%
	1971–1986, 18 reactors	+4%	+60%
West Germany	1958–1973, 8 reactors	-6%	-63%
	1973–1983, 18 reactors	+12%	+200%
Japan	1960–1971, 11 imported reactors	-15%	-82%
	1970-1980, 13 foreign designs	+8%	+100%
	1980–2007, 30 domestic reactors	-1% to +1%	-17% to +33%
India	1964-1972, 5 imported reactors	-7%	-38%
	1971-1980, 8 domestic reactors	+5%	+150%
	1990–2003, 6 domestic reactors + 2 imported	-1%	-10%
South Korea	1972–1993, 9 foreign designs	-2%	-25%
	1989–2008, 19 domestic reactors	-1%	-13%

For the **reprocessing technologies variable costs**, UREX has the same three trends of reactors. Being a more mature technology, PUREX is expected to present a lower relative variation, resulting in +2%/yr for 5 years in N+ and a -2%/yr for 5 years in N-, and constant values from 2040 to 2050, while N= assumes a constant trend. A different evaluation has been made for pyroprocessing. Indeed, being still in an embryonal phase, its costs are higher with respect to other reprocessing options, and they are probably destined to decrease. Remembering that it is introduced in the model starting by 2040, it is kept constant costs in the worst scenario N+. In N= a decrease of -5%/yr up to 2045 and a -2%/yr up to 2050 is assumed, while in N- the decreasing annualized rate is -10% for the first 5 years and -5% for the last 5 ones. At the end of each scenario, it is still the most expensive reprocessing technology in terms of M$/t of reprocessed spent fuel and PUREX is always the cheapest one. All normalized costs are listed in Table 24.

To evaluate the influence they have on results, every possible combination of these values gives a scenario, resulting in 27 configurations, as shown in Figure 9. For easier visualization each scenario is called with a number X.Y in which X and Y correspond to large reactors and SMRs hurdle rates, respectively. This number is followed by +, = or –, representing the normalized costs trend of that scenario.

The last parameter is the **maximum installed capacity**. The analysis of a conservative scenario is presented in [57], which involves the implementation of a nuclear capacity which is half of the maximum potentially installable one. This scenario is used as a reference. However, remembering that nuclear technologies in the model have a discrete capacity, also maximum capacity will be rounded to be a multiple of them. In addition, it is decided to have no nuclear installation before 2040. So obtained values are reported in Table 25 (C2040).

Table 21. Projected GW Deployed and Nuclear Cost Change in the Conservative Scenario [33].

Year	Total Projected GW Nuclear Deployed	SMR % Cost Change Relative to 2030 Reference Value	Large Reactor % Cost Change Relative to 2030 Reference Value
2030	0	Ref	Ref
2035	1	4%	0%
2040	3	20%	4%
2045	6	30%	12%
2050	12	39%	23%

Table 22. Projected GW Deployed and Nuclear Cost Change in the Moderate Scenario [33].

Year	Total Projected GW Nuclear Deployed	SMR % Cost Change Relative to 2030 Reference Value	Large Reactor % Cost Change Relative to 2030 Reference Value
2030	1	Ref	Ref
2035	3	19%	4%
2040	8.5	34%	18%
2045	17	44%	28%
2050	34	50%	37%

Table 23. Projected GW Deployed and Nuclear Cost Change in the Advanced Scenario [33].

Year	Total Projected GW Nuclear Deployed	SMR % Cost Change Relative to 2030 Reference Value	Large Reactor % Cost Change Relative to 2030 Reference Value
2030	1	Ref	Ref
2035	14	41%	25%
2040	58	55%	43%
2045	124	61%	51%
2050	200	64%	55%

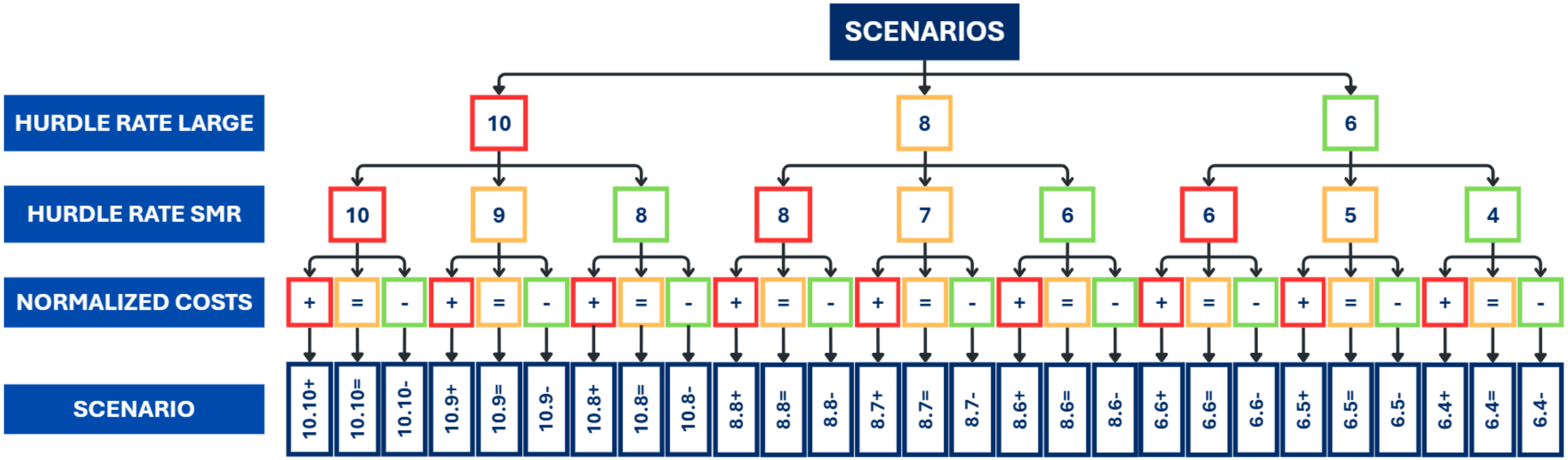

Figure 9. Parameters combinations defining the investigated scenarios.

Table 24. Investment costs in M$/GW including IDC depending on Hurdle Rate.

CostInvest (M$2022/GW)	Hurdle Rate						
	10%	9%	8%	7%	6%	5%	4%
L_LWR	6395	-	5813	-	5289	-	-
S_LWR	6229	6073	5922	5775	5631	5491	5355

Table 25. Values for maximum capacity.

Scenario	Maximum Capacity (GW)			
	2035	2040	2045	2050
C2040	0	1.6	3.2	8.0

Table 26. Normalized investment costs future trends in the different scenarios N+, N= and N-.

Scenario	TECHNOLOGY	2035	2040	2045	2050
N+	REACTORS [M€/M€]	1.00	1.28	1.41	1.41
	PUREX [M€/t]	1.00	1.10	1.10	1.10
	UREX [M€/t]	1.33	1.80	1.99	1.99
	PYRO [M€/t]	-	2.75	2.75	2.75
N=	REACTORS [M€/M€]	1.00	1.00	1.00	1.00
	PUREX [M€/t]	1.00	1.00	1.00	1.00
	UREX [M€/t]	1.33	1.33	1.33	1.33
	PYRO [M€/t]	-	2.75	2.13	1.92
N-	REACTORS [M€/M€]	1	0.77	0.70	0.70
	PUREX [M€/t]	1.00	0.90	0.90	0.90
	UREX [M€/t]	1.33	1.03	0.93	0.93
	PYRO [M€/t]	-	2.75	1.62	1.26

4.2 Conditions concerning policy targets and innovative reactors

An analysis is done to evaluate if the constraint on the first year in which nuclear installation is allowed has an influence on the results. C2045 and C2050 are obtained delaying the first year of 5 and 10 years respectively, starting in 2045 and 2050 instead of 2040. The evolution of this parameter in the three cases is shown in Table 27.

Table 27. Maximum capacity constraints.

Scenario	**Maximum Capacity (GW)**			
	2035	**2040**	**2045**	**2050**
C2040	0.0	1.6	3.2	8.0
C2045	0.0	0.0	1.6	3.2
C2050	0.0	0.0	0.0	1.6

Then, S_LFR and S_GCR are introduced. Given the lack of investment cost data for S_GCR and S_LFR, a sensitivity analysis was conducted to assess their economic competitiveness with respect to the other reactors. Starting with investment costs equal to those of S_LWR, costs were progressively increased by 1% up to identifying the value making S_GCR and S_LFR completely uncompetitive (no capacity deployed) with respect to the alternative reactors. This analysis is necessary because, having higher efficiencies, in the case of saturation of maximum capacity constraint they could be preferred to S_LWR to produce more energy with the same installed capacity. It must be remembered that these three types of reactors have different fuel cycles with different relative costs, but it has been already seen that the investment cost has the biggest impact.

Chapter 5

Results

This chapter introduces the scenario analysis results, focusing on the impact of the three abovementioned parameters – investment costs, hurdle rates, and capacity constraints – on the deployment and competitiveness of nuclear fission technologies within the Italian power sector. Firstly, an overview of nuclear technologies deployment in all the 27 scenarios introduced in Figure 9 is shown. Then, the analysis is carried out by comparing results from two different scenarios, to evaluate the overall effects of nuclear energy production on the system. The impact of varying the imposed maximum capacity is analyzed by applying the three above-mentioned constraints to the same scenario. Finally, results focusing on the potential role of S_GCR and S_LFR are presented.

Figure 10 presents the technology-specific distribution of total discounted costs (i.e., the objective function value) in non-nuclear scenarios, alongside the percentage cost variations observed across all other scenarios. In the non-nuclear case, total system costs amount to 330 B€, with reductions up to 0.4% in the other one. The majority of them are concentrated in natural gas, solar, and imported electricity, which together account for 74% of total expenditures, while other technologies play a more marginal role. While absolute differences in total system costs may appear modest when viewed at aggregate level, this representation highlights how specific technologies are differently affected by the presence of nuclear energy. Notably, its deployment leads to a consistent reduction in natural gas and solar-related expenditures – around 2–3% on average – suggesting a partial substitution effect. Geothermal costs show a sharper decline (12.5%), but this is primarily due to their limited absolute contribution to total system costs, while other technologies remain mostly unaffected.

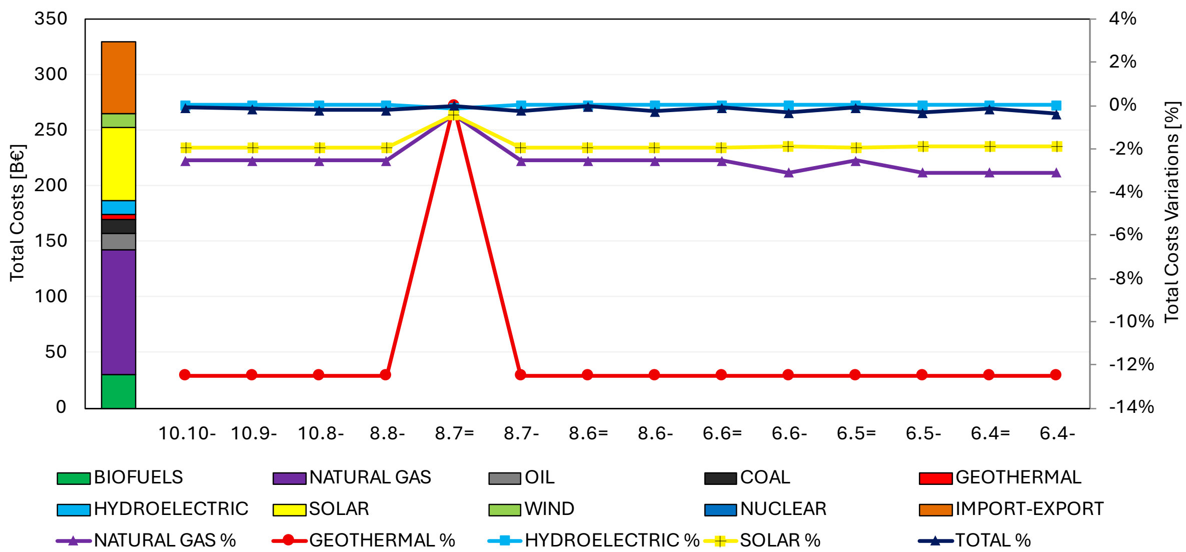

Figure 10. Discounted costs by technology in the non-nuclear scenarios (stacked column and vertical-left axis) and percentage deviations across the other scenarios (lines and vertical-right axis).

5.1 Key determinants of nuclear fission cost-competitiveness

The total installed nuclear reactors capacity in each scenario is reported in Figure 11, including information about type of reactor selected, hurdle rates and normalized costs trends. Scenarios are ordered according to the following hierarchy: decreasing L_LWR hurdle rates, decreasing S_LWR hurdle rates, normalized costs from pessimistic to optimistic. Nuclear technologies are installed in 14 of the 27 scenarios. In particular, in the scenarios with pessimistic normalized costs trend, nuclear is never selected by the model. On the contrary, there is always nuclear deployment whit optimistic normalized costs, meaning that such parameter is significantly influential. It can be noticed that, apart from scenario 8.7=, the installed capacity in 2050 assumes only two values, which are 8 GW (equal to the maximum capacity constraint) or 0. This fact suggests that the model could consider adding other nuclear capacity as economically convenient if higher constraints were considered.

Due to longer construction time and, consequently, higher IDC, hurdle rates have a heavier influence on L_LWR with respect to S_LWR. In particular, L_LWR is the optimal choice when its hurdle rate equals 8% and the S_LWR one. On the contrary, when the hurdle rate of L_LWR is 6%, such reactors prevail except when the hurdle rate of S_SMR is 4%. In all the other cases S_LWR is preferred.

Concerning costs, it is important to note that the model minimizes the total system cost. Being these scenarios free from other constraints (e.g., emission limits), those with nuclear installation have lower total costs with respect to the others. Figure 12 illustrates this difference in undiscounted total system costs, showing for each scenario costs trends and the type of reactor installed (S_LWR or L_LWR) with its relative hurdle rate (hurdle rate for the not selected reactor is not shown). Given that, it must be noticed that 6.6= results equal to 6.5= – they both have L_LWR with 6% hurdle rate and constant costs –, so only one of the two is represented to avoid redundancy, and the same applies for 6.6- and 6.5-. It appears clear that normalized cost trends play a crucial role: all scenarios with decreasing costs show greater cost reductions compared to those with constant trends. Lower hurdle rates result in reduced total costs, but the magnitude of this effect is much more pronounced with L_LWR (2 B€ from 6% hurdle rate to 8%) than with S_LWR (only 60 M€ from 6% to 8%). However, scenarios with L_LWR deployment show greater savings then the ones with S_LWR under similar hurdle rates –2.6 B€ with 6% hurdle rates, 0.7 B€ with 8%–, indicating a higher competitiveness of large reactors when financing conditions are equal. In all nuclear scenarios, the cumulative undiscounted costs for nuclear technologies over the entire time horizon range between 32 and 37 B€. The lowest total cost is observed in scenario 6.4-, with a value 1.2% lower than non-nuclear ones. The latter total costs are about 925 B€, with a difference of approximately 11.7 B€. This means that system-wide savings correspond to roughly 33% of the nuclear investment, highlighting the economic benefit of nuclear deployment under certain economic conditions.

While decreasing cost trends represent supply-side improvements – potentially driven by economies of series and industrial maturity – favorable financing conditions are instead driven by political and institutional decisions. From this point of view, dedicated policies can be crucial from both international (e.g. in 2022 the European Parliament inserted nuclear in EU taxonomy [58], while in 2025 World Bank announced the ending of its ban on providing funding for nuclear energy project [59] and formalized a partnership with IAEA to collaborate in supporting nuclear energy in developing countries [60]) and national (e.g. in 2022, the Inflation Reduction Act extended clean energy tax incentives to nuclear energy in USA, while in 2023 Long-Term Decarbonised Capacity Auction promoted investments in low-carbon power sources, including nuclear, in Japan [2]) side.

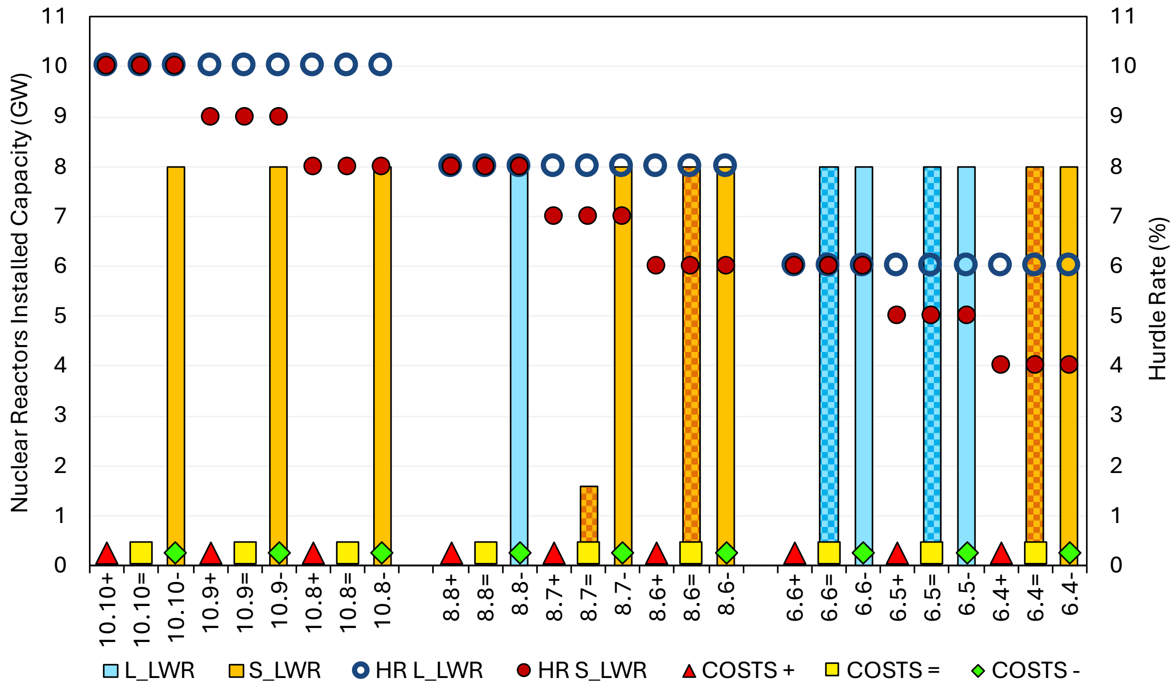

Figure 11. Total installed nuclear reactors capacity in each scenario with relative hurdle rates and costs trend.

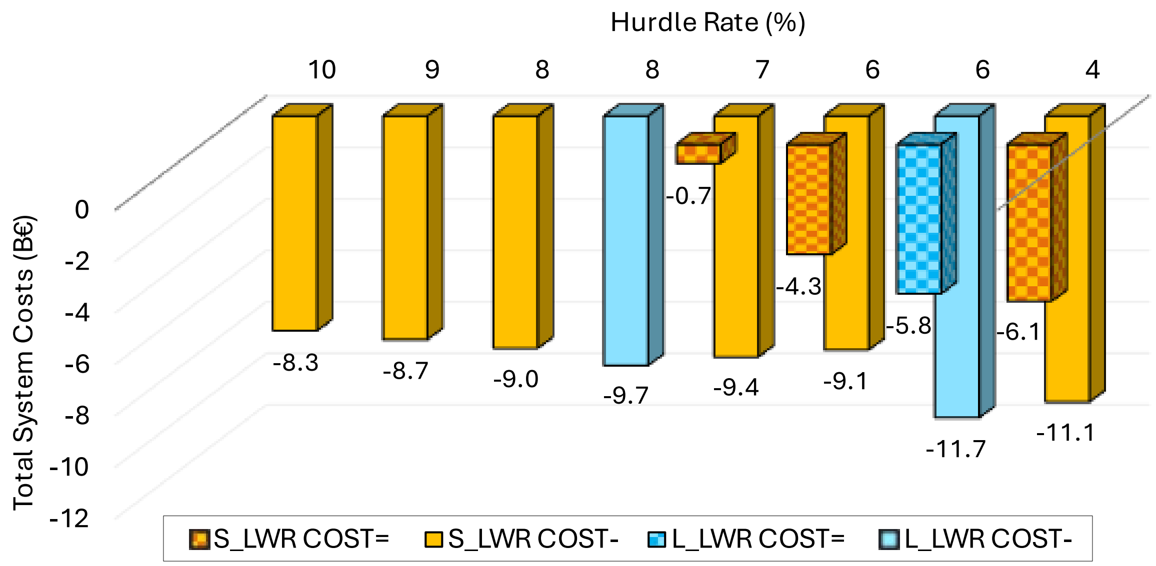

Figure 12. Total system cost difference in scenarios with nuclear deployment depending on type of reactor installed and hurdle rate.

Subsequently, an analysis to understand the impact of nuclear energy introduction is carried on. Two scenarios are selected: 6.6+, with rising normalized costs and no nuclear installation, and 6.6-, with the same parameters, apart from decreasing normalized costs, and where the maximum nuclear capacity constraint is saturated. A comparison is made in terms of new installed capacity for each technology, the portion of electricity demand satisfied by each technology, emissions and material consumption.

In Figure 13 the difference between new installed capacity in 6.6- and 6.6+ from 2025 to 2050 is shown for each energy technology. In absolute values, natural gas and solar are the most negatively affected technologies by nuclear deployment, with -7.3 GW (corresponding to -9%) and -11.1 GW (-12%) installed, respectively. Hydroelectric power difference is -0.9 GW (-3%) while all the 1.4 GW of new geothermal installed capacity in 6.6+ is absent in 6.6-. Thanks to the higher capacity factor (0.94 compared to 0.34 for natural gas, an average of 0.23 for solar, 0.20-0.30 for hydroelectric and approximately 0.90 for geothermal), nuclear technologies can substitute electricity production from all such options with 8 GW of capacity.

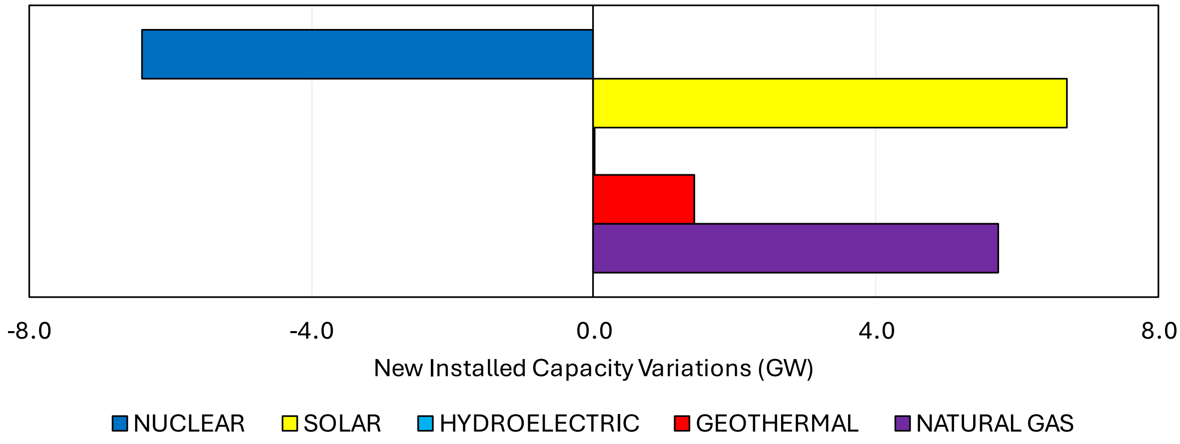

Figure 13. New installed capacity variation from 6.6+ to 6.6- for each power technology between 2025 and 2050.

The demand satisfied in 2050 by each energy technology from 2040 to 2050 is represented in Figure 14. Looking at 2050 in scenario 6.6- nuclear replaces 128 PJ of electricity produced by natural gas (-17%), 60.4 PJ from solar (-15%) and all the 36.8 PJ from geothermal. Nuclear produces a total of 225.3 PJ in 6.6-, corresponding to 15% of 2050 electricity demand. The latter is still largely satisfied by natural gas (43%) in 6.6- but with a significative reduction with respect to 6.6+ (51%). In particular, energy produced by natural gas in 6.6+ has only a reduction of 5% from 2040 to 2050, while in 6.6- this difference is -17%.

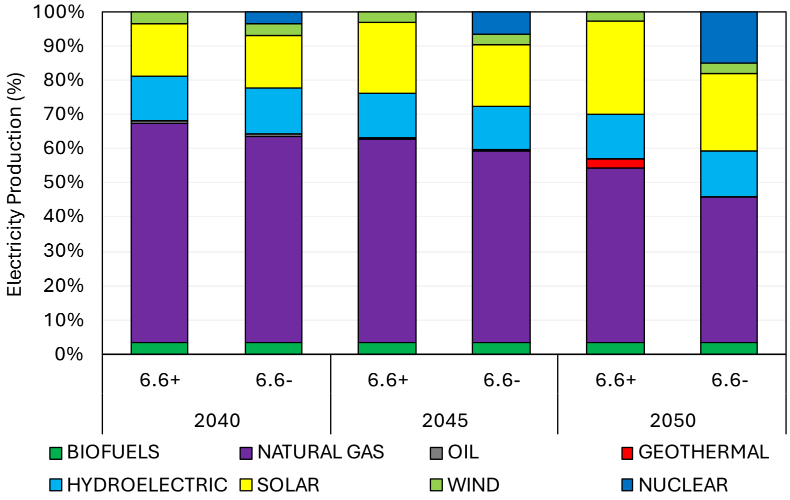

Figure 14. Electricity produced by each power technology between 2040 and 2050 in 6.6+ and 6.6-.

5.2 Environmental impacts: GHGs emissions and materials consumption

As expected, nuclear deployment has an impact on CO_2 equivalent emissions, which evolution from 2035 to 2050 in scenarios 6.6+ and 6.6- is represented in Figure 15. They are computed multiplying each greenhouse gas emissions by the relative Global Warming Potential (GWP), e.g. 1 for carbon dioxide, 25 for methane and 298 for nitrous oxide [61]. It can be noticed that there is a reduction of 6% in 2040 and the same applies for 2045, while in 2050 the difference is more relevant, registering -17%. This is due to the substitution of natural gas combined cycle power plants, with their almost 400 kt/PJ of CO_2 equivalent emissions. It must be underlined that these results are obtained without emissions constraints, so in this scenario nuclear is substituting gas thanks to economic convenience and, at the same time, reducing emissions. Additionally, it is clear that this scenario is not enough for reaching 2050 carbon neutrality, since total CO_2 equivalent emissions are the same as 2025. On the other hand, the electricity demand in 2050 is 45% higher than 2025, resulting in a lower global emission factor of the system and suggesting the need of more investments in clean energy technologies.

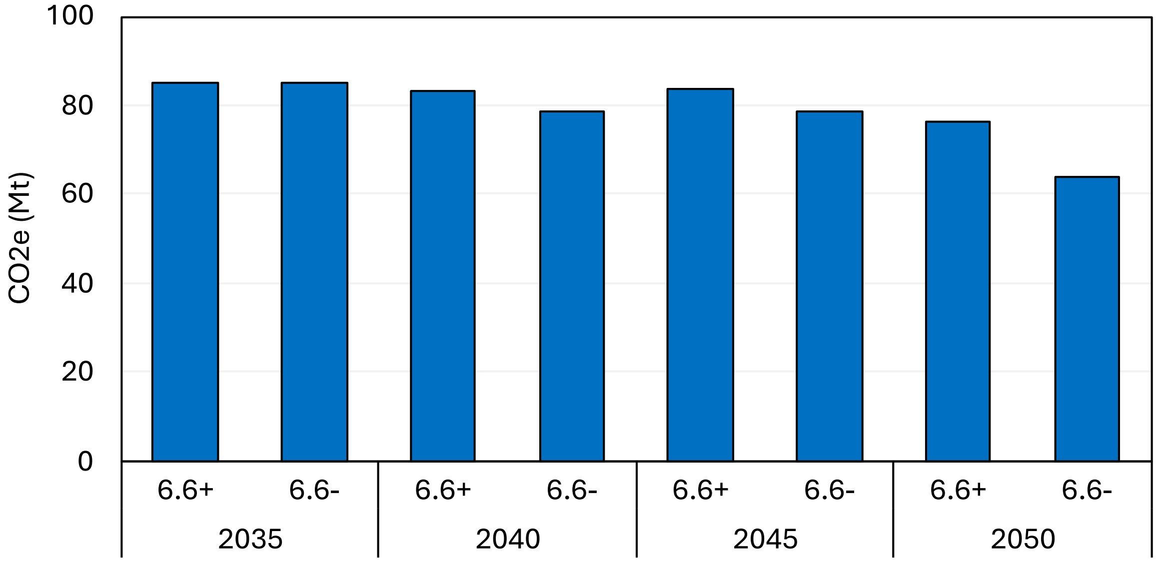

Figure 15. CO_2 equivalent emissions between 2035 and 2050 in 6.6+ and 6.6-.

For what concerns the critical raw materials (CRMs), their consumption for energy technologies is accounted by including in the TEMOA formulation a material intensity parameter measuring the consumption of CRMs per unit of additional capacity installed, as detailed in [62], [63]. Figure 16 shows the CRMs consumption for power sector technologies from 2040 to 2050. A first analysis can be conducted on the scenario 6.6+, considered as a "reference" in the absence of nuclear. It can be noticed that in 2045 material consumption is smaller than 2040, but then, in 2050 it is significantly higher. The main responsibility lies with geothermal new capacity, which causes new demands of Chromium and Nickel for 140 and 810 times the 2045 ones, respectively. In addition, the solar grown causes higher need of Aluminum, Copper and Silicon. However, these last ones are less than double with respect to 2045's values. The impact of introducing nuclear technologies can be evaluated by looking at variations in scenario 6.6- with respect to 6.6+ in some of the most used materials. Aluminum has an increase of 3 kt (+2%) in 2040 due to both solar and nuclear, while in 2045 and 2050 the lower deployment of solar power allows to save 60 (-43%) and 20 (-7%) kt, respectively. Copper behavior is similar to Aluminum one, with almost the same variations. Chromium used in nuclear reactors is more than the quantity saved by reduction of natural gas in 2040 and 2045 (+7 kt), but the absence of new geothermal capacity in 2050 contributes to a total saving of 70 kt (-74%). Silicon is the material with the most relevant increase due to nuclear, not in absolute terms (changes are in the order of 1 kt) but in percentage, where variations are around +1000%. The heaviest reduction regards Nickel, despite an increase of about 6 kt in 2040 and 2045, which has 160 kt (-90%) of material saved in 2050, mostly due to natural gas lower usage. These results are relevant considering the supply characteristics of these materials. In fact, China has been the major global supplier of Aluminum (59%) [64], refined copper (45%, Democratic Republic of the Congo is the second one with 8%) [65], final nickel chemicals (60%) [65] and high-purity silicon (95%, followed by Germany with 2.5%) in 2024, even not being their first mining country [65]. Chromium is the only one with a different situation, since China's external dependence exceeds 99% [66], while the most important supplier is South Africa [67].

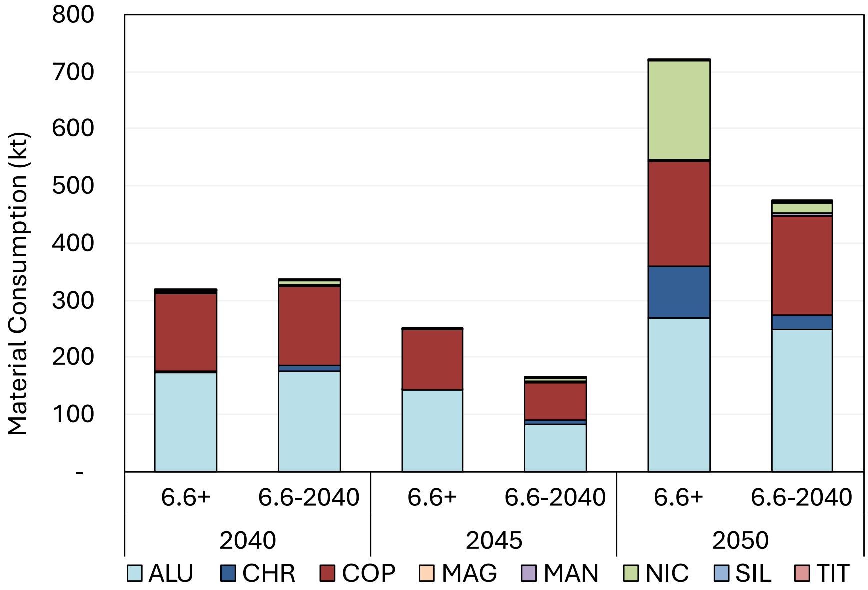

Figure 16. Material consumption between 2040 and 2050 in 6.6+ and 6.6-.

5.3 Effect of different policy constraints

The effects of maximum nuclear capacity constraints are evaluated by applying the 3 different configurations in Table 27 to scenario 6.6- (from this point it will be referred to as 6.6-2040), obtaining two new scenarios: 6.6-2045 and 6.6-2050. Looking at new installed capacity in Figure 17, delaying nuclear introduction by 5 years causes the installation of 3.8 more GW of natural gas (+5%) in 6.6-2045, together with 1.4 GW of geothermal capacity (which has no new capacity installed in 6.6-), 0.5 GW (+2%) of hydroelectric and 5.5 GW (+7%) of solar. If the delay is 10 years, the additional capacity is composed of 5.7 GW of natural gas (+8%), 1.4 GW of geothermal and 6.7 GW (+8%) of solar in 6.6-2050. These results – in particular the ones related to natural gas – show the importance of anticipating nuclear plants construction.

In terms of energy produced (Figure 18), the reduced nuclear capacity produces a vacuum of electricity in 2050 of 135 PJ in 6.6-2045 and 180 PJ in 6.6-2050. In the first case, this void is filled by 67 PJ (+11%) from natural gas, 37 PJ from geothermal and 31 PJ (+9%) from solar. In 6.6-2050 the compensation is composed of 104 PJ (+16%) from natural gas, 37 PJ from geothermal and 39 PJ (+12%) from solar.

The impact on emissions (Figure 19) is relevant as well, having an increase of 6% in 2040, 2% in 2045 and 10% in 2050 from 6.6-2040 to 6.6-2045. In 6.6-2050 the emission growth is even higher in 2045 (+6%) and 2050 (+16%). Again, this variation must be attributed to natural gas different deployment.

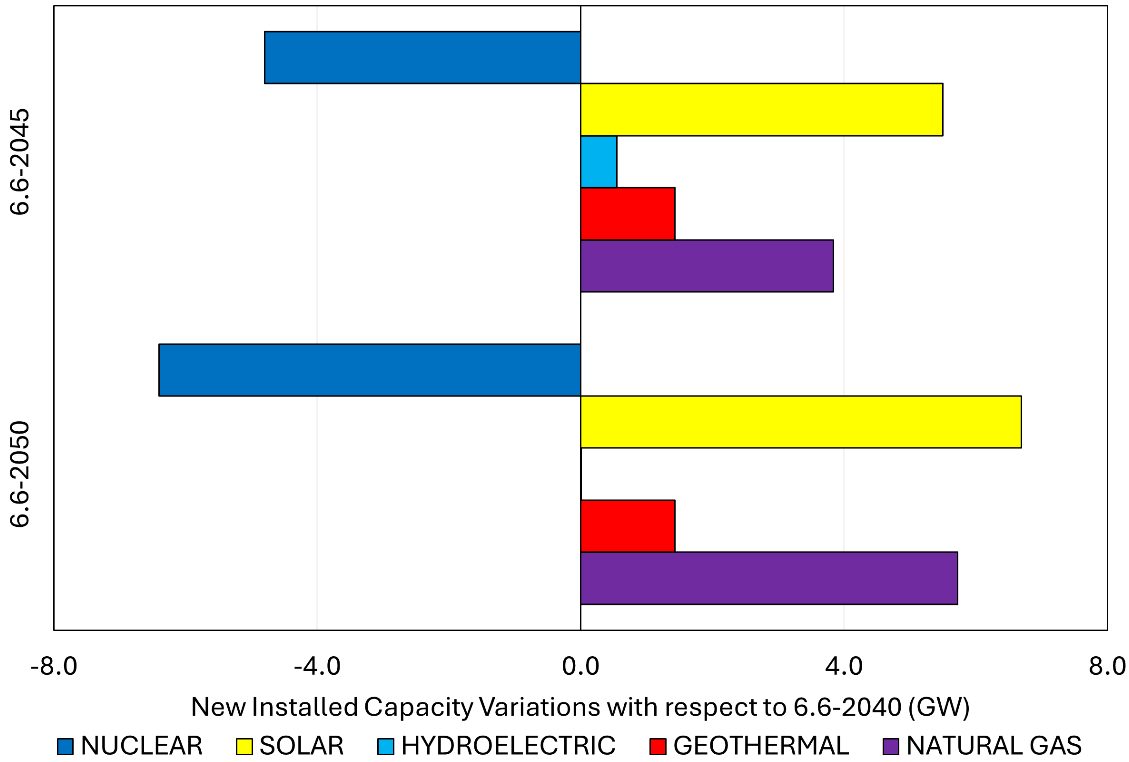

Figure 17. New installed capacity variation in 6.6-2045 and 6.6-2050 with respect to 6.6-2040 for each power technology between 2025 and 2050.

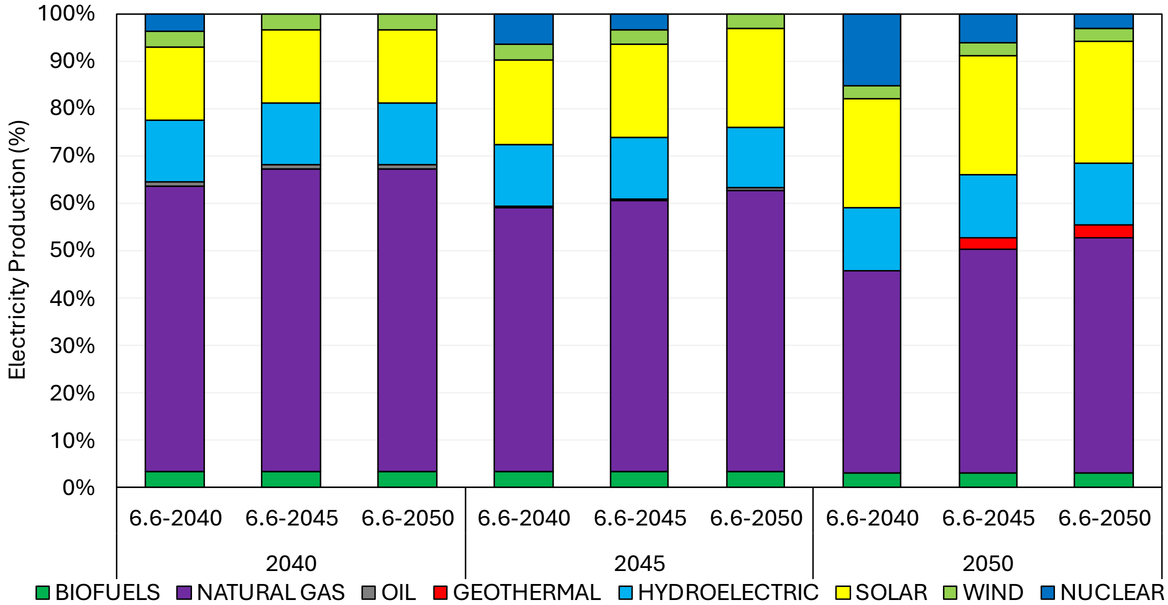

Figure 18. Electricity produced by each power technology between 2040 and 2050 in 6.6-2040, 6.6-2045 and 6.6-2050.

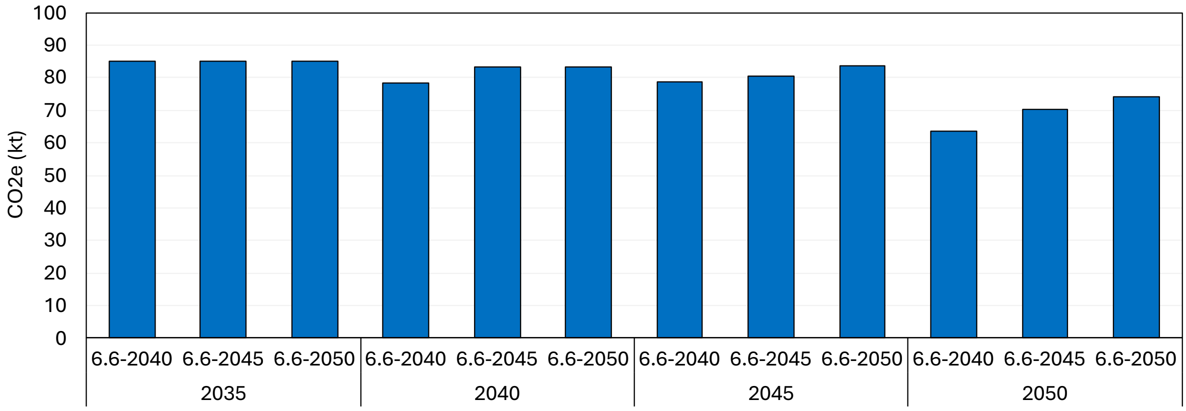

Figure 19. CO_2 equivalent emissions between 2035 and 2050 in 6.6-2040, 6.6-2045 and 6.6-2050.

The effects on materials (Figure 20) are different depending on nuclear introduction delay. Scenario 6.6-2050 has results similar to the ones obtained with scenario 6.6+, apart from 2050, where nuclear starts to be installed. In this time period, materials affected by the biggest demand increase are Chromium (+74 kt) and Nickel (+160 kt), whose demand are 4 and 10 times respectively the 6.6- one. On the contrary, Silicon has a reduction of 64%, even this value corresponds to a much smaller quantity (1.6 kt). Despite the delay limited to 5 years, 6.6-2045 material consumptions are more similar to 6.6+ than 6.6-. This is largely due to the fact that 6.6- is the only scenario with no new installation of geothermal capacity, that, as previously remarked, is the largest source of demand for Chromium and Nickel. In the context of emissions reduction policies, different clean technologies can have substantially different impacts on material consumption, with important implications for supply chain sustainability.

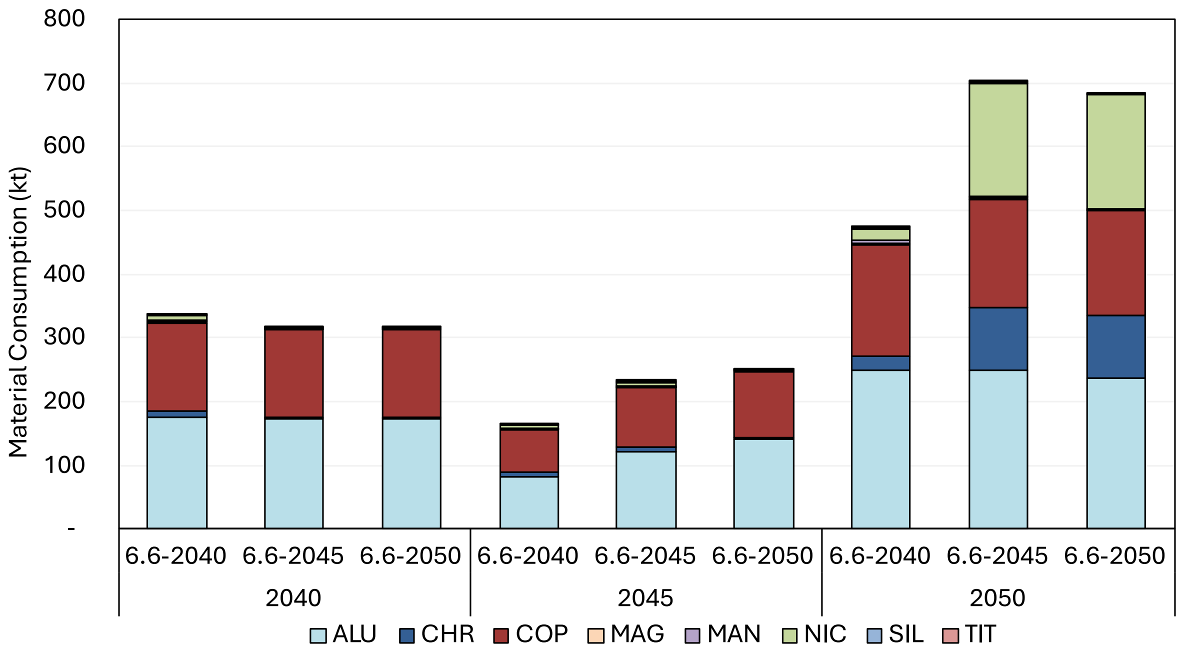

Figure 20. Material consumption between 2040 and 2050 in 6.6-2040, 6.6-2045 and 6.6-2050.

5.4 The influence of the cost of capital

With the aim of having a representative set of scenarios for different economic situations, the analysis on S_LFR and S_GCR investment cost is conducted on scenarios in which SMRs hurdle rate is 1% lower than L_LWR one. The ones with pessimistic normalized costs trend are not considered because they have no nuclear installation, so the object of this study are 10.9=, 10.9-, 8.7=, 8.7-, 6.5= and 6.5-. S_LFR is never selected by model, which always prefers S_GCR instead. Ratios between S_GCR installed capacity in 2050 and maximum capacity constraint of 8 GW are reported in Figure 21. In 10.9=, there is no nuclear installation even in the case of S_GCR investment costs equal to S_LWR one. 8.7= has S_GCR installation up to +8% investment cost, but ratio is smaller than 100% starting from +6%, while it is 100% up to +9% cost in 6.5=. 10.9-, 8.7- and 6.5- have no S_GCR installation from +12%, +13% and +14% respectively. It can be noticed that S_GCR is more competitive in scenario 10.9-, with 9% hurdle rate and constant normalized costs, than in scenario 6.5=, with 5% hurdle rate and decreasing normalized costs. This fact suggests once again that normalized costs trends have a higher impact on nuclear technologies competitiveness than other parameters like initial investment costs or hurdle rates.

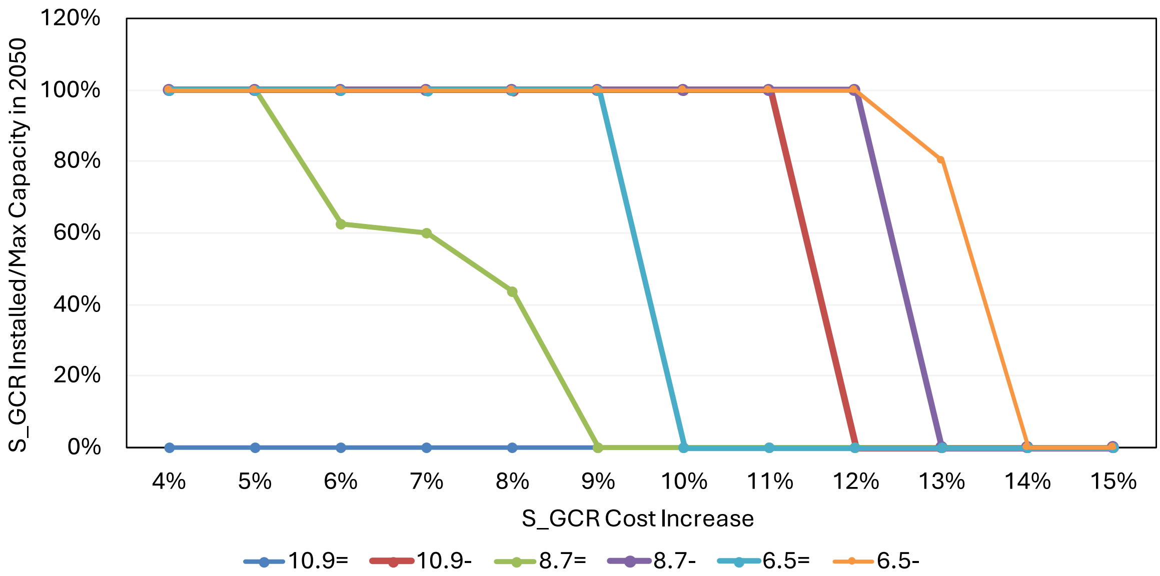

Figure 21. Ratio between S_GCR installed capacity in 2050 and maximum capacity constraint.

The same analysis is conducted on S_LFR excluding S_GCR by the model (Figure 22). It can be noticed that results for 6.5=, 10.9- and 8.7- are exactly the same as the previous ones but shifted by -2%, while 6.5- difference is -3%. In 8.7= the decreasing trend is again irregular, ending with no installation in case of a cost increase of 6%.

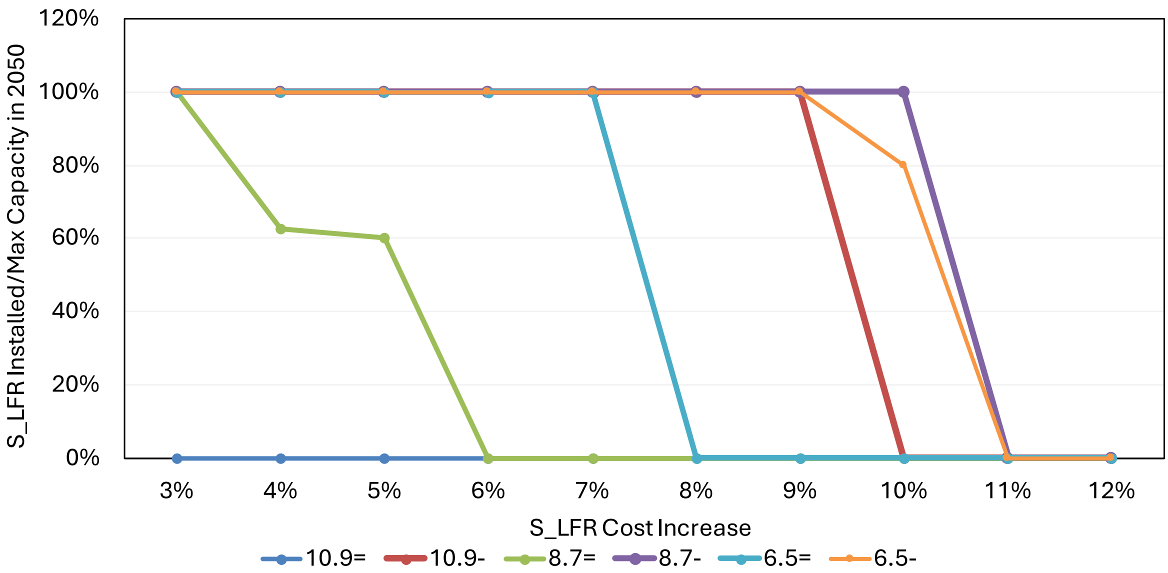

Figure 22. Ratio between S_LFR installed capacity in 2050 and maximum capacity constraint.

Chapter 6

Conclusions

This thesis examined the potential role of nuclear energy in decarbonizing the Italian power sector through a detailed implementation of nuclear technologies in the open-source Energy System Optimization Model TEMOA. The work introduced an extended nuclear module incorporating the full fuel cycle and the techno-economic characteristics of Generation III+, Generation IV and Small Modular Reactors (SMRs). Scenario analysis showed that nuclear energy can play a relevant role in long-term decarbonization pathways, particularly under conditions of favorable financing. Large-scale reactors emerge as the optimal choice when their hurdle rate remains moderate – 6 or 8% –, benefiting from economies of scale. Conversely, SMRs tend to be the preferred option in scenarios where their financing conditions are more favorable – e.g. when their hurdle rate is lower than that of traditional large reactors. Creating suitable financing frameworks through national and international policies may be key to unlocking nuclear investment. Under supportive financial conditions, nuclear deployment may contribute to lowering system-wide mitigation costs and reducing pressure on critical material demand. Overall, the study highlights the importance of technology-neutral planning approaches and robust scenario analysis in supporting evidence-based policymaking. Nuclear energy should not be seen as a competitor to renewables, but rather as a flexible, low-carbon complement within a diversified energy mix.

Some limitations must be acknowledged. Firstly, the analysis is focused on a techno-economic dimension, neglecting some political or social factors (e.g. regulatory delays or public acceptance) that could be relevant. Secondly, assumptions on costs are based on estimates from literature, but they are subject to uncertainty. Moreover, although the results sensitivity on the assumptions for the cost of capital for nuclear plants has been investigated through devoted scenarios, the hurdle rates for other technology groups were not varied from the reference values, since their shorter lifetime and the lower capital cost combined with the future projections for cost reductions makes the cost of capital a less critical issue in determining their cost-competitiveness. Additionally, this study focuses exclusively on the power sector, without considering the impacts in other sectors such as industry, transportation or residential. The model is spatially aggregated in a single region, which limits the ability to capture geographic heterogeneity in resource availability or demand distribution. The time horizon of this study is limited to 2050, neglecting possible effects of some parameters like the long lifetime of nuclear reactors. Finally, the model does not include an explicit representation of the electricity grid. These simplifications may affect the accuracy of results in scenarios where spatial or infrastructural factors are critical.

Several directions emerge for future research. The modeling framework can be used to explore the effects of specific energy and climate policies, crisis scenarios (e.g., fuel and material supply partial or total disruptions) or other technologies investment cost evolutions and hurdle rates. It can also be used to assess the land footprint of nuclear fission reactors deployment. Beyond electricity, nuclear can also provide process heat for district heating, desalination, and industrial heat. Future developments could expand the model to the industrial sector – in particular to investigate the potential role of high-temperature reactors in providing process heat – or integrate waste heat recovery systems for district heating applications in the residential sector. These aspects could be explored using TEMOA-Italy complete energy model or implementing other single sectors only. The time horizon of this study could be expanded beyond 2050, evaluating very long-term effects of nuclear introduction in an energy system.

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