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Economics of nuclear power plants: bottom-up cost estimation model for Small Modular Reactors

TESI DI LAUREA MAGISTRALE IN
MANAGEMENT ENGINEERING

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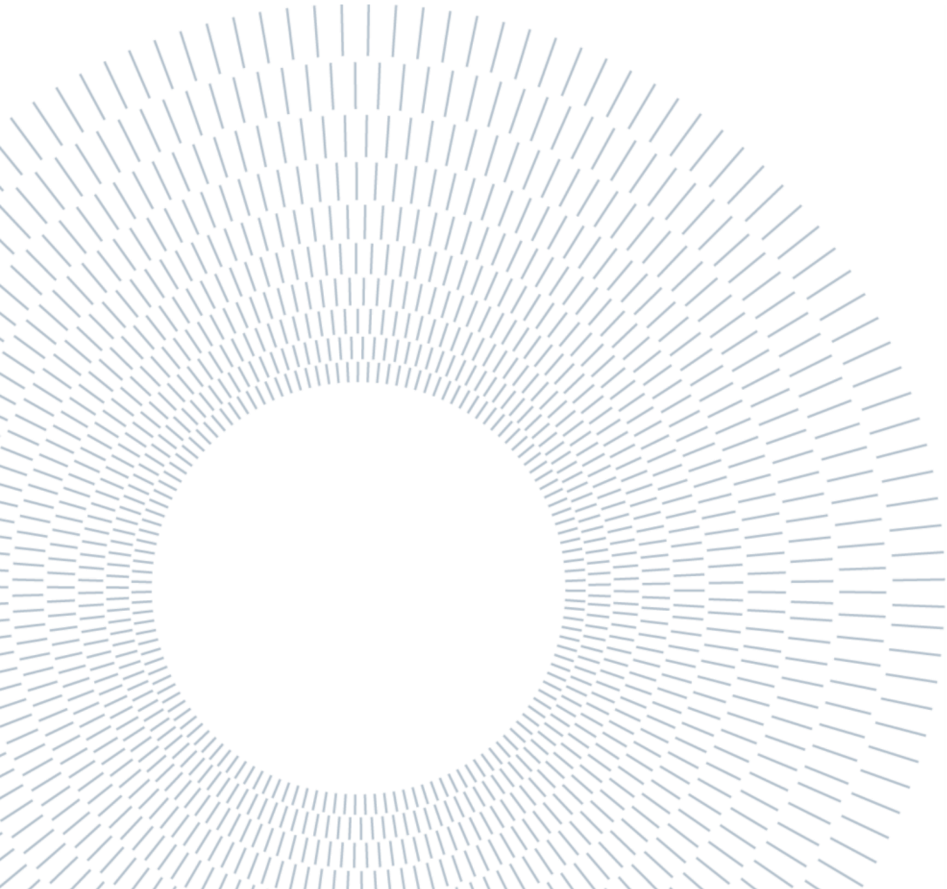

Abstract

As recent history has shown, the construction of large, increasingly complex reactors has led to a dramatic escalation in costs, jeopardising the execution of construction projects and alienating potential investors. SMRs target a smaller market and shift the focus from economies of scale to economies of multiples. Factors such as modularization, passive safety systems and co-siting economies are not considered by top-down cost estimation models based on traditional PWRs. These models will overestimate the costs of NPPs by only charging them for the loss of economies of scale. Therefore, innovative, and more elaborate estimation models capable of capturing all the nuances of designs based on SMRs, are needed. To this end, the Thesis proposes a bottom-up cost estimation, based on the development of specific equations for each cost item defined by the Code of Accounts, proposed by the DOE. The most impactful components of the nuclear power plant, such as the Reactor Pressure Vessel, are discriminated and estimated through detailed cost analysis in collaboration with experienced Italian manufacturers. Other items, such as those related to the civil constructions, are estimated using information from secondary sources, while less relevant items are estimated using traditional methods based on scale factors, considering the impact of SMRs based NPPs characteristics. This approach led to the construction of a model with an estimated accuracy of -30%/+50%. Which was then tested on the two extreme SMR concepts: IRIS with an output of 335MWe and NuScale of 77MWe. Considering the two-module plant of IRIS an Overnight Capital Cost of 2,880 €/kWe is estimated with reference to nth facility built. For NuScale's 12-module plant an OCC of 3,250 €/kWe is estimated. On the other hand, considering an OCC of 3,080 €/kWe for traditional PWR, the results obtained for SMRs demonstrate their competitiveness. The importance of adopting the bottom-up cost model is evident when comparing the values obtained with those derived from the scaling relationships, respectively 9,064 €/kWe and 5,034 €/kWe, for NuScale and IRIS plants respectively.

Key-words: SMR, Cost Estimation, Bottom-up, IRIS, NuScale

Abstract in lingua italiana

Come la storia recente dimostra, la costruzione di grandi reattori, sempre più complessi, ha portato a una drammatica escalation dei costi mettendo a rischio l'esecuzione dei progetti e allontanando i potenziali investitori. Gli SMRs puntano a un mercato più piccolo, spostando l'attenzione dall’ economie di scala a quelle dei multipli. Fattori come modularizzazione, sistemi di sicurezza passivi e economie di co-siting, non sono considerati dai modelli di stima top-down basati su PWRs tradizionali. Questi, infatti, sono destinati a sovrastimare i costi delle NPPs addebitando loro solo la perdita di economia di scala. Pertanto, sono necessari modelli di stima innovativi capaci di catturare tutti i vantaggi dei progetti basati su SMRs. A tal fine, la Tesi propone una stima dei costi bottom-up, fondata sullo sviluppo di modelli specifici per ogni voce di costo definita dal Code of Accounts proposto dal DOE. I componenti più rilevanti della NPP, come il Reactor Pressure Vessel, sono discriminati e stimati attraverso equazioni di costo definite in collaborazione con esperti produttori italiani. Altre voci, come quelle relative alla parte civile, sono stimate utilizzando informazioni da fonti secondarie, mentre le voci meno rilevanti sono stimate con metodi basati su fattori di scala, sempre considerando l'impatto delle caratteristiche delle NPP basate su SMRs. Questo approccio ha portato alla costruzione di un modello con un'accuratezza stimata di -30%/+50%. Questo è stato poi testato sui due concetti estremi di SMR: IRIS con una potenza di 335MWe e NuScale di 77MWe. Considerando l'impianto a due moduli di IRIS un Overnight Capital Cost di 2880 €/kWe è stimato facendo riferimento all’ennesimo impianto costruito. Per l'impianto di NuScale a 12 moduli, un OCC di 3250 €/kWe è stato stimato. D’altra parte, prendendo in considerazione un OCC di 3080 €/kWe relativo a PWRs tradizionali, i risultati ottenuti per gli SMRs dimostrano la loro competitività. L'importanza di adottare il modello di costo bottom-up è evidente quando si confrontano i valori con quelli derivati dalle relazioni di scala, cioè 9064 €/kWe e 5034 €/kWe, relativi agli impianti di NuScale e IRIS.

Parole chiave: SMR, Stima dei Costi, Bottom-up, IRIS, NuScale

Contents

Introduction

Nuclear power around the world

In 2020, the world nuclear fleet, composed of 448 operating reactors with a capacity of 397.78 GW, supplied 2553.2 TWh of electricity worldwide [1], representing 10.1% of global commercial gross electricity generation, Figure 1.

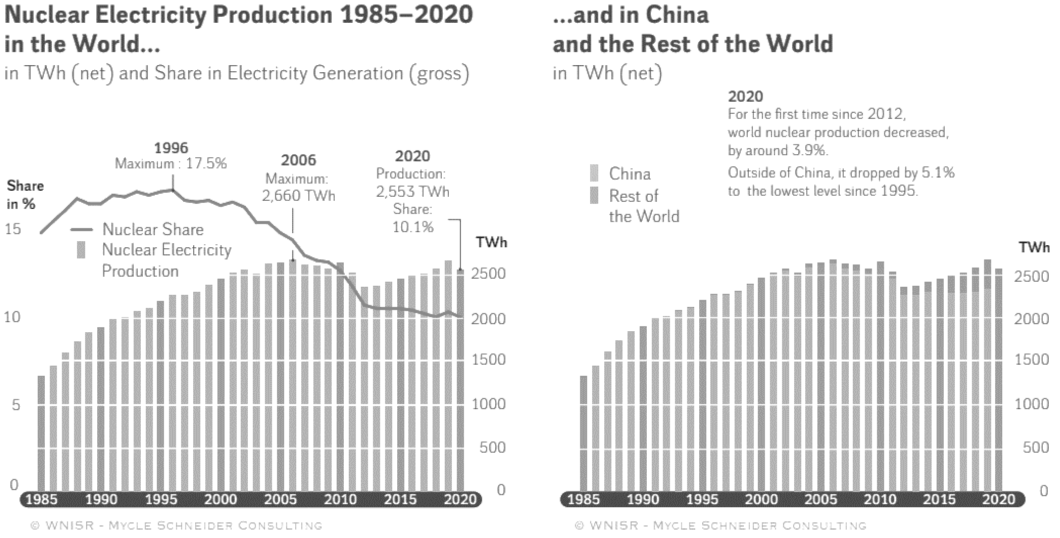

Figure 1 Nuclear Electricity Production 1985-2020, source: WNISR

The three main countries that leverage on this technology for producing electric power are respectively: United State of America (789.92 GW(e)), China 344.75 GW(e) and France (338.67 GW(e)). The Asian country overcame the European one during 2020 and currently represents the main promoter of nuclear energy, with 14 reactors under construction that account for a total additional net electrical capacity of 13.77 GW [1][2], Figure 2.

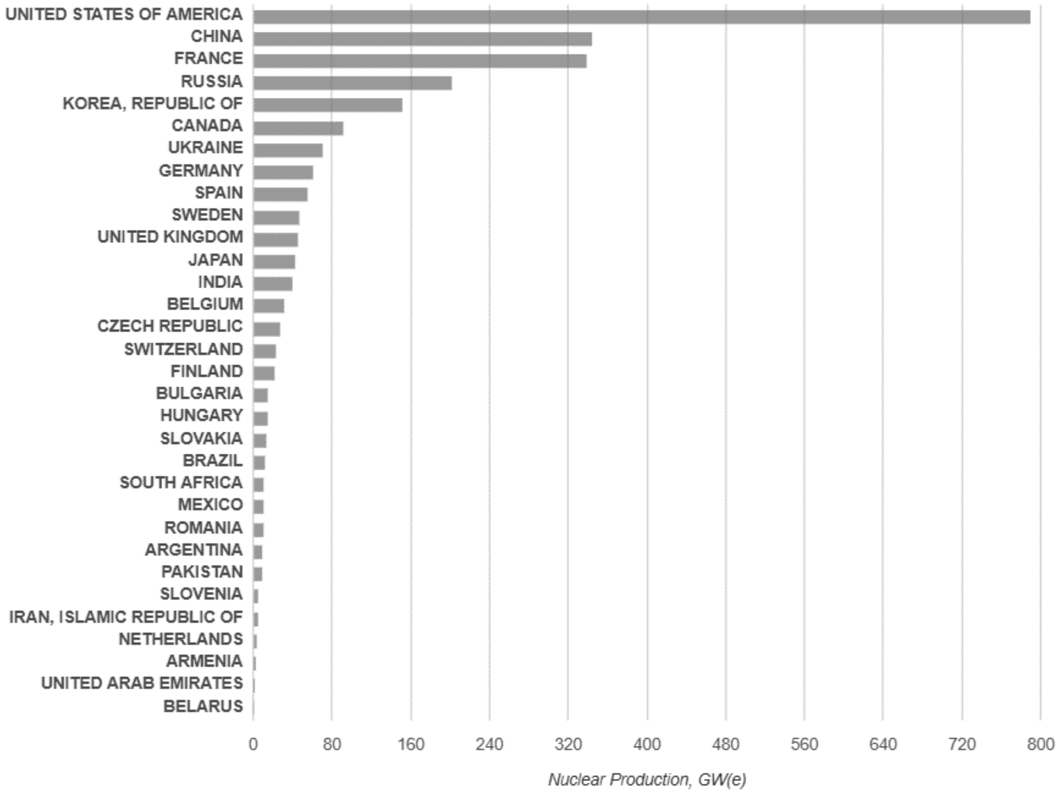

Figure 2 Nuclear production by countries

Nuclear reactor categorization and history

Nuclear reactor designs are categorised by "generations": Generation I, Generation II, Generation III, Generation III+ and Generation IV. The first three generations of nuclear power systems derived from design originally developed for naval use beginning in the late 1940s [3].

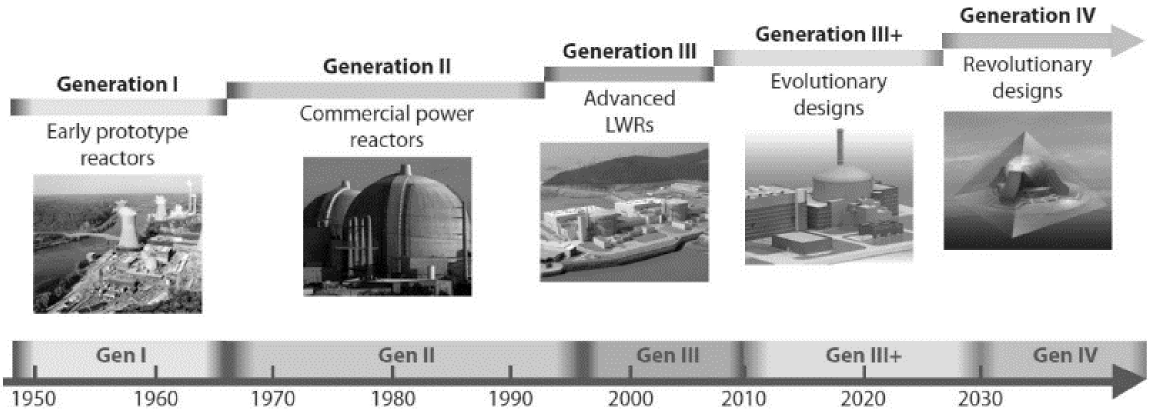

Figure 3 Nuclear reactors generations

Generation I

Generation I reactors represent the first civil use of nuclear power. This generation refers to early reactor prototypes from the 1950s and 1960s, like Shippingport (1957–1982) in Pennsylvania, Dresden-1 (1960–1978) in Illinois, and Calder Hall-1 (1956–2003) in the United Kingdom [3]. Nowadays no reactor of this generation is still operating: the last Magnox power station in the world, Wylfa, stopped generating electricity on 30 December 2015 [4].

Generation II

Generation II reactor types are: Pressurized Water Reactors (PWR); CANada Deuterium Uranium reactors (CANDU); Boiling Water Reactors (BWR); Advanced Gas-Cooled Reactors (AGR) and Vodo-Vodyanoi Energetichesky Reactors (VVER). Most of the Gen II commercial plants built (more than 400) leverage on the BWR and PWR technology, also called Light Water Reactors (LWR). This type of reactor is equipped both with active and passive safety systems. The core damage events are 10^{-5} per reactor year for the BWR [3]. Gen II Nuclear Power Plants were implemented from the late 1960s up to the 2010s and were initially designed with a lifetime of 40 years, but most of them renewed their licenses. In the U.S, the lifecycle of 90% of the plants was extended up to 60 years, moreover, if new plants will replaced the old one, it is planned to increase their operativity for another 20 years [5]. Most of the operative nuclear power plant today used Gen II technology [6]. The main western manufacturing companies are: Westinghouse, Framatome (now part of AREVA), and General Electric (GE) [3].

Generation III

Generation III nuclear reactors can be considered as Gen II reactors with state-of-art design improvement [3], they began to emerge in the mid-1980s onwards, based on learning from the Three Mile Island and Chernobyl accidents [6]. These new reactors embed enhancement in the areas of fuel technology, thermal efficiency, modularized construction, safety systems and standardised design. Improved safety features allowed to reduce the core damage frequency up 6×10^{-7} core damage events per reactor year, for the EPR and 3×10^{-8} core damage events per reactor year, for ESBWR. The estimated lifetime of Gen III nuclear power plant is 60 years with a concrete possibility to extend their life [3]. Different concepts bearing the labels GEN III and GEN III+ are in various stages of development and implementation today. The most important are LWRs. Considering the PWRs, the principal large designs are APWR (Mitsubishi Heavy Industries (MHI)/ Westinghouse), APWR+ (MHI), EPR (AREVA), AP-1000 (Westinghouse), KSNP+ and APR-1400 (Korean Industry) and the CNP-1000

(China National Nuclear Corporation). Regarding the Russian VVERs, an advanced VVER-1000 has been developed by Atomenergoproject and Gidropress. The main small and medium-size advanced PWR designs are the AP-600 (Westinghouse) and the VVER-640 (Atomenergoproject and Gidropress). Passing to the BWR, the main large concepts are the ABWR, (Hitachi, Toshiba, GE), the BWR 90+ (Westinghouse Atom of Sweden), the SWR-1000 (Framatome ANP) and the ESBWR (GE). The HSBWR and HABWR (Hitachi) are small- and medium-sized advanced BWR concepts. Three ABWRs have been already operating in Japan: Two at Kashiwazaki-Kariwa since 1996 and the third started operating in 2004. As of the end of 2018, none of them is operational due to shutdown following earthquakes in July 2007 and March 2011 [6].

Generation III+

Generation III+ reactors are slightly modified Gen III designs initiated in the late 1990s. The scope of this new wave of Gen III reactors is to overcome issues related to safety, cost, and buildability brought by the new safety systems. Construction cost of US$1,000/kW and a schedule of 4 years or less were forecasted, making nuclear competitive with gas [6]. Four AP-1000 and two ERP started operating in China, while other two reactors of the same type are not yet completed in Europe (Okiluoto-3 and Flamanville-3). Two AP-1000 are under construction in the U.S (Vogtle-3 and Vogtle-4) [1], while the construction of other two reactors in VC Summer site in South Carolina, was abandoned in 2017 after builder Westinghouse went bankrupt [6]. Finally, five VVER-1200 are operative (Leningrad 2-1/ 2-2, Novovoronezh 2-1/2-2 and Belarusian-1) while as many units are under construction (Baltic-1, Akkuyu-1/2/3 and Belarusian-2) [1]. Unfortunately, in most of the construction projects, standardization did not take place, and the introduction of modularized design seems to have simply shifted the quality issues from construction sites to module factories. Most of the Gen III+ nuclear power plants are years behind schedule and significantly over budget. [6].

Generation IV

Generation IV reactors are revolutionary designs that will be deployed after 2030. Generation IV International Forum defined four goals for new reactors: sustainability, safety and reliability, economic competitiveness, proliferation resistance and physical protection. Generation IV nuclear reactors design are developed also considering the lessons learnt from Fukushima Daiichi accident (11 March 2011), that demonstrated the need for reliable residual heat removal over long periods as well as the necessity to exclude significant off-site releases in the case of a severe accident [7]. Conceptually, Gen IV reactors have all of the features of Gen III+ units, as well as the ability, when operating at high temperature, to support economical hydrogen production, thermal energy off-taking, and even water desalination [3]. Six systems were selected by the Generation IV International Forum to represent the fourth generation.

Gas-cooled fast reactors (GFR) are high-temperature helium-cooled fast-spectrum reactors with a closed fuel cycle. It combines the advantages of fast-spectrum systems for long-term sustainability of uranium resources and waste minimisation (through fuel multiple reprocessing and fission of long-lived actinides), with those of high-temperature systems (high thermal cycle efficiency and industrial use of the generated heat, similar to VHTR)[7].

Lead-cooled fast reactors (LFR) are Pb or Pb-Bi-alloy-cooled reactors operating at atmospheric pressure and at high temperature because of the very high boiling point of the coolant (up to 1,743°C). The core is characterised by a fast-neutron spectrum due to the scattering properties of lead [7].

Molten salt reactors (MSR) can be divided into two subclasses. In the first subclass, fissile material is dissolved in the molten fluoride salt. In the second subclass, the molten fluoride salt serves as the coolant of a coated particle fuelled core like that employed in VHTRs. To distinguish reactor types, the solid fuel variant is typically referred to as a fluoride salt- cooled high-temperature reactor (FHR) [7].

Sodium-cooled fast reactor (SFR) uses liquid sodium as the reactor coolant, allowing a low-pressure coolant system and high-power-density operation with low coolant volume fraction in the core [7].

Supercritical-water-cooled reactors (SCWR) are high temperature, high-pressure, light water reactors that operate above the thermodynamic critical point of water (374°C, 22.1 MPa). The reactor core may have a thermal or a fast-neutron spectrum, depending on the core design. The concept may be based on current pressure-vessel or on pressure-tube reactors, and thus may use light water or heavy water as a moderator [7].

Very-high-temperature reactor (VHTR) is a next step in the evolutionary development of high-temperature gas-cooled reactors. It is a graphite-moderated, helium-cooled reactor with thermal neutron spectrum. It can supply nuclear heat and electricity over a range of core outlet temperatures between 700 and 950°C, and potentially more than 1,000°C in the future [7].

1 Small Modular Reactor overview

Following the IAEA definition: "SMRs are newer generation reactors designed to generate electric power up to 300 MW, whose components and systems can be shop fabricated and then transported as modules to the sites for installation as demand arises"[8]. From the definition itself emerge immediately the three main characteristics of the technology: the reduced size, the construction efficiency, and the deployment flexibility. This new concept was born for a niche electricity or energy market, where large reactors cannot be deployed. A wider range of applications can be covered by SMRs, such as cogeneration, integration with renewable energy sources (microgrid [9]), substitution of fossil power plants and applications in off grid areas[8]. Many countries, among which Canada, are seeing in SMRs one of the most promising solutions to meet the climate change 2050 objectives and, at the same time, building a reliable and resilient energy supply system[10].

1.1 SMRs state of art

SMRs embrace a high variety of technologies, from standard LWRs until the newest Gen IV concepts. In the next pages an overview of the main technologies adopted by SMRs, and the most considerable designs is provided. Following the IAEA classification, we can divided SMRs in 5 main categories [8]:

- Land-based water cooled SMRs
- Marine-based water-cooled SMRs
- High Temperature Gas Cooled SMRs
- Fast Neutron Spectrum SMRs
- Molten Salt SMRs

Land-based water cooled SMRs

Land-based water cooled SMRs are similar in concept to existing commercial large nuclear units. Designs may use pressurized water reactor (PWR), boiling water reactor (BWR), or pressurised heavy water reactor (PHWR) concepts. These represent most of the currently operating Large Reactors. For this reason, several SMRs, based on this technology are under development. IAEA identifies twenty-five water cooled SMRs, in different maturity stages, the most closed to the deployment is the CAREM (figure 5) that is finalizing construction for operation by 2023, while dozens of designs are being prepared for near-term deployment, including the ACP-100 in China and NuScale in the United States [8]. Typically, the output coolant temperature of this type of reactor is high enough to use the waste heat of electricity production, in water desalinization processes or other low-temperature thermal applications [9].

Figure 4 Installation of one containment liner module, CAREM (Source: CNEA)

Marine-based water-cooled SMRs

Marine-based water-cooled SMRs are pressurized water reactors similar to a land-based water cooled SMR but whose power plant is located in a marine environment, either on a barge or under the water. IAEA identified six marine-based water- cooled SMRs, some of them have been deployed as nuclear icebreaker ships. The first SMR connected to the grid, from this category, was the KLT-40S that became commercially operative in May 2020 (Figure 5).

Figure 5 The Akademik Lomonosov in Murmans (Source: Rosenergoatom)

High Temperature Gas Cooled SMRs

High Temperature Gas Cooled SMRs are in most cases cooled helium. They provide high temperature heat (≥750°C) that can be utilized for more efficient electricity generation, a variety of industrial applications as well as for cogeneration [8]. In particular, they can be used for steam methane reforming, biomass gasification, and high-temperature steam electrolysis for hydrogen production [9]. The enhanced safety characteristics have been demonstrated with severe accidents practically excluded (no core meltdown or massive fission product release is possible even in extreme conditions), even if working temperature >1,000°C would require additional fuel testing and materials development [11]. IAEA identifies eleven HTGR SMRs under development or close to operations, including the HTR-PM, which has been connected to the grid in 2022 in China and three HTGR test-reactors, two that have been in operation for technology testing purposes in Japan and China for over twenty years [8].

Figure 6 HTR-PM reactor pressure vessels (Shanghai Electric Corporation)

Fast Neutron Spectrum SMRs

SMR designs that adopt fast neutron spectrum can be implemented with different coolant options, including sodium, heavy liquid metal (e.g., lead or lead- bismuth) and helium-gas. As stated by [11] “These systems, operate in a fully closed fuel cycle, have the potential to significantly increase the sustainability of nuclear power, i.e., they can extract 60–70 times more energy from uranium than existing thermal reactors, contribute to reducing the plutonium stockpile, and minimize the heat load, volume and required isolation time for high level radioactive waste. They will also have higher efficiency and the innovative concepts promise to have enhanced safety characteristics with respect to evolutionary reactors (a feature not yet proven). Another advantage of liquid metal cooled fast reactors (FRs) is that they operate at very low pressure”. Several types of Fast Neutron Spectrum reactors can reuse the spent fuel of existing LWRs [9]. Finally, the typical high coolant temperatures make the reactors suitable for Hydrogen production or other processes in which those heat is needed. IAEA identifies 11 SMRs that adopted this type of technology. A demo- prototype of a lead-cooled fast neutron reactor (BREST-OD-300, Figure 7) is under construction at a site in Seversk, Russian Federation with a scheduled operation by the end of 2026 [8].

Figure 7 A cutaway of the BREST-OD-300 reactor (Source: Rosatom)

Molten Salt SMRs

The Molten Salt Reactor (MSR) is distinguished by its fuel which is dissolved in molten salt, although some designs use solid fuel and molten salt as a coolant [11]. They promise many advantages including enhanced safety thanks to salt's inherent property, low-pressure single-phase coolant system that eliminates the need of large containment, a high temperature system that results in high efficiency, and flexible fuel cycle [8]. Its technical feasibility still needs to be evaluated, especially the long-term performance of structural materials in molten salt. Some SMR designers circumvent these potential lifetime issues by using innovative equipment replacements. Other challenges are the acceptance of its safety case in licensing and also some proliferation concerns [11]. IAEA identifies 10 SMR designs that uses this technology [8].

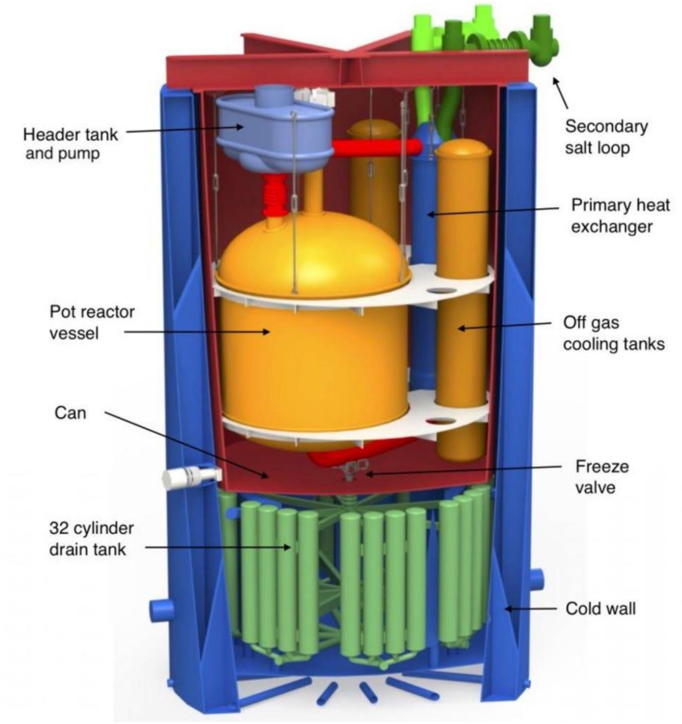

Figure 8 ThorCon MSR conceptual design

Micro-sized SMRs

In recent years, there has been growing interest in microreactors. Typically, they are reactors able to generate a power up to 10 MWe. They fully exploit factory fabrication and all benefits coming from this, are easily transportable and can be connected directly to the end-user. Leveraging on passive safety features, microreactors may be self-regulating reducing at minimum the need of operators [11]. Another feature, which has a good impact on operations, is the long refuelling interval, that for some design is up to 20 and 30 years. This last characteristic, also, allows to reduce drastically stocks and waste management, limiting the environmental impact [9]. Microreactors are targeted to serve niche electricity and district heat markets in remote sites (arctic or island communities), mining operations, industries and fisheries, to provide backup power (also for data centres), to serve oil platforms or to be used in maritime shipping. These reactors embrace different types of coolant, like helium, lead, air, water, liquid metal and heat pipes [11]. IAEA identifies 6 micro reactor designs, some of them are closed to deployment. In 2019 a site application was submitted by Global First Power for a single small modular reactor using USNC's Micro Modular Reactor (MMR) (Figure 9) technology at the Chalk River Laboratories site [8].

Figure 9 USNC’s MMR concept (Source: USNC)

The list of all the projects identified by the IAEA is shown in Table 1, where the reactors are divided according to the categories defined above [8].

Table 1 Design and Status of SMRs (Source: IAEA [8])

Design	Output MW(e)	Type	Designers	Country	Status
1 WATER COOLED SMALL MODULAR REACTORS (LAND BASED)					
CAREM	30	PWR	CNEA	Argentina	Under construction
ACP100	100	PWR	CNNC	China	Detailed Design
CANDU SMR	300	PHWR	Candu Energy Inc (SNC- Lavalin Group)	Canada	Conceptual Design
CAP200	200	PWR	SNERDI/SPIC	China	Conceptual Design
DHR400	400 MW(t)	LWR (pool type)	CNNC	China	Basic Design
HAPPY200	200 MW(t)	PWR	SPIC	China	Detailed Design
TEPLATOR™	50 MW(t)	HWR	UWB Pilsen & CIIRC CTU	Czech Republic	Conceptual Design
N UWARD	2 X 170	PWR	EDF, CEA, TA, Naval Group	France	Conceptual Design
IRIS	335	PWR	IRIS Consortium	Multiple Countries	Basic Design

DMS	300	BWR	Hitachi-GE Nuclear Energy	Japan	Basic Design
IMR	350	PWR	MHI	Japan	Conceptual Design
SMART	107	PWR	KAERI and K.A.CARE	Republic of Korea, and Saudi Arabia	Certified Design
RITM-200	2 X 53	PWR	JSC "Afrikantov OKBM"	Russian Federation	Under Development
UN ITH ERM	66	PWR	NIKIET	Russian Federation	Conceptual Design
VK-300	250	BWR	NIKIET	Russian Federation	Detailed Design
KARAT-45	45 - 50	BWR	NIKIET	Russian Federation	Conceptual Design
KARAT-100	100	BWR	NIKIET	Russian Federation	Conceptual Design
RUTA-70	70 MW(t)	PWR	NIKIET	Russian Federation	Conceptual Design
ELENA	68 kW(e)	PWR	National Research Centre "Kurchatov Institute"	Russian Federation	Conceptual Design
UK SMR	443	PWR	Rolls-Royce and Partners	United Kingdom	Conceptual Design
NuScale	12 X 60	PWR	NuScale Power Inc.	United States of America	Under Regulatory Review
BWRX-300	270 - 290	BWR	GE-Hitachi Nuclear Energy and Hitachi GE Nuclear Energy	United States of America, Japan	Pre-licensing
SMR-160	160	PWR	Holtec International	United States of America	Preliminary Design
W-SMR	225	PWR	Westinghouse Electric Company, LLC	United States of America	Conceptual Design
mPower	2 X 195	PWR	BWX Technologies, Inc	United States of America	Conceptual Design
2 WATER COOLED SMALL MODULAR REACTORS (MARINE BASED)					
KLT-408	2 X 35	PWR in Floating NPP	JSC Afrikantov OKBM	Russian Federation	In Operation
RITM-200M	2 X 50	PWR in FNPP	JSC Afrikantov OKBM	Russian Federation	Under Development
ACPR50S	50	PWR in FNPP	CGNPC	China	Conceptual Design
ABV-6E	6-9	PWR in FNPP	JSC Afrikantov OKBM	Russian Federation	Final design
VBER-300	325	PWR in FNPP	JSC Afrikantov OKBM	Russian Federation	Licensing Stage

SHELF	66	PWR in Immersed NPP	NIKIET	Russian Federation	Detailed Design
3 HIGH TEMPERATURE GAS COOLED SMALL MODULAR REACTORS					
HTR-PM	210	HTGR	INET, Tsinghua University	China	Under Construction
StarCore	14/20/60	HTGR	StarCore Nuclear	Canada/UK/US	Pre-Conceptual Design
GTHTR300	100 - 300	HTGR	JAEA	Japan	Pre-licensing
GT-MHR	288	HTGR	JSC Afrikantov OKBM	Russian Federation	Preliminary Design
MHR-T	4 X 205.5	HTGR	JSC Afrikantov OKBM	Russian Federation	Conceptual Design
MHR- 100	25 -87	HTGR	JSC Afrikantov OKBM	Russian Federation	Conceptual Design
PBMR-400	165	HTGR	PBMR SOC Ltd	South Africa	Preliminary Design
A-HTR-100	50	HTGR	Eskom Holdings SOC Ltd.	South Africa	Conceptual Design
HTMR- 100	35	HTGR	Steenkampskraal Thorium Limited	South Africa	Conceptual Design
Xe-100	825	HTGR	X-Energy LLC	United States of America	Basic Design
SC-HTGR	272	HTGR	Framatome, Inc.	United States of America	Conceptual Design
HTR-10	25	HTGR	INET, Tsinghua University	China	Operational
HTTR-30	30 (t)	HTGR	JAEA	Japan	Operational
RDE	3	HTGR	BATAN	Indonesia	Conceptual Design
4 FAST NEUTRON SPECTRUM SMALL MODULAR REACTORS					
BREST-OD-300	300	LMFR	NIKIET	Russian Federation	Detailed Design
ARC-100	100	Liquid Sodium	ARC Nuclear Canada, Inc.	Canada	Conceptual Design
4S	10	LMFR	Toshiba Corporation	Japan	Detailed Design
microURANUS	20	LBR	UNIST	Korea, Republic of	Pre-Conceptual Design
LFR-AS-200	200	LMFR	Hydromine Nuclear Energy	Luxembourg	Preliminary Design
LFR-TL-X	5-20	LMFR	Hydromine Nuclear Energy	Luxembourg	Conceptual Design
SVBR	100	LMFR	JSC AKME Engineering	Russian Federation	Detailed Design
SEALER	3	LMFR	LeadCold	Sweden	Conceptual Design

EM2	265	GMFR	General Atomics	United States of America	Conceptual Design
Westinghouse LFR	450	LMFR	Westinghouse Electric Company, LLC.	United States of America	Conceptual Design
SUPERSTAR	120	LMFR	Argonne National Laboratory	United States of America	Conceptual Design
5 MOLTEN SALT SMALL MODULAR REACTORS					
Integral MSR	195	MSR	Terrestrial Energy Inc.	Canada	Conceptual Design
smTMSR-400	168	MSR	SINAP, CAS	China	Pre-Conceptual Design
CA Waste Burner 0.2.5	20 MW(t)	MSR	Copenhagen Atomics	Denmark	Conceptual Design
ThorCon	250	MSR	ThorCon International	International Consortium	Basic Design
FUJI	200	MSR	International Thorium Molten-Salt Forum: ITMSF	Japan	Experimental Phase
Stable Salt Reactor - Wasteburner	300	MSR	Moltex Energy	United Kingdom I Canada	Conceptual Design
LFTR	250	MSR	Flibe Energy, Inc.	United States of America	Conceptual Design
KP-FHR	140	Pebble-bed salt cooled Reactor	KAIROS Power, LLC.	United States of America	Conceptual Design
Mk1 PB-FHR	100	FHR	University of California at Berkeley	United States of America	Pre-Conceptual Design
MCSFR	50-1200	MSR	Elysium Industries	USA and Canada	Conceptual Design
6 MICRO MODULAR REACTORS					
Energy Well	8	FHTR	Centrum výzkumu Řež	Czech Republic	Pre-Conceptual Design
MoveluX	3-4	Heat Pipe	Toshiba Corporation	Japan	Conceptual Design
U-Battery	4	HTGR	Urenco	United Kingdom	Conceptual Design
Aurora	15	FR	OKLO, Inc.	United States of America	Conceptual Design
Westinghouse eVinci	2 -3.5	Heat Pipe	Westinghouse Electric Company, LLC.	United States of America	Under Development
MMR	5-10	HTGR	Ultra Safe Nuclear Corporation	United States of America	Preliminary Design

1.2 Prospects and Impediments

After a brief overview of the principal SMRs technologies and concepts, prospects and impediments related to their implementation is provided in this chapter. Those are the ones identified in the IAEA report “Technology roadmap for small modular reactor deployment” 2021 [11].

1.2.1 Prospects

Enhanced safety, energy security and carbon free power

SMR designs incorporate 60 years of operations lessons learned, that permitted to enhance drastically the safety features. Firstly, the size of the reactors itself and the reduced thermal power output represent a lower risk respect large reactor. Secondly, designers had the possibility to eliminate some of the most critical components. For instance, considering the NuScale case, leveraging on natural circulation of the primary coolant, it was possible to eliminate the reactor coolant pumps. Thirdly, more passive safety systems are adopted, eliminating the necessity of external power for remove core decay heat and containment heat and pressure.

Considering energy security, uranium price has been stable along the last 30 years, and its energy density is the highest among the traditional sources of energy. This ensures that few years of uranium supply can easily be stockpiled. All these characteristics make nuclear a valid option to enhance the energy security of a country.

The growth of the world population, and the increasing energy demand, combined with the need to drastically reduce CO2 emission, make nuclear energy one of the most promising solutions for many countries. This implies that SMRs will be in future a potential option to include in the energy mix.

Smaller grids, remote locations, integration with renewables and replacement of ageing fossil fuelled plants

The widespread deployment of intermittent renewable energy sources is challenging the grids’ stability, since in some case more than the 10% of the overall installed capacity of an existing grid comes from a single generating unit. In this scenario, SMR technology may represent the guarantor of grid stability, extending the deployment of nuclear energy in smaller systems and remote locations.

These areas, frequently, are powered by old and inefficient fossil fuel systems closed to disposal. Therefore, these could be substituted by SMRs, moreover the existing grid interconnections and transmission infrastructures could be adapted to accomplish the new technology. The Canadian report [10], demonstrates the economic benefits for substituting the existing diesel generators, installed in remote areas that require up to 20MWe and 10MWe power. Another tangible value of substituting the old technology with SMRs is the CO2 emissions reduction in these areas.

Finally, the possibility to add capacity over time, makes SMRs a suitable candidate to follow the future demand growth projection.

Easier to site and smaller emergency planning zones

Comparing LRs with SMRs, these last ones may be employed in more sites for two main reasons. The first one is that the smaller thermic source, can be used to argue a smaller Emergency planning zones, giving the possibility to be closer to the population's centres and provide process heat to industrial activities (e.g., wood and paper processing, desalinization, biomass). The second reason is that the smaller size of the components, permits to reduce the necessity of big infrastructure and transportation means, giving access to more sites than large reactors.

Capacity factors and incremental additions of generating capacity

The capacity factor of a power plant is expressed as the ration between the actual output over a period to its potential output. The output of a NPP is mainly affected by maintenance and refuelling operation. Several SMR concepts are based on multi-module designs which would allow to perform these operations on one module while other modules continue to operate and produce power, guaranteeing and higher capacity factor than single unit large reactor.

As mentioned before, another key advantage of the multi-module design is the possibility to add units to a power plant when the demand for more electricity increases at only marginal additional cost (i.e., the cost of more modules).

Dispatchable integration with non-dispatchable renewables and the future grid

The increasing market of wind and solar power has dramatically changed the market price of electricity and the challenges associated with managing a highly reliable electrical grid. Large deployments of these renewable sources of energy are resulting in grid power fluctuations, consisting in hundreds of megawatts of electricity being added or subtracted within minutes. SMRs can potentially respond to changing load demands as requested by the grid operator adapting the electric output based on the requests. However, must be highlighted that being nuclear a capital-intensive investment, the load following mode lower the capacity factor, compromising the energy economics. In the article [9] are described three different ways to modify the

NPP output: control rod adjustments, feed water flow rate modifications, and steam bypass initiations (Figure 10).

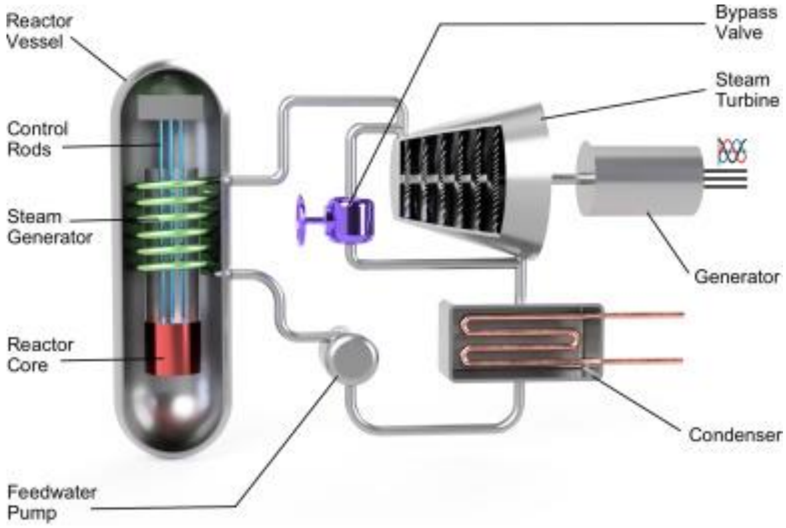

Figure 10 Simplified PWR SMR system

The control rod movements directly influence the amount of thermal power through the rate of the fission reaction. The chain reaction processes can be complex and include transient behaviour that can limit the manoeuvrability. Modifications of feed water flow rate adjust the rate of heat removal from the core, which in turn affects the core reactivity. Finally, the quickest way to reduce the power output is to use a bypass mechanism to divert some steam away from the turbine to the condenser. The main issue, using this method, regards the loss in efficiency and considerable stress on the condenser and its cooling system. An additional way to reduce the output, applicable in multiunit sites is to take one or more modules off-grid and exploit this time for fuelling and maintenance operations. Obviously, the latter option represents the less flexible one, but from another point of view, highlight again the higher flexibility of SMRs (often deployed in multi units) respect to large reactors.

Finally, smart grids of the future may favour more decentralized electricity generation stations that will certainly have a larger percentage of non-dispatchable renewable energy systems. In this configuration, supply and demand are balanced at the local level, thereby restricting the use of traditional large baseload power plants, encouraging the introduction of SMRs.

Non-electrical applications and water usage

In order to improve the overall thermal efficiency, the waste heat coming from the electricity generation can be employed in different fields. These embrace water desalinization, hydrogen production, other thermochemical processing and a variety of petrochemical applications, including ammonia and methanol synthesis, bitumen extraction from oil sands, coal gasification, or hydrocracking of heavy crude oil. The virtuous deployment of heat energy has a double effect on the energy production economy, from one hand the additional products represent a secondary source of income for NPP, on the other, the size of the heat rejection system may be reduced. The different co-generation applications depended on the reactor’s operating temperature. High Temperature Gas Reactor (HTGR) technology can be suitable for hydrogen production, thermochemical and petrochemical application, while the more traditional LWRs, that work with a lower temperature, can be used in the desalinization process or district heating.

Public acceptance, localization and decommissioning

It is believed that the reduced size and the enhanced safety features of SMRs will play a crucial role in the public acceptance of NPPs. In addition, the construction of non-safety-related components offers the prospect of domestic job creation and the improvement of the overall area welfare.

Decommissioning of a SMR appears technically easier for full factory assembled reactors as they can be transported back to the manufacturer in an assembled way. Therefore, the dismantling and recycling of the components can be done quicker and more efficiently reducing the risks related to a local disassembly.

Economics and reduced debt financing

Even if investment in SMRs seems to be less profitable that large reactors (due to their loss in terms of economy of scale) they present several advantages from the financial point of view. First, the lower initial investment is seen by the investors less risky, this has a direct impact on the risk premium rate over the debt. Second, thanks the possibility to move part of the assembly work in factory, a shorter and a more certain schedule is associated with SMRs projects. This guarantees a lower overrunning risk and a lower long-term financing cost. Finally, the SMRs modularity can be transmitted also on the investment that can be spread over more units built along the years, impacting positively on the average financial debt, and giving the possibility of auto-financing the future units. More details of SMR economics and debt financing are explained in the dedicated chapter.

1.2.2 Issues and impediments

Economics and early adopter of first of a kind technology

While several studies have been published about SMR economics, the theories have not been proven yet with a first demonstration plant. Few owners and operating organizations are willing to take this risk, and often government support is needed to build the first of a kind plant. Incentives will be needed to reduce the financial risk of investing in facilities and people that are needed to develop, fabricate, test and qualify FOAK components, systems and structures. Establishing and maintaining, with enough orders, a supply chain with the requisite technical skill sets and quality systems will be a challenge. As a result, the more a reactor designer can incorporate standard commercial items, or rely on existing nuclear suppliers, the less of a challenge this issue will be to manage.

Considering the financial risk, the FOAK SMRs, as for the ones of large reactors, may incur into a high risk of schedule and cost overrun. However, the risks can be mitigated with a careful plan and through the integration of all the items relative to this type of project.

Licensing issues and the need for harmonization

SMRs technologies are evolving rapidly. However, the regulatory guides and processes to assess this emerging technology are lagging and, in some cases, are not yet available. Regulations represent the most significant challenge to SMRs deployment. Regulators and developers must work together to establish consistent regulatory framework, that guarantees the construction of SMRs FOAK plant, the safety of operations and the cost effectiveness. In this optic, in 2015, IAEA facilitated the establishment of the Small Modular Reactors' Forum in charge of identifying, understanding and addressing key regulatory challenges that may emerge in future SMRs regulatory discussions. In 2017, the group released the first report about how the member states are approaching the main issues and had identified the best practice to solve them. The group continued its work realising an interim report in 2020, addressing licensing issues; design and safety analysis; and manufacturing, commissioning and operations.

In addition to these problems SMR developers must analyse the safety issue related to multi-unit plants and the adoption of passive systems.

Parallelly to IAEA, World Nuclear Association's Cooperation on Reactor Design and Licensing (CORDEL) group has established an SMR task force, that in 2015, published a report regarding SMR licencing.

Fuel burnup

Smaller LWR cores, that use current fuel designs and cladding materials, present a less efficient fuel burnup. This is reflected in a larger amount of spent fuel per unit of electricity generated and additional disposal cost. However, this problem may be compensate increasing the enrichment of the fuel or adopted new technologies as gas cooled, metal cooled or salt cooled reactors.

Public acceptance

Like for other nuclear technologies, public concern about reactor safety and fuel disposal remains. The Canadian report [10] demonstrated that people more willing to accept nuclear are the ones have already experienced the benefit of its energy or with a good knowledge about the sector. As a consequence, in Canada, the acceptance changes in different regions depending on the involvement in the nuclear energy supply chain. This means the knowledges spreading and the active involvement of the citizen is key to drive down misconceptions about safety of nuclear sector. Furthermore, the increasingly awareness about climate change and the need to control the temperature increase under the 1.5 C°, may represent an additional boost in accepting the construction of NPPs.

Continued R&D

As mentioned before, most of SMRs are in a developing phase therefore, IAEA in order to drive their development and overcome the implementation barriers, identifies different areas of research that would be most beneficial to SMR technologies:

- Developing new multi-module probabilistic safety assessment methodologies
- Developing new and innovating I&C for diagnostics
- Developing new technologies to increase the automation of controls and safety methodologies that are needed to obtain regulatory acceptance
- Developing new risk metrics for quantifying low risk designs
- Developing fuels and materials for extended refuelling cycles

Infrastructure considerations of SMRs in the context of the IAEA's Milestones approach

Considering the increasing interest of Member States in the near-term deployment of SMRs, it is necessary to understand whether additional guidance on the required nuclear power infrastructure for such reactors is needed. With this aim, the two meetings convened by the IAEA, in 2014 and 2017, produced the assessment of the 19 elements relevant to SMR deployment by considering the technology specificities that may affect infrastructure development. These elements previously defined for LRs were modified considering SMRs characteristics and can be used to evaluate the status of national nuclear infrastructure. More details about differences among LRs and SMRs infrastructure element evaluation are reported in Table 2 [11].

Table 2 Aspects to consider for each infrastructure elements (Source: IAEA [11])

No.	Infrastructure element	Specific aspects or potential impacts of SMRs
1	National Position	The same as that of commercial large reactors; SMRs may facilitate decision making due to the low power, lower radiological risk and the lower upfront capital cost for newcomers with a small electricity grid.
2	Nuclear safety	Enhanced levels of safety through the incorporation of lessons learned from major safety events in the SMR design under development should facilitate faster acceptance by the energy policy maker and stakeholder.
3	Management	Recognize the important role of R&D organizations to address novel technologies; standardization of reactor modules may result in enhanced sharing of management experience and better management efficiency.
4	Funding and Financing	Easier to finance due to a lower upfront capital cost; less interest during construction; phased financing; private sector interest; and potential for minimized investment risk.
5	Legal Framework	Some marine based SMRs may require a non-nuclear legislative framework to address inter-regional transport of modules and maritime aspects.
6	Safeguards	Some SMRs have higher enrichment within the LEU level for long fuel cycles, or new plant layout arrangements including underground construction; these may need novel approaches to implement safeguards.
7	Regulatory Framework	Depending on the licensing readiness level of the design features and technologies, challenges may arise in the establishment of a regulatory framework (regulations, guidance, training and research, operating experience feedback).
8	Radiation Protection	In principle, the same as that of commercial large reactors; some impacts may arise depending on the emergency planning zone size and site selection.
9	Electrical Grid	SMRs can be deployed on smaller grids that require less reserve capacity and be less dependent on off-site power for safety functions.
10	Human Resource Development	A built-in factory setting and the use of modular construction technology can reduce the peak construction workforce and shorten the construction period; may also avoid large workforce fluctuations for refuelling operations.

11	Stakeholder Involvement	Need to evaluate whether SMRs may develop a conducive environment for the introduction of a nuclear power programme; the role of vendor countries to support embarking countries for the new SMR project should be studied.
12	Site and Supporting Facilities	The smaller footprint of SMRs can expand the availability of acceptable sites, lower water usage and lower transmission requirements.
13	Environmental Protection	Allows for geographically distributed power production but may require additional environmental assessments.
14	Emergency Planning	Can result in simplified emergency planning and a smaller evacuation zone.
15	Nuclear Security	Intrinsic design features, such as additional barriers, may provide security advantages and limit vulnerabilities for sabotage.
16	Nuclear Fuel Cycle	Dependent on enrichment and type of fuel cycle. No impact on most SMRs with a refuelling interval of 12–36 months with an enrichment lower than 5%; some SMRs have long fuel cycles of up to 30 years, thus requiring higher enrichment within the LEU scale; some designs adopt an innovative fuel cycle.
17	Radioactive Waste Management	Radioactive waste management may be different for some non-water-cooled SMRs; need to evaluate whether the existing infrastructure is applicable, or adjustment/new solutions will be needed for new radioactive waste streams.
18	Industrial Involvement	Design simplification in SMRs reduces safety grade components, enables more diversity in the supply chain, including increased local industrial participation; on the other hand, standardization could facilitate deployment, yet invite less local industrial involvement.
19	Procurement	Potential for a simplified supply chain due to the smaller components and enhanced standardization, but not proven; need to ensure that suppliers can provide a novel system, equipment and services specific for SMRs

Operation and maintenance of novel technology

There is a misperception that nuclear power plants cannot perform load following. In the past and today most of the plants are operating in a stable way optimizing the plant and fuel efficiency. However, in several markets, nuclear power plants have already successfully performed flexible operations for many years exhibiting good safety and operations performances. In the future, with the introduction of renewable energy sources and more decentralised grids, the need of load following will be increasingly required. SMR designs are expected to have a better load following capability than the conventional large nuclear power plants due to their size (small core), a large number of rod control cluster assemblies (RCCAs), typical lower power densities (larger operating margins), soluble-boron-free reactivity controls, simpler robust designs and a new digital I&C. However, problems related to maintenance and fuel inefficiencies remain, especially for SMRs with an integral PWR configuration.

2 Nuclear power plant cost and drivers

In this chapter are analysed the economic aspects related to nuclear power plant projects. in the first section a brief overview of the cost structure and the main cost voices is provided. In the next one, a temporal scan of NPP cost trend is reported in order to detect the most impacting cost drivers. Finally, is evaluated the impact of the SMR technology characteristics on the cost variables and drivers.

2.1 Cost Structure

Reporting the definition in [12], a common way to cluster NPP life-cycle cost is:

Capital cost: an all-inclusive plant capital cost, or lump- sum up-front cost. This cost is the base construction cost plus contingency, escalation, interest during construction (IDC), owner's cost (including utility's start-up cost), commissioning (non-utility start-up cost), and initial fuel core costs for a reactor

Operation and maintenance (O&M): include costs relative to actions focused on scheduling, procedures, and work/systems control and optimization. Moreover, embeds cost relative to performance of routine, preventive, predictive, scheduled and unscheduled actions aimed at preventing equipment failure or decline with the goal of increasing efficiency, reliability, and safety.

Fuel cost: the sum of the costs for the fissile/fertile materials (natural uranium, low enrichment uranium, highly enriched uranium, mixed oxide fuel, uranium-thorium, etc.) and the enrichment process of the fuel in fissile materials, plus other materials used in the fuel assemblies (zirconium, graphite, etc.), services required to produce the needed materials (mining, milling, conversion, enrichment, fabrication), fuel fabrication, shipment and handling, costs of spent-fuel disposal or reprocessing and waste (including low-level, high level and transuranic waste) disposal.

Decommissioning: costs for the administrative and technical actions taken to allow the removal of some or all of the regulatory controls from a facility. The actions will ensure the long-term protection of the public and the environment, and typically include reducing the levels of residual radionuclides in the materials and on the site of the facility, to allow the materials' safe recycling, reuse, or disposal as 'exempt waste' or as 'radioactive waste' and to allow the release of the site for unrestricted use or other use.

In energy sector all these cost components are summarized in one metric, allowing to easily compare cost performances related to single plants. This KPI is called levelized unit electricity cost or levelized cost of electricity (LUEC/LCOE), it essentially represents the unitary cost of the generated electricity, taking in account the four voices previously defined. The unit of measure is typically [$/kWh]. As stated in [12], capital cost is the main component of the metric, weighting from 50% to 75% on the LUEC, followed by Fuel costs (8-27%), O&M costs (5-23%) and Decommissioning cost (<1-5%). Given its highest impact over the electricity production cost, in this analysis as we are focusing on capital cost estimation.

2.2 NNP cost trend and drivers

Capital investment cost is a key factor that discriminate the success of a project. As reported by [13] an increase average investment cost was experience along the years in France and US (Figure 11).

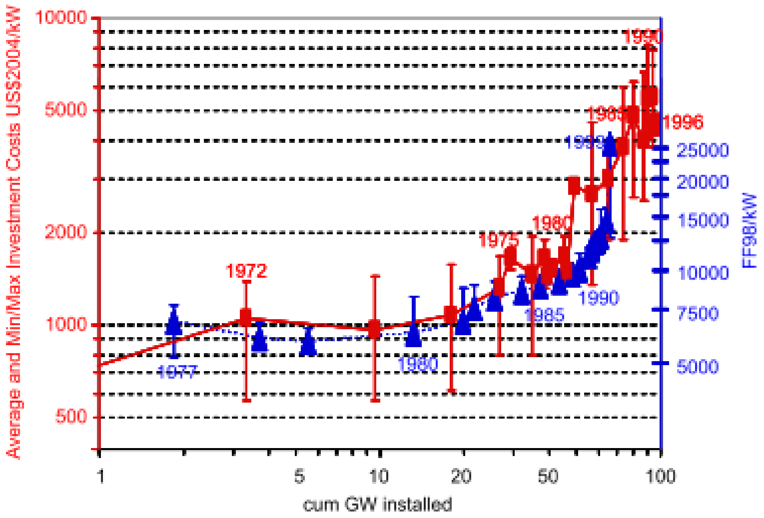

Figure 11 Construction costs per year of completion versus cumulative capacity

In the construction of several western NPPs the costs increase has not been foreseen at the start of the construction. Therefore, huge cost overruns and delays are affecting those projects. In Table 3 some examples are reported [12].

Table 3 Cost increase and commissioning delays of NPP under construction

	Initial cost estimate	Revised cost estimate	Delay on commissioning
Olkiluoto 3 (Finland)	3 Bn€	8.5 Bn€	From 2009 to 2018
Flamanville (France)	3.3 Bn€	8.5 Bn€	From 2012 to 2016
Levy County (US)	5 Bn€	24 Bn€	From 2016 to 2024
South Texas Project (US)	5.4 Bn€	18.2 Bn€	Expected by 2006, then project abandoned in 2011
Hinkley Point (UK)	10 Bn€	16 Bn€	Commissioning delayed from 2017 to 2033

As stated in [13] one of the main reasons of cost escalations can be found in the intrinsic technology complexity. Over the years the trend was to continuously push the reactors' capacity limits to leverage more on economies of scale and the spreading of fix cost over and higher amount of energy produced. But this approach worked until the 1960s when the continued design changes and the increasing plant complexity nullified the advantages. Moreover, this approach did not let to exploit other cost reduction strategy as the construction of quasi-identical plants and the possibility to leverage on learning economies. The latter aspect is not secondary, as the Korean case demonstrated. In particular, the Korea Hydro & Nuclear Power (KHNP) developed a standard nuclear power plant based on the OPR-1000 reactor (two-loop 1,000 MWe PWR Generation II nuclear reactor). They established a consistent nuclear program, including the deployment of twin/multiple units on the same site, avoiding substantial design modification. Thanks, the PWR plants standardization and the control of design complexity, they were able to optimize the project management cost, reducing both manufacturing and assembly cost. By leveraging on experienced workforce, and sharing fix cost on more units on the same site, a consistent reduction of cost and time of projects over the years has been obtained [12] (Figure 12).

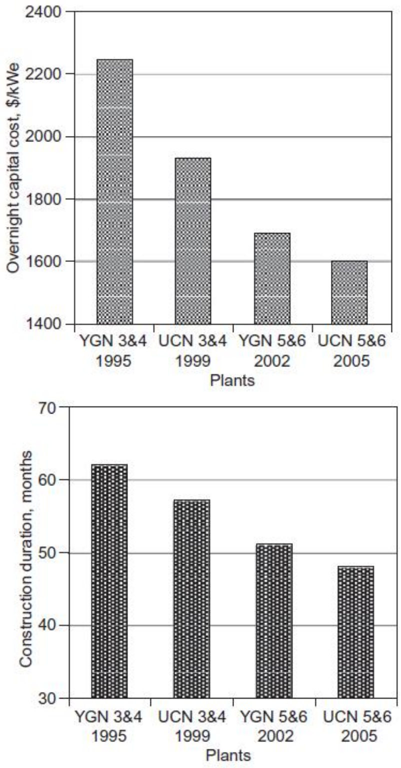

Figure 12 Overnight capital costs and construction duration of Korean NPP

Phase IX Update (1987) Report Energy Economic Data Base Program for The EEDB – IX [14]

Useful insights about reasons behind the cost increasing along years are provided by the America Energy Economic Data Base Program (EEDB), in which are analysed the costs increasing between 1979 to 1987 of a representing 1,144 MWe Gen II PWR. In particular, the study compares an average experience (PWR12-ME) and a plant that represents the base construction costs for a small group of single units' nuclear power plants at the low end of the range of base construction costs (PWR12-BE). Moreover, to assess their market competitiveness, the two plants are compared with the cost of a Coal-fired Power Plant of 488 MWe (HS5), normalized to a plant size providing 1,144 MWe (net). The cost trends can be assessed by splitting them in two macro area: material cost and labour cost.

Material cost can be further divided in direct and indirect cost (Figure 13). The material directly employed in the plant has been affected by a steady increase over the years due to increased safety regulations. Most interestingly, the largest contributor to the cost escalation has been due to the indirect cost of material. Specifically, this cost increased at a rate greater than inflation by approximately 130%, 35%, and 10% for PWR12-ME, PWR12-BE, and HS5, respectively. These increases are due to the longer construction time and the increase in the number of on-site operators, which require more temporary buildings, tools, construction equipment, and temporary services.

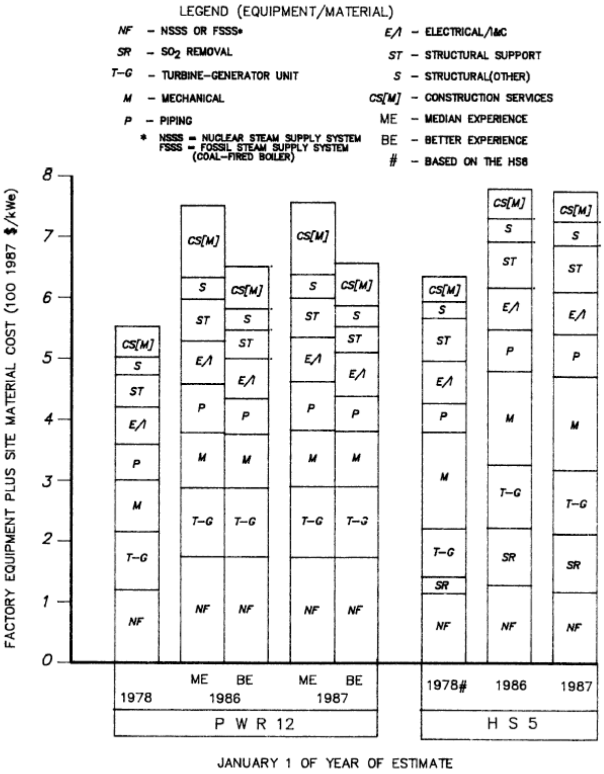

Figure 13 PWR12 and HS5 factory equipment plus site material cost

Labour cost has become the most significant cost since the 1983 update report. It can be divided into craft labour cost and indirect labour cost (Figure 14). The increases in labour cost above general inflation for the three data models between 1978 and 1986 are 223% for the PWR12-ME, 41% for the PWR12-BE, and 29% for the HS5.

SC - Structural craft labour costs increased 66% for PWR12-ME, 4% for PWR12-BE, and 14% for HS5. The PWR12-ME increases resulted from a significant decrease in installation labour productivity and an increase in structural raw material quantities.

MC - Mechanical craft labour costs increased 128% for the PWR12- ME due to a significant decrease in productivity and an increase in the amount of mechanical equipment/piping. PWR12-BE and HS5 increased by 7% and 37%, respectively.

EC - Electrical craft labour costs increased 145% for PWR12-ME, due to increases in quantities of electrical equipment and wiring/I&C coupled with significant decreases in productivity. The increases for PWR12-BE are 46%.

As with material costs, the largest contributor on cost escalation is due to the increase in indirect labour.

CS[L] - Construction services labour costs to install the temporary buildings and other structures increased by 448% for PWR12-ME. These increases are a direct result of the indirect materials cost trend previously described. The increases for PWR12-BE and HS5 are 185% and 32%, respectively.

E - Engineering costs increased 213% for the PWR12-ME. These increases are caused by uncertainties due to regulations and inefficiencies in procedure executions. Similar causes are responsible for the 35% increase for PWR12-BE.

FS - Field supervision costs increased by 923% for the PWR12-ME. The dramatic increase in this account resulted from the increased number of workers on site to supervise and the uncertainties caused by regulation and inefficiencies in current practice. Similar causes were responsible for the 107% increase in field supervision costs for PWR12-BE.

O - Other professional costs grew by 231% for the PWR12-ME, 51% for the PWR12-BE and 49% for the HS5 this account reflects cost trends in the E and FS accounts.

I&T - Insurance and taxes costs are primarily a direct function of the cost for craft plus construction services labour. Between 1978 and 1986, however, the average percentage and the wages to which insurance costs and taxes were applied increased, so this account increased faster than the direct labour account. The increases amount to 179% for the PWR12-ME, 51% for the PWR12-BE.

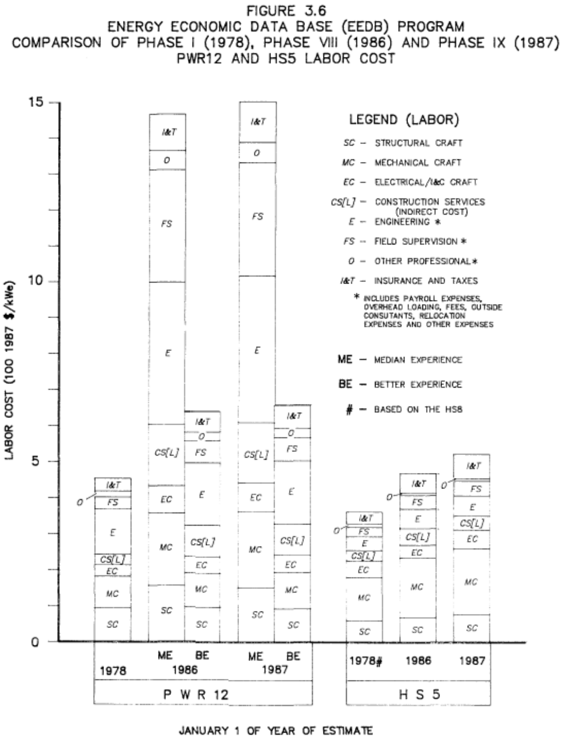

Figure 14 PWR12 and HS5 labour cost

Table 4 summarizes the preceding information in absolute and relative values.

Table 4 Cost Increases between 1978 - 1987 (1987 Mln U.S. dollar)

Cost Category	PWR12-ME		PWR12-BE + % (78 - 87)	Cost drivers
	+ % (78 - 87)	$ (78 - 87)		
Material cost trend				
Indirect Material Cost trend	130%	73.7	35%	- # of workers (more services and temporary buildings)
				- Project schedule (rental cost. maintenance etc…)
Labour cost trend				
Craft labour				
SC - Structural craft labour costs	66%	67.7	4%	- Material quantities
				- Productivity
				- Change in job scope
MC - Mechanical craft labour costs	128%	138.9	7%	- Piping labour & quantities
				- Productivity
				- Welder qualification
EC - Electrical craft labour costs	145%	54.7	46%	- Material quantities
				- Productivity
Indirect labour costs				
CS[L] - Construction services labour costs	448%	157.5	32%	- Material quantities (indirect materials)
E - Engineering costs	213%	319.9	35%	- Regulations, codes and standards
				- Design complexity
				- Design changes and reviews
				- Control procedures
				- Lead time from engineering to construction (too short)
FS - Field supervision costs	923%	328	107%	- Site labour hours
				- Construction schedule
				- Engineering hours
				- Field change request/engineering change notice procedures
0 - Other professional costs	231%	45	51%	- Quality assurance/control
I&T - Insurance and taxes costs	179%	89.5	51%	- Labour cost
				- Tax rates
				- Builder's all-risk insurance

Analysing the EEDB data, two main insights can be extrapolated:

- While increasing complexity generates a proportional increase in direct materials cost, the need for more workers has a huge impact on the cost of craft labour, it also creates management complexity that is reflected in lower productivity and a dramatic escalation in indirect labour costs.
- On the other hand, while for obvious reasons the direct cost of materials is not differential between PWR12-ME and PWR12-BE, we cannot say the same for the escalation of labour cost, both direct and indirect. This means that there is tremendous room for improvement from a project management perspective.

Continuing the analysis, the EEDB authors sought to assess and quantify the primary causes of cost increases from 1978 to 1987. The nearly $1.42 billion (1987 U.S. dollars) increase in PWR12 construction costs is distributed across 7 categories of change. Their absolute and relative impact is shown in Table 5.

Table 5 Change category cost increase distribution

Change Category (Cause of Increase)	Cost Increases in Excess of Inflation (1987 Mln U.S dollar)	Percentage of Total Increase
1 Major Equipment Cost Changes	80	6%
2 Design Feature Changes	41	3%
3 Scope changes	67	5%
4 Quantity Changes	277	20%
5 Productivity Changes	95	7%
6 Other Direct Cost Changes	96	7%
7 Undistributable Indirect Cost Changes		
7a Engineering Cost (E) Changes	253	18%
7b Field Supervision cost (FS) Changes	276	19%
7c Other Indirect Cost (CS+ O + I&T) Changes	233	16%
Total Base Construction cost increase	**1,418**	**100%**

Items 1 through 6 are direct costs plus distributed indirect costs (those that are directly related to the change category). Item 7 are the undistributable indirect costs i.e., those that cannot be linked to the basic change categories. As stated in [14]: "Quantity Changes (Item 4) is the most important cost increase driver for the direct cost increase, accounting for 42% of the direct cost increase (including distributable indirect costs) and almost 20% of the 1978 to 1987 PWR12 base construction cost increase. This finding supports the perception that additional expansion of design features for safety improvements, too much information responses and other reasons have been major cost drivers during the last ten years. The Undistributable Indirect Cost Changes for field supervision, engineering and construction services (Item 7) are the major cost drivers, accounting for over half of the PWR12 total base construction cost increase above inflation between 1978 and 1987. Of this amount, almost 70% is for engineering and field supervision expenses. Considering the reasons for these changes, the major factors in nuclear power plant base construction cost increases appear to be those activities and practices that result from striving to meet accountability type requirements. In the past, the major cost factors were those activities and practices that resulted from improving the traditional design/construction process or the technical and safety features of plant designs."

Finally, was point out how improved and advanced PWRs design may potentially reduce un-distributed indirect cost. These results can be achieved from adopting a plant design basis that:

- relied on the availability of certified (pre-licensed) designs to reduce regulatory uncertainty in the areas of licensing, design and construction activities
- included a standardized approach to design and construction
- included modular construction to reduce site labour and associated field supervision, and to improve interfaces among engineering, field supervision and site labour.

ETI Nuclear Cost Drivers Summary Report [15]

The ETI Nuclear Cost Drivers Summary Report provides other useful insights into key cost drivers and best practices for controlling them. This project aims to investigate the reasons behind the recent cost escalation of nuclear power plant projects in North America and Europe, in contrast to plants built elsewhere during the same period, demonstrating that nuclear power can be highly cost competitive (Figure 15). In addition, an analysis of how different design solutions impact cost factors is provided.

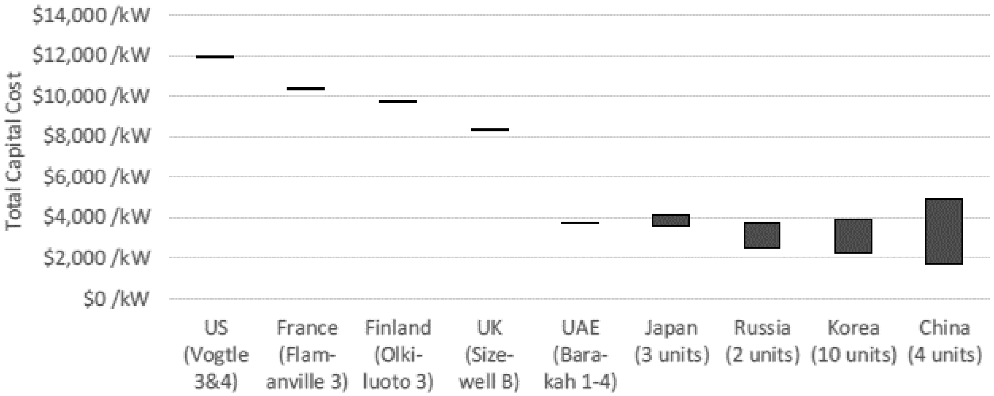

Figure 15 Total Capital Costs for Historical and Ongoing Nuclear Projects

The methodology that they adopted can be briefly summarize in the following steps:

- Identify Cost Drivers and related “indicators”
- Capture unit-specific drivers and costs using a “Scorecard”
- Store unit-specific Cost Driver Scores and Costs in Database(s)
- Collapse Costs and Scores into unit “Genres”
- Develop interactive Cost Model using Drivers and Genres

The PWR12 previously described is taken as the reference plant, but in this case the data used are from 1986. Eight Cost Drivers are identified:

- *Vendor Plant Design*: Includes all pre-construction efforts related to plant design, including design decisions, design completion, and ability to leverage past project designs.
- *Equipment and Materials*: Encompasses quantities of equipment, concrete, and steel (both nuclear and non-nuclear grade) used in the plant but also covers strategies used to address materials cost.
- *Construction Execution*: Covers all the decisions and practices carried out and support tools used by the EPC during project delivery.
- *Labour*: Involves all direct and indirect construction labour performed on the project site.
- *Project Governance and Project Development*: This driver includes all factors related to developing, contracting, financing, and operating the project by the project owner.
- *Political & Regulatory Context*: Includes the country-specific factors related to regulatory interactions and political support (both legislatively and financially).

- *Supply Chain*: Involves factors that characterise supply chain, experience, readiness, and cost of nuclear qualification as well as nuclear-grade and non-nuclear-grade equipment and materials.
- *Operations*: Covers all costs related to nuclear power plant operations (e.g.., fuel price, staff head count, wages, capacity factor, unplanned outages, etc.)

A "scorecard" is used to capture a qualitative score for each cost driver category, as well as the underlying logic that supports the assigned score. A simple scoring methodology was chosen to allow respondents to score each category using a range of -2 to 2 (Table 6).

Table 6 Cost Driver Category Scores

Category	Score
Significantly Reduces Cost	-2
Somewhat Reduces Cost	-1
Neither Increase nor Decreases Costs	0
Somewhat Increases Costs	1
Significantly Increases Cost	2

The ZERO score is associated with the benchmark facility with a total capital cost of $6,870/kW, while facilities with average scores above zero have higher costs (up to about $12,000/kW) and facilities with average scores below zero have lower costs (up to about $2,000/kW) (Figure 16).

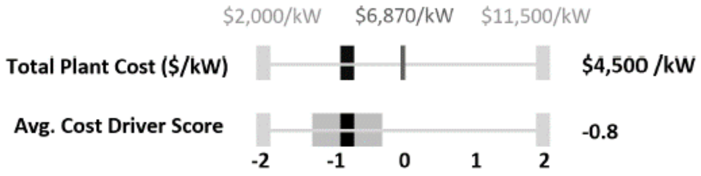

Figure 16 Dynamic Cost and Cost Driver Sliders on the plant "Scorecard”

Report findings

A strong pattern emerged that high-cost projects had started with incomplete designs, while low-cost projects were started after managers had completed the plant design and planned the construction project in detail (Figure 17). The percentage of design completion prior to the construction is one of the most important cost driver indicators. This is in line with the suggestions coming from the EEDB database.

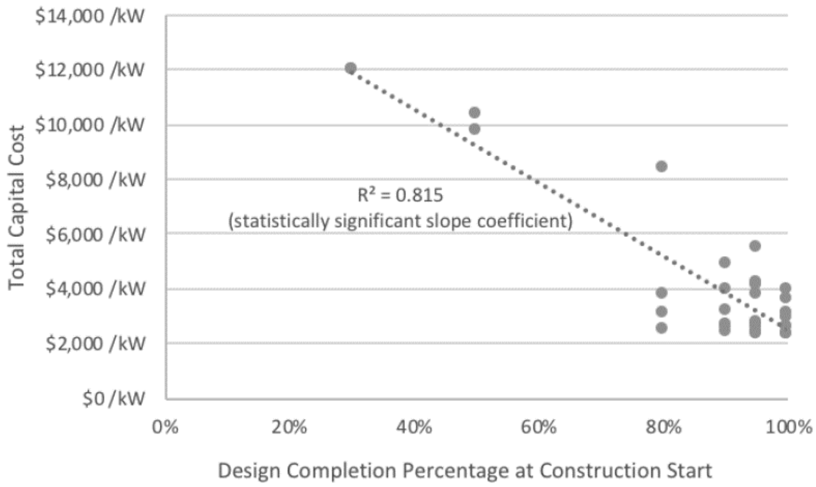

Figure 17 Design Percentage and Total Capital Cost

A total of 33 conventional nuclear plants are included in the ETI Cost Database: 25 pressurized water reactors (PWRs); 5 heavy water reactors and 3 boiling water reactors (BWRs). Several countries were involved: UK, US, France, Finland, Russia, UAE (United Arab Emirates), China, Japan and South Korea. It can be stated that Conventional Plants in Europe and North America have an average driver score of +1.4, while conventional plants in ROW have an average of -1.4. In Figure 18 are reported the LCOEs for the different Conventional Plants.

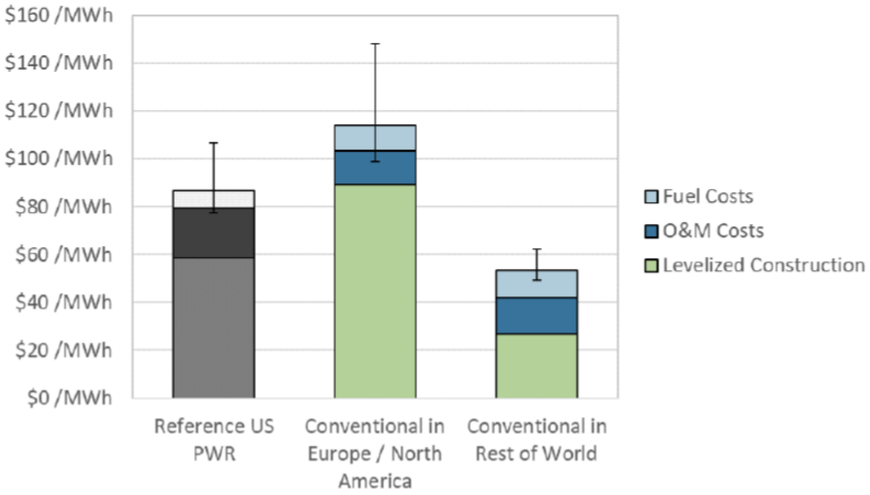

Figure 18 LCOE for Conventional Reactor Genres

While it may seem that cost depends primarily on geography, a group of lower-cost facilities demonstrates that low-cost projects are not necessarily attributable to country or context alone but are the result of a concerted effort to reduce costs across all drivers

(Figure 19). The evidence suggests that the ROW genre is the result of a highly focused, deliberate, and intentional program to reduce costs and increase performance over time. As demonstrated by Korea, which was able to lower the capital investment costs of nuclear power plants by leveraging the replication of similar plants over a short period of time.

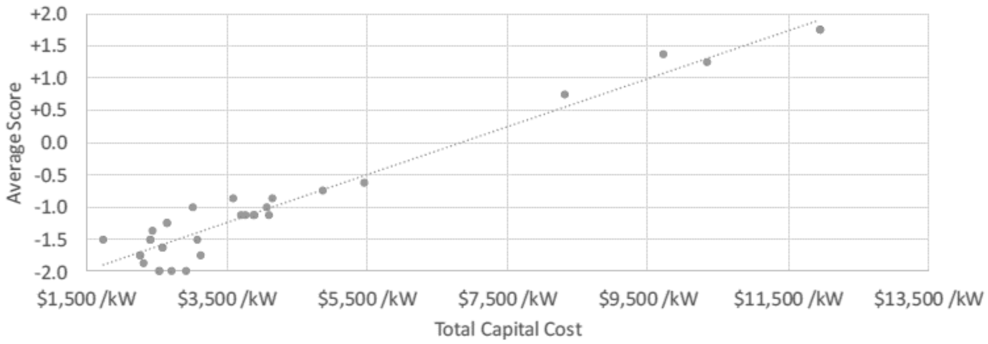

Figure 19 Relationship between Total Capital Cost and Average Score

Going deeper into the components of the total cost of capital, we see that although average wages in Western countries are higher than in the rest of the world, the ratio of direct labour costs of US/ North America plants to ROW does not reflect that of indirect cost, which is drastically higher in Western countries. This further emphasizes that the location factor is not the predominant reason for cost escalation. Another component that differs greatly between the two genders is the financial cost. obviously, this will be proportional to the amount of debt required, although in the case of western countries its weight seems to be greater than other cost items. this could be due to a higher risk premium and longer project timelines (Figure 20).

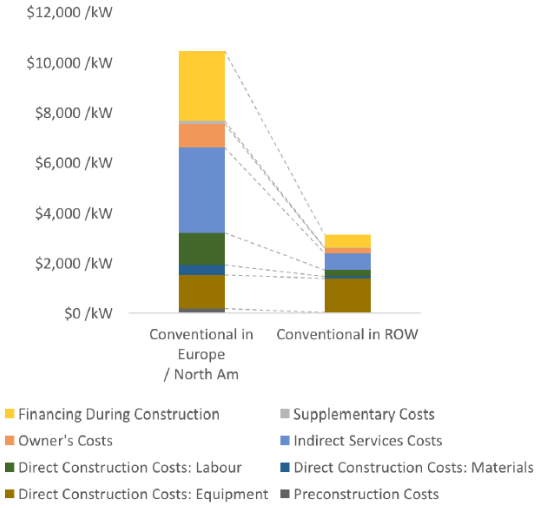

Figure 20 "Genre" Cost Comparison: EU/ North America and ROW Costs

A scenario analysis that aims to assess the impact of different capital cost rates of European and North American plants with different average driver scores is provided in Table 7. This highlights the impact of interest during construction on the final cost of electricity.

Table 7 Alternative Cost Scenarios for Conventional Nuclear in EU/North America

Avg. Score	Capex/kW	Opex	7%		6%		9%	
			Capex/MWh	LCOE	Capex/MWh	LCOE	Capex/MWh	LCOE
+1.4	\$10,454 /kW	\$25 /MWh	\$89 /MWh	\$114 /MWh	\$75 /MWh	\$99 /MWh	\$123 /MWh	\$148 /MWh
0	\$6,826 /kW	\$24 /MWh	\$58 /MWh	\$83 /MWh	\$48 /MWh	\$72 /MWh	\$84 /MWh	\$108 /MWh
-1.4	\$4,386 /kW	\$23 /MWh	\$38 /MWh	\$61 /MWh	\$29 /MWh	\$53 /MWh	\$57 /MWh	\$81 /MWh

Summarizing the information collected, the authors of the ETI report identified common characteristics of high-cost and low-cost projects, reported Table 8.

Table 8 Characteristics of Low-Cost Plants and High-Cost Plants

Low-Cost Plants	High-Cost Plants
▪ Design at or near complete prior to construction	▪ Lack of completed design before construction started
▪ High degree of design reuse	▪ Major regulatory interventions during construction
▪ Experienced construction management	▪ FOAK design
▪ Low cost and highly productive labour	▪ Litigation between project participants
▪ Experienced EPC consortium	▪ Significant delays and rework required due to supply chain
▪ Experienced supply chain	▪ Long construction schedule
▪ Detailed construction planning prior to starting construction	▪ Relatively higher labour rates and low productivity
▪ Intentional new build programme focused on cost reduction and performance improvement	▪ Relatively higher labour rates and low productivity
▪ Multiple units at a single site	▪ Insufficient oversight by owner
▪ NOAK design	

By associating these characteristics with different kinds of plants, an assessment of the unit cost of electricity is provided. Then considering advanced and SMR reactors, the impact of different strategies that can be adopted by vendors to lower the risk and cost of capital employed is assessed. These include:

- Reduced construction scope, duration, and labour, particularly at site due to fewer buildings and fewer safety systems needed due to passive safety design.
- Designed to enable a much higher percentage of factory production of key components and assemblies.
- Simpler plants design enabling a less labour-intensive Quality Assurance and verification.
- Highly standardised, modular designs
- Design for design reuse and constructability
- Designed-in seismic isolation reduces site specific design costs
- Fewer operating staff due to the inherent safety characteristics of the reactor/plant design and fuel type. In some cases, incorporating virtual/remote operation enhancements.

As shown in Figure 21, advanced reactors do present the possibility of a step change in cost reduction in EU/US markets compared to conventional EU/North America.

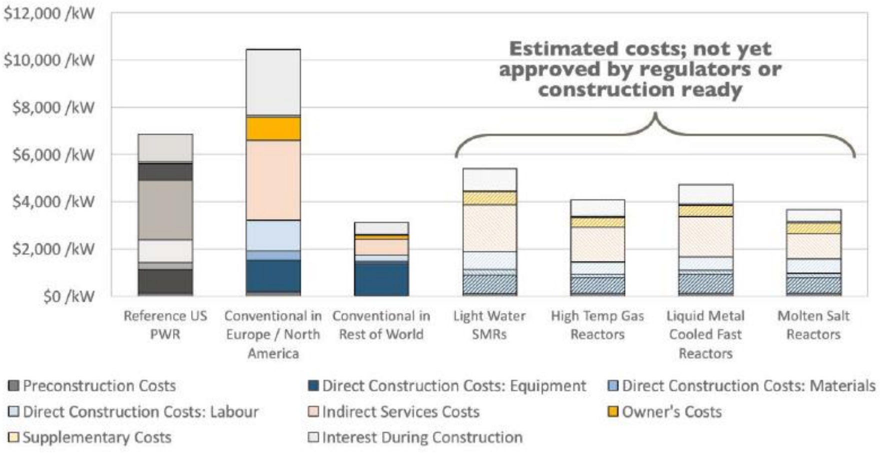

Figure 21 Comparison of Capitalised Across All Genres

In conclusion the authors of the ETI report estimated that, in Western countries it may be possible to lower the average score associated with conventional cost by -2.4 from approximately $100/MWh to $40/MWh Figure 22.

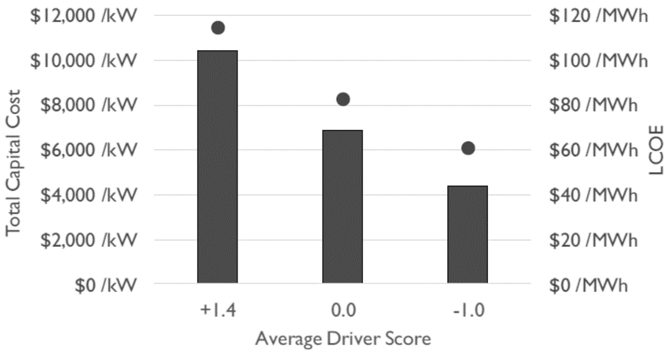

Figure 22 Cost Reduction Opportunities for EU/US Genre

In order to achieve these results, some guidance for each cost driver is provided in Table 9. Because the report is commissioned by the United Kingdom, the strategies refer to that country; however, they may apply to any other Western country.

Table 9 Cost Reduction Strategies by Cost Driver

Cost Driver	Responsible Party	Key Cost Reduction Strategies
Project Governance and Project Development	Owner	The owner's organisation needs an experienced, multi-disciplinary team
		Project owner should develop multiple units at a single site
		Follow Contracting Best Practices
		Consider an owner-led (not vendor/EPC-led) project delivery model for the UK
		Establish Cooperative partnership between owner and vendor
		Commission "cradle to grave" inspection by Independent 3rd party
Construction Execution	EPC	Projects must be guided by effective, charismatic, and experienced leaders
		Projects should be guided by an integrated, multidisciplinary project delivery team
		Leverage off site fabrication
		Sequence multiple projects to maintain labour mobilisation and consistency in delivery teams
Political and Regulatory Context	Owner	Government support should be contingent on systematic application of best practices and cost reduction measures
		Government must play a role in supporting the financing process
		Design a UK program to maximise and incentivise learning, potentially led by a newly created entity
		Support regulator exposure to projects outside the UK

		Transform regulatory interaction to focus on cost-effective safety
		Engage the Regulator early and agree on a process for resolving licensing issues
		Reform and update nuclear safety culture
Equipment and Materials	EPC / Vendor	Reduce quantity of nuclear-grade components as much as possible
		Substitute concrete with structural steel where possible
		Follow best practices to reduce material use
		Develop opportunities to use emerging technologies being used in other sectors
Supply chain	Supplier Vendors	Embrace a highly proactive approach to supply chain management and qualification
		Increase the percentage of local content over time as part of a programme of multiple units
		Develop incentive programme for suppliers against a schedule of milestones
Vendor Plant Design	Vendor	Complete design prior to starting construction
		Design for constructability
		Increasing modularity in the design should be prioritised by its potential to shorten and de-risk the critical path
		Plant design team should be multidisciplinary and include current construction expertise
		Design for plant design reuse
		Consider specific design improvements against full costs and potential benefits of implementation
Labour	Labour	Innovate new methods for developing alignment with labour around nuclear projects
		Improve labour productivity
		Invest in the labour force
		Apply principles of the Kaizen system
Operation	Operator	Involve commissioning staff and operators in project planning and related construction activities
		Develop excellence in plant operations and maintenance through training and benchmarking such as the World Associated of Nuclear Operators peer review programme

Digitalization

Another trend that cannot be ignored in the analysis is digitization. This phenomenon may be the enabler of several previously identified strategies. In fact, digital tools are improving the efficiency and effectiveness of operations in several EPC projects. As reported in [16], "It is expected that the role of digitalization will increase in the conditions of serial production of nuclear power units due to the elimination of a number of factors that caused the delay and increase in the cost of their construction for the first power units."

Organisation and management represents the dimension most affected by digital transformation. [17] identifies four opportunities:

- Increased productivity: As labour represents approximately 60% of total EPC costs, the higher degrees of automation, simplification and streamlining that can be achieved with digital tools may offer significant cost savings.
- Detailed engineering: System engineering approaches can be digitally enabled to accommodate more simulations, analyses and verification in the early stages of design, thus reducing reworking risks.
- Supply chain integration: Digital platforms shared among suppliers based on extended enterprise frameworks enable greater alignment and coordination of the supply chain.
- Quick and well-informed decision-making: Digitalisation also allows for greater unification, synchronisation and traceability of information. Plus, information can be more easily retrieved, facilitating exchanges among stakeholders.
- New operational modes: Digital tools provide the opportunity to explore processes characterised by higher collaboration, reactivity, agility and innovative thinking.

The two most impactful technologies in nuclear sector are identified by [17]: Product Lifecycle Management (PLM) and Building Information Management (BIM) systems.

PLM system acts as backbone, feeding all tools, activities and stakeholders involved in the lifecycle of an NPP with updated information. It codifies data exchanges and validation processes from systems to subsystems, and from design engineers to subcontractors throughout the entire lifecycle. PLM systems can be used to enhance and/or enabling the adoption of good practices as the "V model". This tool enables detailed front-end engineering and early verification and validation of the different components of the system. This increases the chances of getting the design right the first time and avoiding very expensive construction delays (Figure 23).

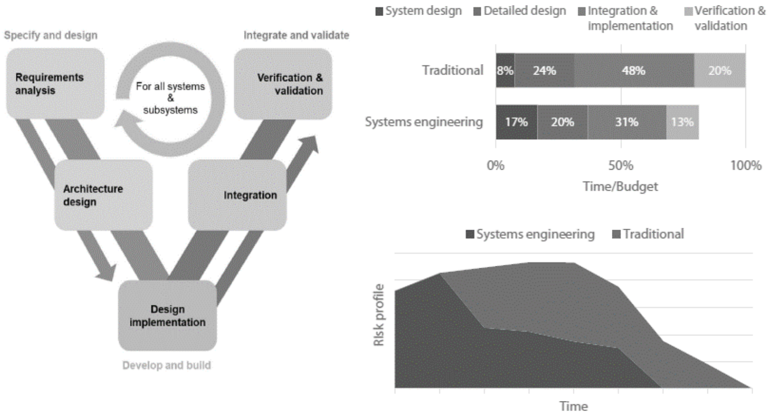

Figure 23 The SE "V model" and potential return on investment

Another benefit of PLM relates to knowledge management. Currently, business knowledge and lessons learned are closely tied to the experiences of the individual person, meaning that if that person cannot be employed in the next project, their knowledge is lost. In this context, the PLM system would become a virtual environment that can ensure continuity of data, information and knowledge throughout the supply chain, enabling learning effects in the nuclear industry.

The other digital tool is BIM. [18] defines it as "a combination of Computer Aided Design (CAD) tools and additional functionality, which gives a digital representation of the physical and functional characteristics of a facility. This can be used to collect and share facility information in order to improve decision making over the course of the life cycle". Three deployment levels are identified:

- Level 1: object-based modelling in 2D or 3D with a small degree of integration within the delivery chain, such as sharing through a common data environment. Common formats and data standards may be used.
- Level 2: situation where all parties own their own 3D CAD model, but these are not all necessarily retained on a shared model. Collaboration occurs through the sharing of information through a common file format, enabling a central federated BIM model.
- Level 3: full collaboration exists between all disciplines, using a single shared project model held in a central location. This enables all parties to view and modify the model and removes risk of conflicting information.

[18] estimates that the application of BIM has the potential to reduce capex in SMR projects by 10%. Greater savings will be achieved when the entire project delivery chain uses a single, shared platform from the earliest stages of design. These benefits are reached through:

- Reduced reworks
- Improved programming capability
- Enabling other techniques as modularisation and advanced construction methods
- Regulating paperwork

At present, not all the benefits and opportunities can be captured. In order to make the most of these tools, some major issues need to be resolved. The report [17] estimates that two-thirds of digital transformations fail and identifies the main implementation barriers:

- Organizational change. Manage and sustain the impact of digitalization on the organization may require strong leadership and a dedicated budget to absorb emerging risks and for employee training, communication and empowerment.
- Extending IT transformation throughout the supply chain. Change management, IT infrastructure and harmonization efforts must extend across the entire industry ecosystem, and this can take considerable time and effort.
- Safety and security regulations. Information sharing among stakeholders is limited by the sensitivity of nuclear industry data, which requires the highest security standards to be applied.

2.3 SMR economics and financing

An overview of the main cost drivers for nuclear power plants was provided in the previous section. Those identified are valid for both large reactors and SMRs. As shown in the results of the report [15], by design SMRs mitigate the effects of several cost drivers. As demonstrated in [12] these features allow SMRs to bridge the loss of economies of scale relative to LRs, improving the affordability and sustainability of nuclear power plant investments. In addition, SMRs can be a solution to stop the dramatic cost trend identified in [14]. In the following section, an in-depth economic and financial analysis of SMRs is provided; all information reported refers to the book chapter [12].

Investment and risk factors

Nuclear power plant projects are capital-intensive investments that require long payback periods. This condition exposes the project to high uncertainty related to market and socio-political conditions, which can affect construction execution or operations. Any change in cost or plant performance at these stages can have huge effects on returns. These risks and uncertainties are common to all capital-intensive projects, but in addition to these, nuclear power plants are also affected by industry-specific risks, putting even more of a challenge to their implementation. Table 10 provides an overview of the major risks.

Table 10 Main risk factors of capital-intensive and nuclear-specific industry

Risk factors, common to capital-intensive industries	Risk factors, nuclear-specific
▪ Complex and highly capital intensive: high up-front capital costs ▪ Cost uncertainty ▪ Completion risks: construction supply chain risks ▪ Long lead times (engineering & construction, etc.) and long payback periods ▪ Sensitive to interest rates ▪ Plant reliability/availability/load factor ▪ Market price of output (i.e., electricity)	▪ Unstable public support ▪ Negative public acceptance ▪ Regulatory/policy risks (revised safety measures) ▪ Decommissioning and waste cost/liabilities

The most challenging phase is construction, during which time various risks such as raw material prices, supply chain, vendor credit engineering, and construction contract performance affect investment KPIs. As experienced in the past, these can generate significant time and cost overruns that are difficult to predict and recover from. Risk and uncertainty result in a low financial rating for the project, leading to a high-risk premium. Therefore, the resulting interest during construction (IDC) represents a significant portion of the capital cost. By taking these factors into consideration, SMRs can improve the attractiveness of the investment:

- Reducing up-front investment and business risk diversification
- Controlling construction lead times and costs
- Controlling market risk

Reducing up-front investment and business risk diversification

Financial risk is related to the amount of investment. A typical strategy adopted by banks to mitigate credit risk is to diversify the loan portfolio. The same is true for the shareholder investor. A very high capital exposure in a single project represents a stress on the balance sheet and a significant exposure to financial and industry risk.

The risk premium can be estimated by comparing the amount of the investment with the size of the investing company; in particular, the risk premium increases at an exponential rate as the size of the project approaches the size of the investing company. If the size of the investment in various baseload technologies is compared to the average annual revenue of a utility (Figure 24), it becomes apparent that SMRs should be viewed more favourably by the investment community and bear a lower risk premium than very large reactors.

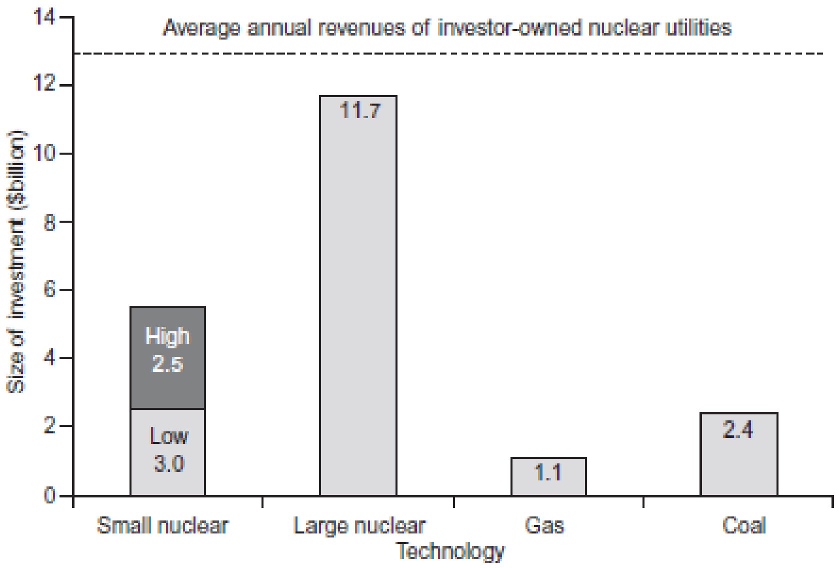

Figure 24 Confront of investment size with average annual revenues of investors

Due to increased accessibility, SMRs provide business diversification in small and/or budget-constrained markets. Finally, if the SMR units are deployed

Controlling construction lead times and costs

The reduced plant size and complexity and design simplifications that characterize SMRs are expected to:

- improve control over a shorter construction time through greater factory fabrication content and reactor modularization
- reduce supply chain risks by leveraging the availability of more suppliers and less need for specialized manufacturing and installations
- increase control over construction costs by leveraging standardization and learning economies.

Controlling over market risk

Multiple SMRs represent both a "modular" design concept and a "modular" investment model. In fact, multiple SMRs can offer the investor a gradual entry into the nuclear market, in some cases providing self-funding for the units built subsequently. This guarantees a minimum of flexibility to the design, enabling it to respond to changes in the market or regulatory environment, or to adapt to technological innovations.

Economy of scale

As mentioned earlier, the construction of nuclear power plants requires huge upfront investments constituting the heaviest component of LUEC. So, over the years, in order to spread that cost over more capacity, designers have focused on increasing reactor power. Citing [12], "The US utilities converged to 1,000–1,400 MWe sized plants, French NPPs were scaled from 950 to 1,550 MWe in the 1971–1999 period, up to the recent 1,600 MWe European Pressurized Reactor (EPR)". However, as recent experience has shown, increasing plant size was matched by a dramatic increase in plant construction complexity, negating all the benefits of economies of scale. In contrast, SMRs aim to reduce reactor size, promising to overcome most of the problems that emerged for LRs. As a result, [19] estimates that the loss of economies of scale for a stand-alone 335MWe SMR respect to a 1,340 MWe LR corresponds to 70% cost increase on a unit base (€/kWe). However, the economic disadvantage is offset by leveraging other cost factors. In particular, [19] identifies the most important differential economic characteristics between SMRs and LRs:

- learning effect
- degree of modularization
- co-siting economies
- simplified design

Figure 25 shows how the economic characteristics of SMRs allow them to make up for the loss of economy of scale relative to LRs. Specifically, the chart compares the investment opportunity on multiple SMRs and a single LR for the same total energy produced. Only the projected capital cost is considered without accounting any overrun and delay costs, which are more likely in LRs construction.

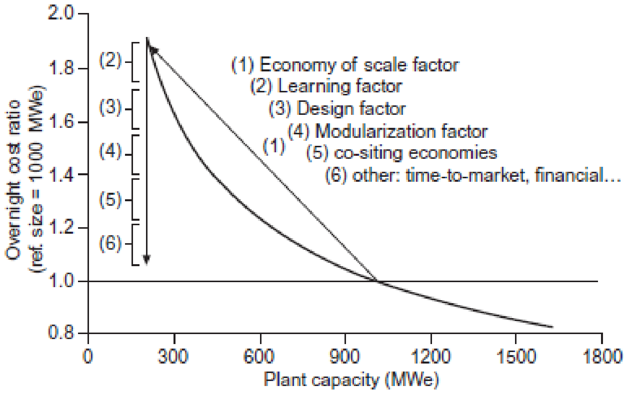

Figure 25 Overnight cost ratio between SMR and LR and the impact of cost factors

Multiple units

This factor refers to the deployment of successive NPPs based on the same technology and in the same site. Although the benefits of using multiple units apply to both SMRs and LRs, smaller reactors may benefit more from this factor. A smaller, simpler nuclear power plant with high factory content and modularization is better able to leverage standardization in both assembly and manufacturing operations. This increases the replicability of the project and the amount of knowledge that is valid in other contexts. In addition, simply because for the same amount of power, more SMR units must be built, the benefits of learning are achieved faster. Referring to the characteristics of low-cost plants defined in [15], building multiple plants and deploying a well-structured nuclear program allows setting up a powerful learning process, establishing expert supply chains, improving design reuse, and sharing the fixed cost at the same site. In line with this statement, [12] differentiates the effect of multiple units' construction in learning and co-siting economies.

Learning economies. Two types of learning are considered, a "worldwide" learning and an on-site learning. Worldwide learning "may be recorded at the engineering procurement and construction (EPC) level residing in the human resources knowledge and approach to the project management, and to the organization and procurement issues, such as supplier selection". While Worldwide learning is intended to fade out over the first five to seven units "Site-level learning accumulation is also applicable on successive NPP units built on the same site, residing in the best, refined practices and actions by local staff". On-site learning represents the key differentiator between SMRs and LRs.

Co-siting economies. This includes the sharing of common facility systems and services by multiple units built on the same site. Therefore, fixed costs, such as the indirect material cost category discussed in[14] are shared among multiple units.

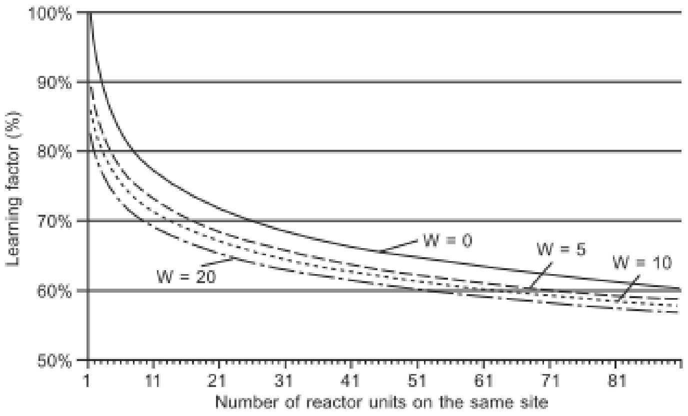

Figure 26 Learning factor vs. number of units at the same site and NNPs built (W)

Size-specific factors

Modularization

Traditionally, the construction phase of a nuclear power plant has been performed on site, starting with the raw material and major equipment. Each nuclear power plant was built specifically for each site. In contrast, SMR plants are based on the concept of modularization. As stated in [18], "Modularization is a way of simplifying construction by dividing the plant into packages (modules) that can be manufactured at the factory, transported to the site, and assembled on site (or nearby in an assembly area before being installed)".Moving more of the work to the factory allows [12]:

- better control working conditions and improve quality standards
- apply mini-serial production, promoting learning accumulation and decreasing production line overhead costs
- use less specialized on-site personnel
- reduce the construction schedule by shift from series to parallel activities
- lower financial cost escalation during construction

[18] reports that for the amount of work transferred to the factory, a 20% non-recurring cost savings can be achieved. On the other hand, however, an increase in transportation costs and supplier coordination complexity is expected. Therefore, the greatest benefits can only be achieved by overcoming these two obstacles. Although modularization can be applied to both LRs and SMRs, the latter can potentially achieve a larger portion of factory construction due to their smaller size. In [18] it is reported that SMRs can potentially displace up to 60% of the total work content in the factory, while for LRs the percentage stops at 45% (Figure 27).

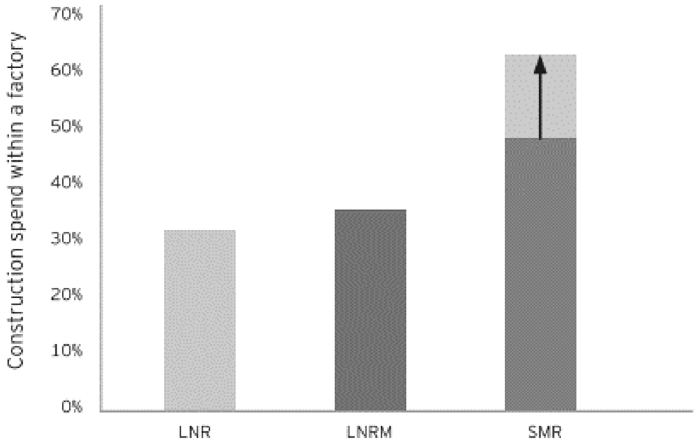

Figure 27 Percentage of factory construction for different reactor types

Design factor

SMRs are not a smaller version of LRs, but a new paradigm. With lower energy density and power, SMRs can take full advantage of passive safety systems, reducing the need for active components. For example, the ability to adopt natural circulation of the primary coolant eliminates costly reactor cooling pumps (RCPs) and the risks associated with their failure, or again, the integration of the primary circuit into the reactor vessel eliminates large coolant leakage incidents (LOCAs) and the active safety system to contain them. Design savings are specifically tied to reactor concepts, and their benefits can only be captured by bottom-up estimation. The lower the power output the higher the cost savings achievable through design choices (economics of small), which is why it can be considered as a lever that can be used by developers to achieve economic goals. Figure 28 shows the design savings factors associated with reactor size.

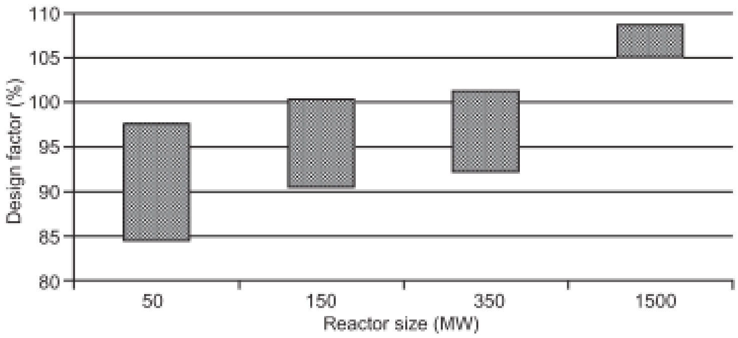

Figure 28 Design saving factor of different SMR fleets deployed in large sites

3 Methodology

Small modular reactors are an advanced technology close to deployment. Nonetheless, over the past decade there have been significant uncertainties and concerns about the cost of building nuclear power plants based on this technology. There are two main reasons for the concerns, the first being the cost and schedule overruns that have affected the most recent nuclear power plant projects in the United States and the European Union; and the second being the use of a new technology and the construction of a FOAK plant. Given the growing interest of governments in including nuclear power in their energy mix, a more in-depth estimate of the costs of SMR nuclear power plants is called for.

Several estimates have been made in the past; most are based on historical data from large-scale nuclear power plants to which scaling, and adjustment factors have been applied to account for SMR characteristics. Some of these studies are applied at a lower level of aggregation, 2-digit or 3-digit COA detail, while others consider LUEC directly. One study that has taken this approach is [15], in which different cost factors and their impact are evaluated through several interviews, then based on the inherent characteristics of SMRs and their effect on the factors, an estimate of the unit cost of electricity is provided.

Due to the lack of information on specific designs and projects, a top-down estimate is the most widely adopted approach. Nevertheless, the main problem in adopting this approach for SMR nuclear power plants is identifying a reference plant. In fact, directly scaling the available cost to a large reactor underestimates the potential of SMRs, assuming as a hypothesis that the plants are completely identical, and size is the only differential factor. In this way, only the loss of economy of scale is accounted for, distributing the fixed cost of construction over a smaller amount of energy produced, worsening the energy economy. One way to overcome this problem is to adjust the values based on plant design and project management differences, as proposed in [12].

In this paper, a bottom-up estimation is provided, assuming an approach like that proposed by [20].Therefore, the most relevant cost items are identified. For these items, an in-depth analysis on the characteristics and effects of SMRs is performed and through interviews with manufacturers, a specific estimation model is built for each of them. On the other hand, non-relevant items are estimated through the scaling method or/and by obtaining information from other sources. This approach allows balancing the effort based on the importance of the individual item while considering the main differences between SMRs and LRs. Another advantage of bottom-up estimation is that, assuming a random error in the estimate, by summing the different cost items affected by estimation errors, they are balanced in the total calculation, making the result more consistent.

3.1 Code Of Account

3.1.1 Code Of Account Selection

The analysis focuses on the cost of capital, as it is the primary contributor to LUEC. The first step in bottom-up estimation is to define the cost structure of the project, i.e., identify all cost items that make up the cost of capital. Fortunately, standard Code Of Account (COA) are already available in literature.

For many years the standard COA for construction and design costs was that adopted in the Engineering Economic Data Base (EEDB) [14], derived from an older Nuclear Utilities Services (NUS) COA. The International Atomic Energy Agency (IAEA) has developed its own system of accounts [21] that incorporates the EEDB for capital costs and develops additional codes for operation and maintenance, fuel cycle services, and other parts of the life cycle of a reactor system. The IAEA system of accounts was slightly modified to create the Generation IV International Forum (GIF) COA (2007) [22].

As one is the successor to the other, all COAs are quite similar, but some accounting differences persist. Although the GIF COA is derived from the IAEA COA and their "two-digit" structure is nearly the same, different philosophies drive the two cost decompositions. The GIF and EEDB COAs separate costs on a system-by-system basis, associating manufacturing, materials, and installation/assembly labour costs with each cost item; this allows direct and indirect costs to be separated into two separate sections. Through this approach more emphasis is placed on identifying the cost of each system (i.e., Reactor Equipment 9% of total investment cost). In contrast, the IEAE COA clearly distinguishes between material/equipment and labour costs, this allows the impact of each cost category to be assessed rather than each system (i.e., Construction and Installation 30% of total investment cost). The IAEA approach is closer to the practical approach where raw materials and labour hours are expressed as mass quantities.

In this work, the EEDB COA is adopted. In fact, a large amount of data is available in this format and its wide dissemination allows to compare the cost estimation with other authors.

3.1.2 The EEDB COA

An analysis of the EEDB COA is reported in this section. The cost structure information comes from the report [23]. Table 11 shows the composition of the total cost of capital. An analysis of direct and indirect costs is provided on the following pages. The items are analysed up to the third digit of the COA.

Table 11 Plant total capital coat estimate

EEDB Account No.	Account descriptions
20	Land and land rights
21	Structures and improvements
22	Reactor plant equipment
23	Turbine plant equipment
24	Electric plant equipment
25	Miscellaneous plant equipment
26	Main condenser heat rejection system
	Total direct cost
91	Construction services
92	AE home office engineering and services
93	Field office supervision and services
94	Owner's expenses
95	RM home office engineering and services
	Total indirect costs
	BASE CONSTRUCTION COST (Total or $/kWe)
	CONTINGENCY
	TOTAL OVERNIGHT COST (Total or $/kWe)
	ESCALATION
	INTEREST DURING CONSTRUCTION
	TOTAL CAPITAL COST (Total or $/kWe)

3.1.2.1 Direct costs

Direct cost accounts include those construction and installation costs directly associated with the operating plant structures, systems, and components. Each voice is defined as the sum of equipment costs, site labour cost and site material cost. Equipment costs include the costs for all design, analysis, fabrication, documentation preparation, pre delivery testing, and follow-up engineering performed by equipment vendors; materials for all plant equipment; equipment; transportation and insurance expenses; provision of shipping fixtures and skids; warranties; preparation of maintenance and operations manuals and handling instructions; delivery of start-up and acceptance test equipment; on-site unloading and receiving inspection expenses; and overhead expenses. The site labour portion of the construction and equipment installation costs includes all on-site activities related to permanent plant structures, systems, and equipment required for all aspects of power plant operation. Site materials include all materials purchased in the field and/or bulk items such as paint, concrete, rebar, welding rod, formwork, wire, cable, raceways and piping.

The next few pages show the cost items that make up this category; note that the representation is generic, and the items may vary from one plant drawing to another.

20 Land & land rights

This account includes the acquisition of new land for the reactor site and the land required for any co-located facilities, such as dedicated fuel cycle facilities [22].

21 Structure & Improvements

This account covers costs for civil work and civil structures, mostly buildings, excluding those for cooling towers [22]. The cost items at the third level of detail are as follows:

211 Yard work

212 Reactor containment building

213 Turbine room and heater bay

214 Security building

215 Primary auxiliary building and tunnels

216 Waste processing building

217 Fuel storage building

218 Other structures

22 Reactor plant equipment

This category is more dependent on the technology of the reactor under consideration because the subaccount descriptions and costs are highly dependent on the coolant used and whether the subsystems are factory produced or site built [22]. The cost items at the third level of detail are as follows:

220A Nuclear steam supply (NSSS)

221 Reactor equipment

222 Main heat transfer transport system

223 Safeguards system

224 Radwaste processing

225 Fuel handling and storage

226 Other reactor plant equipment

227 Reactor instrumentation and control (I&C)

228 Reactor plant miscellaneous items

23 Turbine Plant Equipment

This category assumes that electricity is the primary product. The following categories apply primarily to a steam turbine; however, similar categories would exist for gas turbines [22]. The cost items at the third level of detail are as follows:

231 Turbine generator

233 Condensing systems

234 Feedwater heating system

235 Other turbine plant equipment

236 Instrumentation and control

237 Turbine plant miscellaneous items

24 Electric Plant Equipment

Accounts 21 through 23 all have interfaces with the plant's electrical service system and its associated equipment. This equipment is located both inside and outside the main reactor/BOP buildings. I&C costs are not included in this category, but directly in the turbine and reactor equipment [22]. Cost items at the third level of detail are reported:

241 Switchgear

242 Station service equipment

243 Switchboards

244 Protective equipment

245 Electric structure and wiring

246 Power and control wiring

25 Miscellaneous plant equipment

This category is adopted to cover items that do not fall into the previous categories [22]. These include:

251 Transportation and lifting equipment

252 Air, water and steam service systems

253 Communications equipment

254 Furnishings and fixtures

255 Wastewater treatment equipment

26 Main condenser heat rejection system

This account includes heat rejection equipment such as circulating water pumps, piping, valves, and cooling towers, which may be required even if the plant does not produce electricity[22]. Costs are divided in:

261 Structures

262 Mechanical equipment

3.1.2.2 Indirect costs

Indirect cost accounts include those construction support activities necessary to design and construct the facilities and systems described in the direct cost accounts. At the two-digit account level of detail, indirect cost accounts describe construction services, central office engineering and services, and field office engineering and services.

91 Construction services

Construction services includes costs for AE-related activities associated with construction as indicated below:

911 Temporary construction facilities. This sub account includes temporary structures and facilities, janitorial services, maintenance of temporary facilities, guards and security, roads, parking lots, laydown areas, and temporary electrical, heat, air, steam and water systems, general clean-up, etc.

912 Construction tools and equipment. Construction tools and equipment include rental and/or purchase of construction equipment, small tools and consumables (fuel, lubricants, etc.), as well as maintenance of construction equipment.

913 Payroll insurance and taxes. These expenses include insurance and taxes related to craft labour (direct and indirect including guards and janitors), such as social security taxes and state unemployment taxes, workmen's compensation insurance, and public liability and property damage insurance.

914 Permits, insurance, and local taxes. Consistent with other EEDB estimates, builder's all-risk insurance will be the only cost included in Account 914.

92 Engineering and home office services

The engineering costs include all AE management, engineering design, and associated support activities. This cost element includes activities as given below.

921 Engineering and home office expenses. These costs include AE engineering and design (both field and home office), procurement and expediting activities, estimating and cost control, engineering planning and scheduling, reproduction services, and expenses associated with performance of the above functions (e.g., telephone, postage, computer use, travel, etc.). The costs for these services include salaries of personnel, direct payroll-related costs, overhead loading expenses, and fees for these services.

922 Home office quality assurance. This account includes the services of home office QA engineers and staff personnel engaged in work on the project. Services include reviews, audits, vendor surveillance, etc. as required for design and construction of the nuclear safety-related portion of the facility. Costs for these services include salaries, direct payroll-related costs, overhead loading, and expenses (e.g., travel) of these individuals.

923 Home office construction management. These services include those of the construction manager and his assistants. Services of construction planning and scheduling, construction methods, labour relations, safety, and security personnel are utilized as required. Costs for these services include salaries, direct payroll-related costs, overhead loading, and expenses.

93 Field supervision and field office services

Field Supervision and Field Office Services includes costs for AE-related activities associated with on-site management of construction, site Q/A, start-up and testing, and the supporting costs for these functions as indicated below.

931 Field office expenses. These expenses include costs associated with purchase and/or rental of furniture and equipment (including reproduction), communication charges, postage, stationery, other office supplies, first aid, and medical expenses.

932 Field job supervision. This management function includes the resident construction superintendent and his assistants; craft labour supervisors; field accounting, payroll, and administrative personnel; field construction schedulers; field purchasing personnel; warehousemen; survey parties; stenographers; and clerical personnel. Costs of these services include salaries, DPC, overhead loading, relocation costs of key personnel, and fees.

933 Field QA/QC. These services include those of personnel located at the job site engaged in equipment Inspection, required documentation of safety-related equipment, and inspection of construction activities. Costs included are salaries, DPC, and overhead loading.

934 Plant start-up and test. These services are associated with preparation of start-up and plant operation manuals and testing procedures, direction and supervision of testing of equipment and systems as the plant nears completion, and direction of start-up of the facility. Costs of these services include salaries, DPC, overhead loading, and miscellaneous related expenses. Costs of any craft labour required for start-up and testing activities are included in the appropriate direct cost line items.

94 Owners' cost

Owners' cost includes the costs of the owner for activities associated with the overall management and integration of the project and other costs not included in the direct capital costs incurred prior to start of commercial operations. It is recommended by [23] that total owner's cost is estimated as 10% of the sum of the total direct and other indirect costs plus the cost of any special coolants.

95 Reactor manufacturer's engineering

This account includes all the costs of RM services and support for the lead plant that are over and above the normal charges included in the cost of an NSSS package (EEDB Account 220A). This cost is assumed to be zero for the replica and target plant.

3.1.3 Other capital cost components

Contingency

The contingency cost should be calculated as a percentage of the overnight base cost. However, different percentages should be used for different systems or components in a facility because the amount of contingency cost should be related to the current stage or level of design, the degree of technological advancement represented by the design, and the level of quality/reliability of the given system/component. For those systems that are innovative, represent a substantial departure from previously constructed designs, or require high quality assurance in construction and operation (e.g., nuclear grade systems), a contingency cost of 25% of the applicable base cost should be calculated. For systems or components that are standard, current, off-the-shelf technology items that are being applied in a normal, industrial-grade application, a contingency cost of 15% of the applicable base cost shall be calculated. Contingency amounts for basic indirect costs are calculated as above, distinguishing the portion of indirect costs associated with innovative systems and the portion associated with standard system.

Escalation

Escalation during the design and construction period is assumed to occur at the same rate as inflation; that is, there is no real escalation during this period. Since the total cost must be expressed in constant dollars for the given year, the escalation will be zero when expressed in constant dollars.

Interest During Construction

Interest costs will be calculated based on the real, effective tax-adjusted cost of money. Interest will be calculated using cash flow summaries and the real cost of money without inflation. All interest costs will be capitalized up to the commercial operation date using the following Equation 1.

Equation 1 Interest during construction

$$Interest\ during\ construction = \sum_{t=0}^{T} C_t\left[(1+i)^{T-t}-1\right] \quad (1)$$

Where:

T = point of commercial operation.

C_t = cash flow at time t.

i = real cost of money.

If the cash flow data developed does not explicitly contain contingency costs, then the interest calculated using the cash flow summaries must be adjusted by the ratio of the total overnight cost to base construction cost as follows.

Equation 2 IDCs adjusted considering contingency cost

$$IDC_{total} = \frac{base\ cost + contingency}{base\ cost} \times IDC_{base\ cost} \quad (2)$$

3.2 Cost Items Analysis and Cost Model

As anticipated earlier, cost estimation is based on an approach similar to that of [20]. Thus, the first step is to determine the major cost items and the items that are most affected by project execution performance. A model will be built for these items by gathering information directly from the equipment manufacturer. While the remaining items are estimated using scaling factors or information from other studies.

3.2.1 Main cost items

In order to assess the most impactful costs, a Pareto analysis is performed. Specifically, the study considers the direct cost values (equipment + installation cost) of PWR12-BE [14] adjusted to 2011 $ as reported in [24]. Therefore, the three-digit COA direct cost weight is calculated on the total direct costs and three different classes are defined. Specifically, the first items accounting for 80% of the cost are class A items, 80 to 95% class B items, and the remaining up to 100% class C items. Table 12 and Figure 29 show the results of the analysis.

Table 12 Pareto Analysis - Main cost items

EEDB Account No.	Account descriptions	PWR12-BE (2011 $)	Weight	Cumulative Weight	Class 1
231	Turbine generator	$ 321,562,255.00	15%	15%	A
221	Reactor equipment	$ 197,406,910.00	9%	24%	A
212	Reactor containment building	$ 155,606,498.00	7%	31%	A
222	Main heat transfer transport system	$ 152,881,006.00	7%	38%	A
226	Other reactor plant equipment	$ 112,143,626.00	5%	43%	A
262	Mechanical equipment	$ 107,155,788.00	5%	48%	A
218	Other structures	$ 104,838,449.00	5%	53%	A
223	Safeguards system	$ 94,361,424.00	4%	57%	A
227	Reactor instrumentation and control	$ 73,253,448.00	3%	61%	A
233	Condensing systems	$ 69,556,766.00	3%	64%	A
252	Air water and steam service systems	$ 68,941,570.00	3%	67%	A
211	Yard work	$ 59,982,046.00	3%	70%	A
234	Feedwater heating system	$ 56,613,122.00	3%	73%	A
213	Turbine room and heater bay	$ 55,565,592.00	3%	75%	A
235	Other turbine plant equipment	$ 53,575,666.00	2%	78%	A
245	Electric structure and wiring	$ 53,524,039.00	2%	80%	A
224	Radwaste processing	$ 50,261,777.00	2%	82%	B

246	Power and control wiring	$	49,442,606.00	2%	85%	B
242	Station service equipment	$	48,392,131.00	2%	87%	B
215	Primary auxiliary building and tunnels	$	44,333,148.00	2%	89%	B
216	Waste processing building	$	34,481,563.00	2%	90%	B
225	Fuel handling and storage	$	29,121,984.00	1%	92%	B
241	Switchgear	$	28,671,079.00	1%	93%	B
217	Fuel storage building	$	23,709,847.00	1%	94%	B
237	Turbine plant miscellaneous items	$	19,310,160.00	1%	95%	C
228	Reactor plant miscellaneous items	$	17,885,460.00	1%	96%	C
236	Instrumentation and control	$	16,450,109.00	1%	97%	C
253	Communications equipment	$	15,396,110.00	1%	97%	C
251	Transportation and lifting equipment	$	14,385,192.00	1%	98%	C
261	Structures	$	10,398,528.00	0%	99%	C
244	Protective equipment	$	10,227,326.00	0%	99%	C
255	Wastewater treatment equipment	$	6,795,322.00	0%	99%	C
254	Furnishings and fixture	$	6,566,362.00	0%	100%	C
243	Switchboard	$	4,917,355.00	0%	100%	C
214	Security building	$	3,268,692.00	0%	100%	C

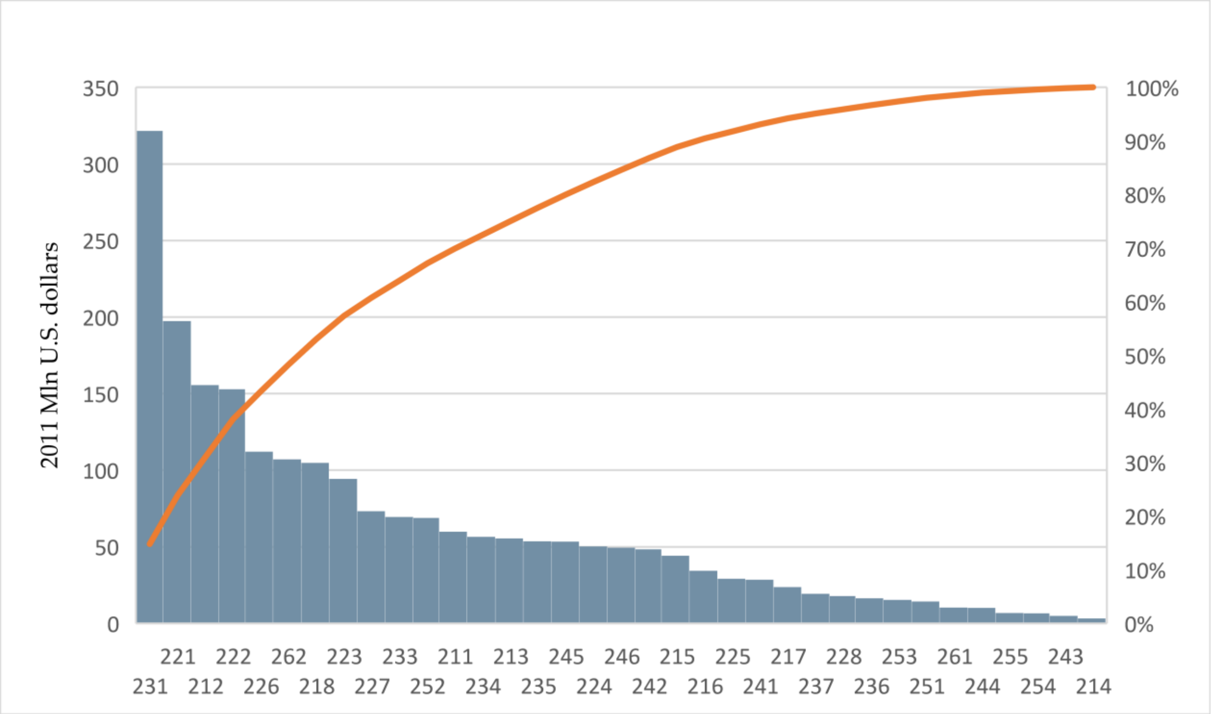

Figure 29 Pareto Analysis Chart – Main cost items

As shown in Table 13. 46% of the cost items (class A) account for 80% of the direct cost, and the top 4 account for 38%. Almost all 2-digit COA categories are represented by one or more class A items. As can be guessed, reactor equipment (22) and turbine generator equipment (23) represent the major cost drivers; class A items in these categories account for 52% of the total direct cost. Importantly, the reactor equipment item includes the NSSS as reported in [24]. The two item categories are followed by the civil structure (21), representing 17%, finally electric structure and wiring (24), heat rejection mechanical system (26) and air water and steam service system (25) consist of the remaining 10%. The results are summarized in Table 13.

Table 13 Class A items distribution over 2-digit COA – Main cost items

21 Structures and Improvements			
211	Yard work	$ 59,982,046.00	3%
212	Reactor containment building	$155,606,498.00	7%
213	Turbine room and heater bay	$ 55,565,592.00	3%
218	Other structures	$104,838,449.00	5%
			17%
22 Reactor Equipment			
221	Reactor equipment	$197,406,910.00	9%
222	Main heat transfer transport system	$152,881,006.00	7%
223	Safeguards system	$ 94,361,424.00	4%
226	Other reactor plant equipment	$112,143,626.00	5%
227	Reactor instrumentation and control	$ 73,253,448.00	3%
			29%
23 Turbine Generator Equipment			
231	Turbine generator	$321,562,255.00	15%
233	Condensing systems	$ 69,556,766.00	3%
234	Feedwater heating system	$ 56,613,122.00	3%
235	Other turbine plant equipment	$ 53,575,666.00	2%
			23%
24 Electrical Equipment			
245	Electric structure and wiring	$ 53,524,039.00	**2%**
25 Miscellaneous Equipment			
252	Air water and steam service systems	$ 68,941,570.00	**3%**
26 Heat Rejection System			
262	Mechanical equipment	$107,155,788.00	**5%**

Class A 3-digit cost items are selected to represent their category. Lesser items are estimated by scaling the cost of a benchmark facility and adjusting the values based on project-specific characteristics or by gathering information from other studies. Therefore, costs are inflated from 01/01/2011 to 01/01/2019 using a factor of 1.14 [25] and converted using the rate EUR/Dollar at 01/01/2019 equal to 1.146 [26]. The scaling factors used for each cost category are the ones reported in [27] (Table 14).

Table 14 Scaling factors

EEDB Account No.	Account descriptions	Scaling factor
21	Civil construction material	0.5
22	Reactor Plant Equipment	0.6
23	Turbine Plant Equipment	0.8
24	Electric Plant Equipment	0.4
25	Miscellaneous Plant Equipment	0.3
26	Main Condenser Heat Rej. Equip.	0.8

3.2.2 Critical cost items

From the analysis reported in Section 2.2, it is evident that cost factors related to project performance strongly influence the cost of the nuclear power plant. Therefore, to assess which cost items are most susceptible to these factors, a pareto analysis is performed based on the change in costs between 1987 PWR12-BE and PWR12-ME. Unlike the analysis in [14], the changes refer to the difference in cost between the two plants in the same year, so this is not a cost trend analysis. Costs are inflated as of January 2011 as reported in [24]. The results are shown in Table 15 and Figure 30.

Table 15 Pareto Analysis – Critical cost items

EEDB Account No.	Account descriptions	Δ PWR12-BE/ ME (2011 $)	Weight	Cumulative Weight	Class 1
212	Reactor containment building	$ 86,098,844.00	13%	13%	A
226	Other reactor plant equipment	$ 71,050,760.00	10%	23%	A
245	Electric structure and wiring	$ 58,495,431.00	9%	32%	A
218	Other structures	$ 58,146,929.00	9%	40%	A
252	Air water and steam service systems	$ 53,690,428.00	8%	48%	A
235	Other turbine plant equipment	$ 43,111,828.00	6%	55%	A
213	Turbine room and heater bay	$ 35,328,293.00	5%	60%	A
246	Power and control wiring	$ 30,308,763.00	4%	64%	A
223	Safeguards system	$ 28,735,118.00	4%	69%	A
222	Main heat transfer transport system	$ 25,467,638.00	4%	72%	A
224	Radwaste processing	$ 23,816,429.00	4%	76%	A
233	Condensing systems	$ 22,231,196.00	3%	79%	A
234	Feedwater heating system	$ 21,898,481.00	3%	82%	B
215	Primary auxiliary building and tunnels	$ 20,859,972.00	3%	85%	B

216	Waste processing building	$	19,227,619.00	3%	88%	B
211	Yard work	$	18,061,260.00	3%	91%	B
262	Mechanical equipment	$	14,970,655.00	2%	93%	B
231	Turbine generator	$	9,049,767.00	1%	94%	B
217	Fuel storage building	$	7,564,289.00	1%	96%	C
227	Reactor instrumentation and control	$	4,925,177.00	1%	96%	C
228	Reactor plant miscellaneous items	$	4,012,085.00	1%	97%	C
237	Turbine plant miscellaneous items	$	3,403,404.00	1%	97%	C
261	Structures	$	3,345,000.00	0%	98%	C
236	Instrumentation and control	$	2,702,424.00	0%	98%	C
225	Fuel handling and storage	$	2,594,916.00	0%	99%	C
253	Communications equipment	$	2,057,254.00	0%	99%	C
244	Protective equipment	$	1,713,413.00	0%	99%	C
221	Reactor equipment	$	1,619,668.00	0%	99%	C
214	Security building	$	1,326,562.00	0%	100%	C
251	Transportation and lifting equipment	$	880,286.00	0%	100%	C
255	Wastewater treatment equipment	$	464,306.00	0%	100%	C
254	Furnishings and fixture	$	398,179.00	0%	100%	C
242	Station service equipment	$	372,331.00	0%	100%	C
243	Switchboard	$	102,958.00	0%	100%	C
241	Switchgear	$	204.00	0%	100%	C

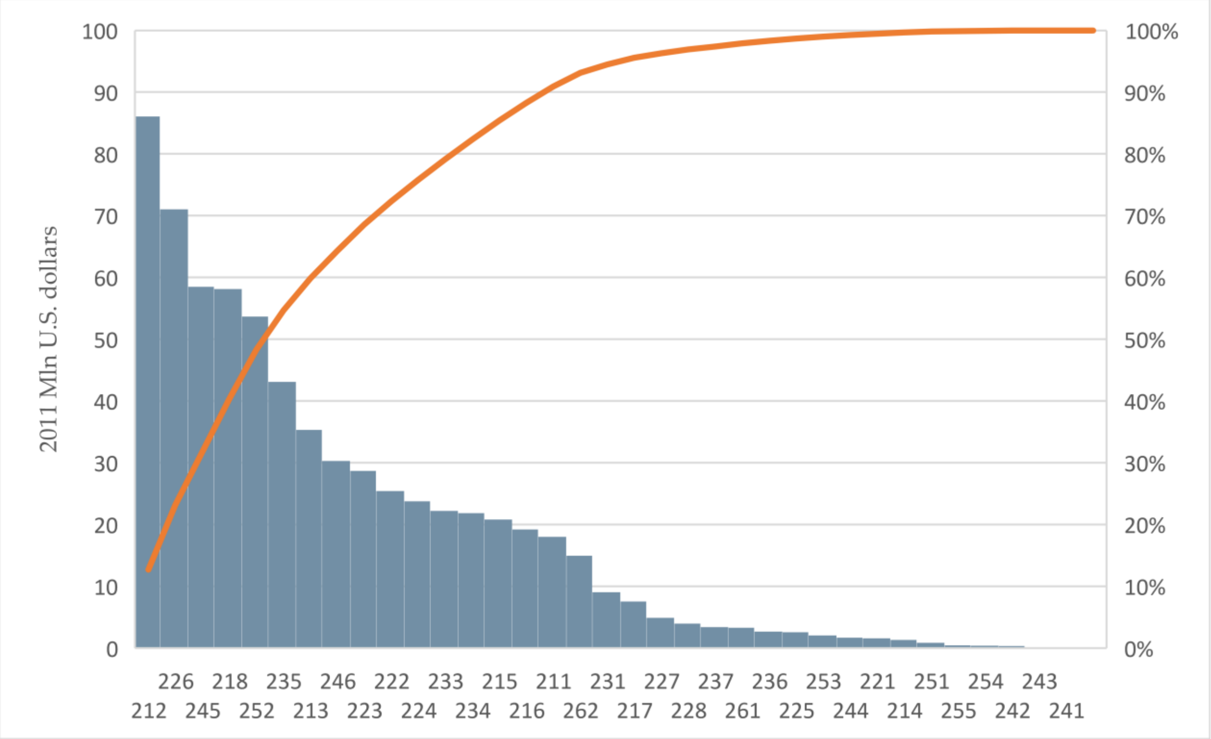

Figure 30 Pareto Analysis Chart – Critical cost items

The study shows that 34% of direct cost items account for 79% of the cost variance related to project performance. Acc. 21 Structure and Improvements is the most affected by cost variance, critical cost items (Class A items) in that category account for 26% of the overall cost variance. The item is followed by Acc. 22 Reactor equipment (22%), Acc. 24 Electrical Equipment (13%), Acc. 23 Turbine Generator Equipment (10%), and Acc. 25 Miscellaneous Equipment (8%) as shown in Table 16.

Table 16 Class A items distribution over 2-digit COA – Critical cost items

21 Structures and Improvements			
212	Reactor containment building	$86,098,844.00	13%
213	Turbine room and heater bay	$35,328,293.00	5%
218	Other structures	$58,146,929.00	9%
			26%
22 Reactor Equipment			
222	Main heat transfer transport system	$25,467,638.00	4%
223	Safeguards system	$28,735,118.00	4%
224	Radwaste processing	$23,816,429.00	4%
226	Other reactor plant equipment	$71,050,760.00	10%
			22%
23 Turbine Generator Equipment			
233	Condensing systems	$22,231,196.00	3%
235	Other turbine plant equipment	$43,111,828.00	6%
			10%
24 Electrical Equipment			
245	Electric structure and wiring	$58,495,431.00	9%
246	Power and control wiring	$30,308,763.00	4%
			13%
25 Miscellaneous Equipment			
252	Air water and steam service systems	$53,690,428.00	**8%**

The purpose of the analysis is to assess for which cost item the project management factors need to be considered. Then, the second step is to figure out what portion of that cost is subject to variation. In fact, direct costs are the sum of equipment, site materials and site labour. Then a subsequent analysis of the components of cost variation between PWR-BE and PWR-ME is performed. The data are from the 1987 DOE report [14]. The results are shown in Table 17 and Figure 31.

Table 17 Components of cost variation (1987 U.S. dollars)

EEDB Account No,	Account descriptions	Equipment cost	Site labour cost	Material cost	Total
21	Structures and improvements	$871,330.00	$76,716,707.00	$25,167,699.00	$102,755,736.00
22	Reactor plant equipment	$5,476,883.00	$56,774,429.00	$5,341,101.00	$67,592,413.00
23	Turbine plant equipment	$4,884,871.00	$34,438,890.00	$3,341,697.00	$42,665,458.00
24	Electric plant equipment	$101,866.00	$32,433,969.00	$5,377,956.00	$37,913,791.00
25	Miscellaneous plant equipment	$1,437,185.00	$21,320,441.00	$1,196,730.00	$23,954,356.00
26	Main condenser heat rejection system	$558,476.00	$6,301,061.00	$771,986.00	$7,631,523.00
	Total cost variation	**$13,330,611.00**	**$227,985,497.00**	**$41,197,169.00**	**$282,513,277.00**
21	Structures and improvements subtotal	1%	75%	24%	100%
22	Reactor plant equipment	8%	84%	8%	100%
23	Turbine plant equipment	11%	81%	8%	100%
24	Electric plant equipment	0%	86%	14%	100%
25	Miscellaneous plant equipment	6%	89%	5%	100%
26	Main condenser heat rejection system	7%	83%	10%	100%
	Cost component weight	**5%**	**81%**	**15%**	**100%**

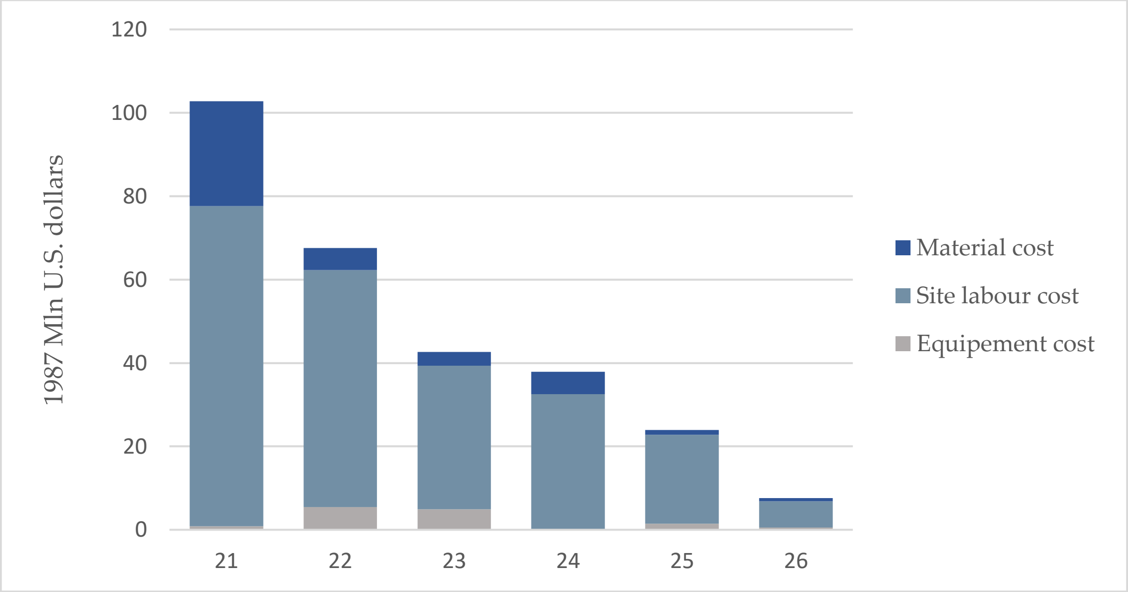

Figure 31 Components of cost variation (1987 Mln U.S. dollars)

As the Table shows, it is quite clear that most of the variation is driven by the cost of site labour (81% of the total variation), followed by the cost of materials (15%) and the cost of equipment (5%). For that matter, it is important to note that the comparison is between plants based on the same technology at the same site, so both quantities and costs of equipment and materials are similar. However, it is interesting to note that for civil construction the material cost participates in 24% of the variation in the cost item, this may not depend on site specific characteristics given the EEDB assumptions. Thus, it must be attributed to design choices and materials management capabilities.

Assuming that unitary labour cost is the same in PWR12-ME and PWR12-BE, the variation of the overall labour cost will depend on the amount of equipment/materials and work productivity. Therefore, discriminating the effect of the two factors is essential to understand the reasons behind the increase. For this purpose, the number of man-hours on the cost of equipment and material is calculated for PWR12-BE (Mh/$). Assuming the same value for PWR12-ME, can be estimate the difference in site labour hours attributable to changes in material and equipment quantities (by multiplying the PWR12-BE productivity rate (Mh/$) by the change in material plus equipment costs between PWR12-ME and PWR-BE). The result is that only 11% of the additional man-hours between PWR12 ME and BE is attributable to changes in material quantities. Therefore, the remaining 89% is due to declines in the productivity rate. It is estimated that construction of median experience facilities required +66% more on-site labour hours per dollar spent on equipment and materials than a better experience facility.

Once the main critical elements, the main cost category, and the source of cost variation have been identified, an analysis of the factors that influence productivity is needed to assess the impact of SMRs on them. As stated in [14]: " Craft labour productivity in nuclear power plants has two components. One is controlled by the workers and is related to their competence, thoroughness, organization, and incentive to do quality work. The second is outside their control and is related to rework and delays. It is the second component that appears to predominate in the causes for decreased productivity." [14] also reports the main reasons behind the inefficiencies:

- rework caused by design changes, interferences, incomplete documentation or backfitting
- increasing stringency in regulatory requirements or interpretation of requirements, particularly with respect to tolerances and worker qualification/requalification
- special training or instruction for safety-class installation procedures and documentation

- lost time beyond the control of the craftsperson (e.g., material and tool unavailability, crew interference, overcrowded work areas, inspection delays);
- scheduled overtime, use of multiple shifts and overmanning to cope with schedule slippages and cash flow problems
- extended schedules due to licensing, design, or construction delays, particularly with respect to fixed construction services (e.g., security, site maintenance, storekeepers).

Although the report refers to issues raised over time, the same factors can be considered when comparing average and better experienced facilities. Interestingly, the factors that influence site labour productivity ultimately relate to indirect labour performance.

The final step in the analysis is to identify how SMR features can reduce the influence of these factors. As stated in [15], typical strategies being pursued by advanced reactor and AMR/SMR vendors that may reduce construction costs include:

- Reduced scope, duration, and labour of construction, particularly on site, due to fewer buildings and fewer safety systems required due to passive safety design
- Leverage on a much higher percentage of factory production of key components and assemblies
- Design simpler systems that allow for less intensive verification and quality control
- Highly standardized, modular designs
- Project reuse and constructability
- Use seismic isolation that reduces site-specific design costs

Putting in place a consistent learning process through the construction of several identical NPPs, project management performances can be improved overtime reducing the cost escalation that emerged between PWR12-ME and PWR12-BE. Therefore, in the analysis costs related to the PWR12-BE and PWR12-ME are considered respectively as the NOAK and FOAK NPP. In the model the PWR12-BE represents the reference plant, while in order to account also the learning process, the cost related to the SMR FOAK is estimated by applying corrective factors on site labour and equipment plus material cost. These are defined as a ration between the respective PWR12-BE and PWR12-ME costs. Table 18 shows the corrective factors.

Table 18 Adjusting factors

EEDB Account No.	Account descriptions	Max cost adjusting factors	
		Site Labour	Equipment and Site Material
21	Structures and improvements subtotal	1.68	1.30
22	Reactor plant equipment	2.16	1.04
23	Turbine plant equipment	1.82	1.05
24	Electric plant equipment	1.93	1.12
25	Miscellaneous plant equipment	1.94	1.11
26	Main condenser heat rejection system	1.41	1.04

As a conclusion, the two pareto analyses are combined to outline the cost estimation methodology for each cost voice. Four classes of items are defined and summarized in Table 19 below:

Table 19 Cost items estimation classes

Cost item cost over total direct cost	Low	High
High	HL	HH
Low	LL	LH

Cost item variation weight over total direct cost variation

In particular:

- LL items are estimated by modelling the cost through secondary sources of information, without considering any savings between the FOAK and NOAK SMR plant
- LH items a are estimated by modelling the cost through secondary sources of information, savings between the FOAK and the NOAK are considered

- HL items are estimated gathering information directly from specific components' manufacturers without considering any savings between the FOAK and NOAK SMR plant
- HH items are estimated gathering information directly from specific components' manufacturers, savings between the FOAK and the NOAK are considered

In Table 20 below, each cost item is associated with one of the above categories.

Table 20 Cost items estimation category

EEDB Account No.	Account descriptions	Class 1 - Main Cost Items	Class 2 - Critical cost items	Cost Item Category
212	Reactor containment building	A	A	HH
226	Other reactor plant equipment	A	A	HH
245	Electric structure and wiring	A	A	HH
218	Other structures	A	A	HH
252	Air water and steam service systems	A	A	HH
235	Other turbine plant equipment	A	A	HH
213	Turbine room and heater bay	A	A	HH
223	Safeguards system	A	A	HH
222	Main heat transfer transport system	A	A	HH
233	Condensing systems	A	A	HH
234	Feedwater heating system	A	B	HL
211	Yard work	A	B	HL
262	Mechanical equipment	A	B	HL
231	Turbine generator	A	B	HL
227	Reactor instrumentation and control	A	C	HL
221	Reactor equipment	A	C	HL
246	Power and control wiring	B	A	LH
224	Radwaste processing	B	A	LH
215	Primary auxiliary building and tunnels	B	B	LL
216	Waste processing building	B	B	LL
217	Fuel storage building	B	C	LL
228	Reactor plant miscellaneous items	C	C	LL
237	Turbine plant miscellaneous items	C	C	LL
261	Structures	C	C	LL
236	Instrumentation and control	C	C	LL
225	Fuel handling and storage	B	C	LL
253	Communications equipment	C	C	LL
244	Protective equipment	C	C	LL
214	Security building	C	C	LL

251	Transportation and lifting equipment	C	C	LL
255	Wastewater treatment equipment	C	C	LL
254	Furnishings and fixture	C	C	LL
242	Station service equipment	B	C	LL
243	Switchboard	C	C	LL
241	Switchgear	B	C	LL

3.2.3 Indirect cost

Indirect cost are estimated following the methodology provided by [28]. In the study, correlations between direct and indirect costs are extracted using data for PWR12-BE and PWR12-ME. Like direct costs, EEDB divided indirect costs into factory equipment cost, on-site labor hours, on-site labor cost, and on-site material cost. For both PWR12-ME and PWR12-BE, the indirect site labor hours and site labor costs are ~36% of the direct cost of site labor hours and site labor costs, respectively. For PWR12-BE, indirect site materials costs are 78.5% of direct site materials costs, but for PWR12-ME, indirect site materials costs are 95.1% of direct site materials costs. Indirect site materials costs are primarily tools and equipment, and PWR12-ME has an average of 33% more craftsmen on site. Thus, escalating the indirect-to-direct site material cost ratio by the increase in onsite labour modelled the indirect site material cost well. Finally, the indirect costs of factory equipment are actually most of the supervision of field labor and home office services, so these costs are modelled to scale with the direct cost of site labor and construction time. In the EEDB data, the ratio of indirect factory equipment costs to direct site labor costs for PWR12-BE is 1.32 and for PWR12-ME is 1.99. The construction time for PWR12-ME is 36% longer than for PWR12-BE, so escalating the indirect factory equipment cost-to-direct site labour cost ratio by 36% modelled the indirect factory equipment cost well. Relations are reported in Table 21.

Table 21 Indirect cost modelling assumption and relations

	Base Scaling Relation	**Base Scaling Value**	**Escalation Relation**
Site Labour Cost	$\frac{PWR12\ BE\ Indirect\ Site\ Labor\ Cost}{PWR12\ BE\ Direct\ Site\ Labor\ Cost}$	36%	
Site Material Cost	$\frac{PWR12\ BE\ Indirect\ Site\ Material\ Cost}{PWR12\ BE\ Direct\ Site\ Material\ Cost}$	79%	$\frac{New\ Plant\ Average\ \#\ Workers}{PWR12\ BE\ Average\ \#\ Workers}$
Factory Equipment Cost	$\frac{PWR12\ BE\ Indirect\ Factory\ Cost}{PWR12\ BE\ Direct\ Site\ Labor\ Cost}$	132%	$\frac{New\ Plant\ Construction\ Time}{PWR12\ BE\ Construction\ Time}$

3.3 Cost equations

3.3.1 HH and HL cost items

In this section are defined the parametric equations adopted to assess the cost of the main cost items.

211 Yardwork (HL)

This cost item is estimated assuming a unitary cost equal to 69.5 €/m^2 as reported in [29]. The unitary cost is then multiplied by the total plant footprint.

212 Reactor containment building (HH)

The cost of this structure is obtained by scaling the volume of concrete from a reference plant and deriving the other components by concrete volume ratios.

The concrete volume (V_{New}) of is estimated through the use of scaling factor applied at the 1970s PWRs concrete volume, reported in [30], using the following Equation 3:

Equation 3 Concrete volume scaling equation

$$V_{New} = V_{PWR(70')} \times \left(\frac{P_{New}}{P_{PWR(70')}}\right)^{n} \qquad (3)$$

Where $V_{PWR(70')}$ is the concrete volume of the reference case cost item, while P are the electric power output of new and reference case plant, which is 1,000 MWe, and n is the scaling factor equal to 0.50, taken from [27].

Despite 1970s PWR being a GEN II reactor, this plant reflects the concreate decreasing amount trend from GEN III to GEN III+. This was possible thanks the introduction of passive safety system in the new designs [30]. Since no information about GEN III+ PWR concrete amount are available, GEN II 1970s PWR represents the more suitable reference case.

Starting from the concrete volume other recurrent cost items can be defined. Following the procedure in [30], is possible to estimate the rebar steel weight using the following Equation 4:

Equation 4 Rebar steel weight

$$M_s = f_s \frac{Vc}{\frac{1}{d_c} + \frac{1}{d_s}} \qquad (4)$$

where Vc is the volume of reinforced concrete, dc and ds are the densities of concrete (3.6 – 4.6 t/m^3) and steel respectively (7.8 – 8.0 t/m^3), and fs is the ratio of rebar mass to concrete mass. This last parameter, fs, varies for different types of structures. In the estimation the same value reported in [30] are used (Table 22).

Table 22 Rebar mass to concrete mass PWR 1970's

EEDB Account No.	Account descriptions	Rebar to concrete mass ratio (fs)
211	Site improvements	0.04
212	Reactor building	0.11
213	Turbine building	0.03
214	intake and discharge	0.03
215	Reactor auxiliaries	0.04
217	Fuel storage	0.03
218	Miscellaneous buildings	0.07
231	Turbine-generators	0.05
232	Heat rejection systems	0.03

Another recurrent cost item quantified from the concrete amount, consists in the formwork. The ratio between formwork area and concrete volume was estimated from the report [14] considering both PWR12-ME and PWR12-BE. The value used to convert the cubic metre of cement into a square metre of work is 1.68.

Material cost, of concrete, rebar, and formwork commodities, is computed as:

Equation 5 Civil material cost

$$C_M = Q_c \times C_{um} \qquad (5)$$

Where Q_c is the material quantity while C_{um} is the commodity unitary cost reported in [22]. This cost is adjusted inflating and converted to the U.S. dollars in EUR at 01/2019.

Based on the same quantities direct labour cost is estimate as:

Equation 6 Civil labour cost

$$C_L = Q_c \times F \times C_{ul} \qquad (6)$$

In which F is the productivity rate suggested in [22] and adjusted on a country base, with factors coming from [31]. C_{ul} is the unitary craft labour cost, reported in [22]. The value is inflated by a factor equal to 1.24 [25] and converted to EUR 01/2019 with a rate EUR/Dollar equal to 1.146 [26].

Other cost items such as the internal equipment (that includes plumbing and drains, HVAC, lighting and service power and elevators) and cost for minor structures are estimated scaling directly PWR12-BE actualized cost reported in [24].

Equation 7 Internal equipment scaling equation

$$C_{InEq} = C_{InPWR12-BE} \times \left(\frac{P_{New}}{P_{PWR12-BE}}\right)^n \qquad (7)$$

The scaling factor adopted is equal to 0.50, referring to the one defined in [27] for the Acc. 21 .

Excavation works are computed estimating the amount of removed soil, multiplying the building area by the average foundation depth. The amount is then multiplied by a unitary cost equal to 30 €/m^3, inclusive of material, equipment and labour cost. Both quantities and costs are taken from [29].

Finally, design specific items as the reactor containment structure and the reactor pool are quantified, in terms of material, using public information and their cost is estimated using unitary cost and productivity rates reported in [22].

As emerge from the pareto analysis the cost related to this structure are highly dependent from project execution performance that influence labour productivity. Therefore, the FOAK cost is estimated. Specifically in order to obtain the highest value the number of hours related to the concrete, rebar and steel labour are increased by a factor equal to 1.67. While material plus equipment by a factor equal to 1.3. Those values represents respectively the ratio among the PWR12-ME and PWR12-BE [14] Acc. 21 labour costs and material plus equipment costs.

213 Turbine room and heater bay (HH)

For the cost estimation of this account the same approach used for Acc. 212 is adopted. This account is affected by project execution performances, therefore in order to obtain the FOAK cost value, the cost related to concrete, rebar and steel labour are increased by a factor equal to 1.67. While material plus equipment by a factor equal to 1.3.

218 Other structures (HH)

Since a detailed plant design is not available, those items are estimated by scaling the cost from the PWR12-BE. The cost values come from the report [24]. The value is inflated by a factor equal to 1.14 [25] and converted to EUR 01/2019 with a rate EUR/Dollar equal to 1.146 [26]. Adjustments are performed to account SMRs plant differences.

The scaling factor adopted is equal to 0.5 [27]. Therefore, the following equation 8 is used:

Equation 8 Other structures cost

$$C_{218,SMR} = C_{218,PWR12-BE} \times \left(\frac{P_{SMR}}{1144\ [MWe]}\right)^{0.5} \tag{8}$$

Being an HH cost items, cost adjustments are performed. Specifically, in order to obtain the FOAK cost value, the cost related to the concrete, rebar and steel labour are increased by a factor equal to 1.68. While material plus equipment by a factor equal to 1.3. Those values represents respectively the ratio among the PWR12-ME and PWR12-BE [14] labour costs and material plus equipment costs. It is assumed that the same cost structure of Acc. 21 persists for this voice, therefore site labour cost representing 57% while, site material and equipment the remaining 43%.

221 Reactor equipment (HL)

This cost originally belonged under Acc. 220 that represent the entire NSSS but as reported in [24], the cost is distributed over different items 22x. As consequence under this voice are included costs related to the reactor pressure vessel, shell, nozzles, internal and Control rods and drives.

Acc. 221 weights 9% over the total direct cost and represent the main cost after turbine equipment. Therefore, a specific model based on primary source information is developed.

Reactor Pressure Vessel Shell

The parametric cost model of the equipment is derived interviewing high experienced companies in nuclear sector. Specifically, a high detailed cost breakdown, reported in aggregate manner in Table 23, was provided by the experts.

Table 23 Reactor pressure vessel shell costs breakdown

Items	Cost breakdown
MATERIALS	58%
FABRICATION	13%
QUALITY	27%
ENGINEERING	2%
REACTOR SHELL BASE COST	**100%**

Since the interviewed manufacturer directly purchased the forged parts, material cost includes the work related to this activity.

Once we have defined the breakdown of the reactor shell cost, the second step has been identifying the main cost drivers and how these impact on cost structure. From the discussion with the experts two factors appeared to be determinant:

- Reactor pressure vessel diameter size
- Integration of the nozzle in the forged part

The cost drivers impact on the cost distribution previously reported specifically on the cost of "Material" and "Construction".

Considering the diameter, it is realist to consider that the higher is the length the higher is the forging complexity and vice versa. Therefore, the material cost of the forging is related to those values. The same logic can be applied on the construction cost of the reactor pressure vessel. It emerged in the meetings that the impact of this specific driver corresponds to ± 2% of "Forging's shell courses" and "Construction" weights over the total cost.

On the other hand, the integration of the nozzle impact in different ways over the two cost voices. Specifically, it is expected that integrating the nozzle in the forged piece are going to reduce the construction cost of the RPV manufacturer moving part of the operation to the forged parts supplier, which will carry out more onerous work reflected on the cost of piece. In line with this logic the choice to integrate the nozzle are going to increase the weight of "Forging's shell courses" by +2% and reducing the one of "Construction" by -4%, resulting in an overall positive impact on cost equals to -2%.

To obtain the total cost of the reactor shell, transportation, manufacturer contingency and profitability are included in the model. These are expressed as percentage of Reactor shell base cost, Table 24.

Table 24 Other manufacturer reactor pressure vessel shell costs

Other costs	Weight over RVSBC
TRANSPORTATION	4%
MANUFACTURER CONTINGENCY	30%
MANUFACTURER PROFIT	10%

Finally, on-site costs are included through the model developed by [32]. The following equations 9 and 10 are used respectively for site labour cost and site material cost related to the Reactor shell installation:

Equation 9 Reactor pressure vessel shell site labour cost

$$C_{221,RVS,site\ labour} = Weight_{reactor\ shell} \times 11580\ [\frac{€}{ton}] \qquad (9)$$

Equation 10 Reactor pressure vessel shell site material cost

$$C_{221,RVS,site\ material} = Weight_{reactor\ shell} \times 1158\ [\frac{€}{ton}] \qquad (10)$$

Reactor pressure vessel internals

In the PWR the reactor vessel interiors are made up of forged stainless steel 304. Assuming the weight of this material as the main cost driver, following the guideline reported in [32], the total cost including material, manufacturing and installation are computed as:

Equation 11 Reactor pressure vessel internals cost

$$C_{221,RV\ internals} = Weight_{reactor\ internals} \times 285000\ [\frac{€}{ton}] \qquad (11)$$

Control rods and drives

To estimate this equipment the model proposed by [32] is assumed. Specifically, the following assumptions are considered for the SMRs control rods:

- control rods are mainly made of silver (80%)
- each of the control rods is composed by 24 rodlets
- the rodlets weight about 2.6 kg each

given this information the cost of the Control rods, including material and fabrication are estimated as (equation 12):

Equation 12 Control rods cost

$$C_{221,control\,rods} = N_{control\,rods} \times 55000\ [\frac{€}{each}] \tag{12}$$

Regarding control rod drives, [32] propose to estimate them through the following equation 13:

Equation 13 Control rod drives

$$C_{221,control\,rod\,drives} = N_{control\,rod\,drives} \times 0.56\ Mln\ [\frac{€}{each}] \tag{13}$$

The adoption of a multi units plant allows manufacturer to structure a consistent learning process. This is particularly relevant for standardized SMRs. Therefore, taking inspiration of the results reported in [33], the cost of the 2nd and 3rd couples of units built are reduced by 11% while the saving increased to 18% from the 4th couple of units onward. These cost adjustments are adopted to compute FOAK and NOAK cost of Acc. 221

222 Main heat transfer transport system (HH)

A detailed cost estimation based on primary information collected from manufacturers is reported in [29]. Despite this cost being a critical cost item, significant difference between the FOAK and the NOAK are not expected. In fact, thanks to the adoption of integral design, reactor coolant piping cost is completely avoided, therefore being this equipment, the main cause of cost escalation no adjusting factors is used to determine FOAK cost.

Steam Generators

This equipment is evaluated considering as the main driver the tubes' length, the pipe flow rate and their shape. Indeed, once have identify the total tube weight their cost, including manufacturing and material is computed as (equation 14):

Equation 14 Steam Generators tubes cost

$$C_{SG,tubes} = Weiht_{SG,tubes}[Kg] \times 92 \left[\frac{€}{Kg}\right] \qquad (14)$$

Continuing, even the cost of material relative to collectors is estimated based on their weight (equation 15)

Equation 15 Collectors material cost

$$C_{SG,mat,collectors} = Weiht_{SG,collectors}[Kg] \times 80 \left[\frac{€}{Kg}\right] \qquad (15)$$

The fabrication cost of collectors is evaluated based on the estimation of working time provided by the manufacturer (equation 16):

Equation 16 Collectors manufacturing cost

$$C_{SG,man,collectors} = MH_{SG,collectors}[h] \times 110 \left[\frac{€}{h}\right] \qquad (16)$$

Other equipment includes all the steam generator's supports, internals, guides and plates necessary to the construction. This is estimated as percentage of material cost of collector and tubes, through the following equation 17:

Equation 17 Steam generator other equipment cost

$$C_{SG,others} = (C_{SG,mat,collectors} + C_{SG,tubes}) \times 15\% \qquad (17)$$

Some new SMRs, as IRIS and NuScale, adopted steam generators with helicoidally shape, this are going to increase manufacturing complexity resulting in an additional cost for bending operations. Indeed, this is accounted as:

Equation 18 Tubes banding cost

$$C_{SG,tube\ banding} = N_{SG,tubes} \times 400 \left[\frac{€}{each}\right] \tag{18}$$

In order to complete fabrication cost auxiliary task are included in the model, these refers to special controls, general materials' test, engineering, miscellaneous activities, welding checks and various heat treatment. The cost of these items is directly taken from [29] based on the design under evaluation. Moreover, being part of these costs non-recurring, a saving of 20% is considered from the second to the nth systems.

Finally the cost of site installation and material are estimated using the actualized model proposed by [32]. Specifically, site installation cost for installation is reported in equation 19, while site material cost in equation 20:

Equation 19 Steam generators site installation cost

$$C_{SG,intallation} = N_{SG,} \times\ 0.48\ Mln \left[\frac{€}{each}\right] \tag{19}$$

Equation 20 Steam generators site material cost

$$C_{SG,site\ material} = N_{SG,} \times\ 0.045\ Mln \left[\frac{€}{each}\right] \tag{20}$$

On site installation cost a saving of 10% from the second unit installed onward is considered to account economies of multiple and learning.

Reactor coolant pumps

The cost of this equipment is estimated through the information reported in [29]. Since NuScale is designed to work based on natural circulation of primary reactor coolant, cost reported in this section referrers only to IRIS' components. RCPs of integrated SMRs are designed to operate submerged in the reactor coolant at hot temperatures and full reactor pressure, this allows to eliminate the need for large reactor vessel penetrations for mounting the pumps, and the necessity for the pump motor to have a high-pressure casing. In accordance with the experts, [29] proposed to consider a total cost of 4 Mln €, for each pump installed.

223 Safeguards system & 227 Reactor instrumentation and control

Acc. 223 and 227 costs are estimated from primary source information reported in [29]. Following the methodology proposed in the thesis a detail cost evaluation is computed referring to the safety systems of IRIS, for which are available technical schemas. In order to estimate the cost of reactors that adopt similar passive safety systems, specific cost adjustments are performed.

Finally taking in consideration that Acc. 223 is highly affected by project execution performances, adjustment factors are used to estimate FOAK cost. Specifically, labour cost, representing about 19% of total Acc. 223&227 cost, is multiplied by 2.16. Instead, for material and equipment, the remaining 81%, a factor equals to 1.04 is used. Cost distribution and increment factors are estimated from [24].

226 Other reactor plant equipment (HH)

The other reactor plant equipment cost is estimated directly scaling the cost of the PWR12-BE using a scaling factor equals to 0.6 (equation 21):

Equation 21 Acc. 226 scaled cost

$$C_{226,SMR} = C_{226,PWR12-BE} \times (\frac{P_{SMR}}{1144\ [MWe]})^{0.6} \tag{21}$$

To account for sharing economies, the power of multiples reactors laying under the same building is considered in the equation 21.

Finally, to estimate FOAK cost a factor equal to 2.16 is applied over the 35% of total cost, representing labour, while equipment plus material (65%) are increased by 1.04.

231 Turbine generator (HL)

Turbine generator equipment represents the most expensive components of a nuclear power plant, corresponding to 15% of total construction direct costs. The cost model proposed is developed in collaboration with one of the main experienced companies of the sector. From the interview with the experts emerged that the most appropriate method to estimate this voice is using a scaling factor equal to 0,8. Therefore, for the first step, the following equation is adopted to estimate the overall cost related to Acc. 231:

Equation 22 Acc. 231 scaled cost

$$C_{231,SMR} = C_{231,PWR12-BE} \times \left(\frac{P_{SMR}}{1144\ [MWe]}\right)^{0.8} \quad (22)$$

In order to have a more detail view of the cost structure related to this account, the output of Equation 22 is distributed over the different voices through the following Table (Table 25), extracted from cost reported in [14].

Table 25 Turbine generator cost distribution

	Equipment Cost	Site labour cost	Site material cost
Turbine-generator purchase	96,12%	0,00%	0,00%
Other turbine-generator cost	0,00%	3,41%	0,34%
Associated piping	0,00%	0,11%	0,02%

Turbine generators with a power output lower than 350 MWe present design simplification respect to the one use for large reactor. In fact, a different valve actuation fluid as well as a different turbine lubrication system is used. Moreover, the hydrogen generator is substituted by a less expensive air generator. All those characteristics are considered decreasing cost related to the purchase of Turbine generator equipment by 15%.

Considering the deployment of more units into the same plant, a discount related to a bigger job order is included. Indeed, from the manufacturer perspective, units following the first take advantage from the sharing of project and construction management cost as well the avoiding of non-recurring cost as design. All these elements are then translated into an additional cost reduction equal to 10% applied from the second unit onwards. The installation of more than one turbine in the same site also has a positive impact on installation labour cost that can leverage on economies of learning. Therefore, assuming a time lag of 8 months or less between the installation of two turbines, a saving factor equal to 4% is considered from the second unit onwards over site labour cost.

233 Condensing systems (HH)

In order to estimate Acc. 233 a model similar to the one of Acc. 231 is adopted. Therefore, costs are scaled from the relative voice of the PWR12-BE based on the amount of heat rejected, using the following equation 23:

Equation 23 Acc. 233 scaled cost

$$C_{233,SMR} = C_{233,PWR12-BE} \times \left(\frac{P_{SMR}}{2287[MWth]}\right)^{0.8} \tag{23}$$

Indeed, in order to account equipment simplification for powers lower than 350 MW a discount of 15% is assumed, moreover an additional discount on the second unit onward of 10% is considered as a learning effect on site labour cost of 4%.

Since Acc. 233 is a critical cost item, to consider complexity in the FOAK project execution factors equal to 1.05 and 1.82 are used to adjust material plus equipment cost and site labour cost respectively.

234 Feedwater heating system (HL)

Due to the strict relation of this voice with Acc. 231, a similar cost estimation model is adopted. In this case costs are scaled from the relative voice of the PWR12-BE based on the amount the thermal output of the reactor. The following equation 24 is used:

Equation 24 Acc. 234 scaled cost

$$C_{234,SMR} = C_{234,PWR12-BE} \times \left(\frac{P_{SMR}}{3431[MWth]}\right)^{0.8} \tag{24}$$

The same saving factors used for Acc. 231 and 233 are assumed to adjust cost for the first and the nth installed heating system.

235 Other turbine plant equipment (HH)

To estimate this voice experts suggest to adopt the model developed by Ganda [32]. Specifically, the model derives Acc. 235 cost from the ones of Acc. 231 based on they relation reported in [14], Table 26.

Table 26 Ratios among account 235 and 231 [32]

	Factory equipment	Site labor	Site material	Total
PWR12-BE Account 235	\$32.1 Mln	\$28.5 Mln	\$3.5 Mln	\$64.1 Mln
Account 235/account 231 cost	8.9%	130.3%	85.8%	16.7%

Therefore, account 235 costs are then calculated as:

Equation 25 Acc. 235 equipment cost

$$C_{235,eqipment,SMR} = C_{231,equipment,SMR} \times 0.089 \qquad (25)$$

Equation 26 Acc. 235 site labour cost

$$C_{235,labour,SMR} = C_{231,labour,SMR} \times 1.303 \qquad (26)$$

Equation 27 Acc. 235 site material cost

$$C_{235,material\ SMR} = C_{231,material,SMR} \times 0.167 \qquad (27)$$

Finally, being Acc. 235 costs highly affected by project management performances the FOAK cost is estimated increasing labour cost by a factor equals to 1.82 while for material plus equipment by 1.05.

245 Electric structure and wiring (HH)

Acc. 245 voice represents about 2% of total construction direct cost and based on the historical information reported in [14], it is strongly effected by project management performances. The interview with the experts revealed that the cost of such equipment has risen dramatically in recent decades due to the development of increasingly sophisticated safety devices to meet the most stringent plant safety regulations. Therefore, comparing the PWR12 developed during the 80′ with a modern PWR based on active safety systems a factor equal to 2 is suggested to be used to actualize cost of electric structure and wiring. On the other hand, the mass adoption of passive safety system allows to drastically simplify the electric system, for instance eliminating the need for emergency diesel generators and the use of class 1E equipment. Those characteristics are going to balance the cost escalation, so ultimately the model assumes a rather small increase in costs for this item, i.e., only +15% applied on PWR12-BE Acc. 245 total cost.

Once to have actualized Acc. 245 costs, the experts suggest using the scaling equation 28 with a factor equal to 0.4. Considering material cost, it is suggested to use in the formula the power of a single module and multiply the result by the number of reactors.

Equation 28 Acc. 245 material and equipment cost

$$C_{245\,eq+mat,SMR} = C_{245adj\,mat,PWR12-BE} \times (\frac{P_{SMR}}{1144\,[MWe]})^{0.4} \tag{28}$$

On the other hand, considering site labour cost, experts encourage to consider in the equation the power of two units. This allows to account the sharing of common labour activities among the modules. The hypothesis at the base is that the modules lay under the building and part of the activities are shared among the units. Therefore, the following equation 29 is adopted:

Equation 29 Acc. 245 site labour cost

$$C_{245\,labour,SMR} = C_{245adj\,labour,PWR12-BE} \times (\frac{2 \times P_{SMR}}{1144\,[MWe]})^{0.4} \tag{29}$$

The result must be multiplied by the half of the modules installed in the plant.

Acc. 245 is a critical item so cost adjustments related to project performances must be considered. Analysing the data reported in [14] emerged that between PWR12-BE and PWR12-ME labour costs increased by a factor equal to 1.93 while material plus equipment by 1.12, their weights over the total cost are respectively 81% and 19%.

252 Air water and steam service systems (HH)

Air water and steam service systems accounts for the 3% of total construction direct cost. By interviewing the experts, it emerged that the equation 30 using a scaling factor equal to 0.4, is the most appropriate method to estimate this voice. Specifically different plant's electric outputs are considered based on the NPP arrangement. For instance, the number of turbine buildings is used to fragment the total power output.

Equation 30 Acc. 252 scaled cost

$$C_{252,SMR} = C_{252,PWR12-BE} \times (\frac{P_{SMR}}{1144\ [MWe]})^{0.4} \qquad (30)$$

The FOAK cost related to this voice is estimated multiply labour and material plus equipment cost, respectively by a factor of 1.94 and 1.11.

262 Mechanical equipment (HL)

In order to estimate Acc. 262 costs, costs are scaled from the respective of PWR-12 based on the heat rejected by the system. Equation 31:

Equation 31 Acc. 262 scaled cost

$$C_{262,SMR} = C_{262,PWR12-BE} \times (\frac{P_{SMR}}{2287[MWth]})^{0.8} \qquad (31)$$

As for the Acc. 23 cost voices, cost adjustments due to the reduced size of the equipment and the purchasing and installation of multiple units, are considered. The output of the equation 31 is decreased by 15% and from the second installed unit onward a discount of 10% as a site labour leaning of 4% are accounted.

3.3.2 LH and LL items

In this section are described the cost estimation model adopted for less impacting items.

214 Security building (LL)

This item is estimated scaling the Acc. 214 cost from the PWR12-BE. The cost values coming from report [24] are inflated and converted to EUR 01/2019.

The scaling factor adopted is equal to 0.5. Therefore, the following equation 32 is used:

Equation 32 Acc. 214 cost

$$C_{214,SMR} = C_{214,PWR12-BE} \times (\frac{P_{SMR}}{1144\ [MWe]})^{0.5} \qquad (32)$$

215 Primary auxiliary building and tunnels (LL)

The same model of Acc. 212 is adopted without considering project execution performances factors.

216 Waste processing building (LL)

The same model of Acc. 212 is adopted without considering project execution performances factors.

217 Fuel storage building (LL)

The same model of Acc. 212 is adopted without considering project execution performances factors.

224 Radwaste processing (LH)

This item is estimated by scaling the cost from the PWR12-BE [24]. Values are inflated and converted to EUR 01/2019.

Costs are scaled adopting a factor equals to 0.6 [27]. The following equation 33 is used:

Equation 33 Acc. 224 cost

$$C_{224,SMR} = C_{224,PWR12-BE} \times (\frac{P_{SMR}}{1144\ [MWe]})^{0.6} \tag{33}$$

This voice is highly affected by project execution performances; therefore, the FOAK cost value is obtained applying a factor equal to 2.16 on 19% of the total cost, representing the labour. For material and equipment (81%) a factor equals to 1.04 is used. Cost distribution and increment factors are estimated from [24].

225 Fuel handling and storage (LL)

This item is estimated by scaling the cost from the PWR12-BE. The cost values coming from the report [24] are inflated and converted to EUR 01/2019.

The scaling factor adopted is equal to 0.6. Therefore, the following equation 34 is used:

Equation 34 Acc. 225 cost

$$C_{225,SMR} = C_{225,PWR12-BE} \times (\frac{P_{SMR}}{1144\ [MWe]})^{0.6} \tag{34}$$

228 Reactor plant miscellaneous items (LL)

Those items are estimated by scaling the cost from the PWR12-BE. The cost values coming from the report [24] are inflate and converted to EUR 01/2019.

The scaling factor adopted is equal to 0.6 [27]. Therefore, the following equation 35 is used:

Equation 35 Acc. 228 cost

$$C_{228,SMR} = C_{228,PWR12-BE} \times (\frac{P_{SMR}}{1144\ [MWe]})^{0.6} \tag{35}$$

237 Turbine plant miscellaneous items (LL)

Those items are estimated by scaling the cost from the PWR12-BE. The cost values coming from the report [24] are inflate and converted to EUR 01/2019.

Costs are scaled adopting a factor equals to 0.8 [27]. The following equation 36 is used:

Equation 36

$$C_{237,SMR} = C_{237,PWR12-BE} \times (\frac{P_{SMR}}{1144\ [MWe]})^{0.8} \tag{36}$$

236 Instrumentation and control (LL)

Those items are estimated by scaling the cost from the PWR12-BE. As performed [24], cost values are adjusted taking into account systems digitalization. Then costs are inflated and converted to EUR 01/2019.

In order to estimate SMR cost a factor equals to 0.8 [27], is used the following equation 37 is used:

Equation 37 Acc. 236 cost

$$C_{236,SMR} = C_{236,PWR12-BE} \times (\frac{P_{SMR}}{1144\ [MWe]})^{0.8} \tag{37}$$

241 Switchgear (LL)

This item is estimated by scaling the inflated and converted cost of the PWR12-BE plant reported in [24].

Costs are scaled adopting a factor equals to 0.4 [27]. The following equation 38 is used:

Equation 38 Acc. 241 cost

$$C_{241,SMR} = C_{241,PWR12-BE} \times (\frac{P_{SMR}}{1144\ [MWe]})^{0.4} \qquad (38)$$

242 Station service equipment (LL)

This item is estimated by scaling the cost from the PWR12-BE. The values are reduced taking into account technology modernization as performed by [24]. Then costs are inflated and converted to EUR 01/2019

Costs are scaled adopting a factor equals to 0.4 [27]. The following equation 39 is used:

Equation 39 Acc. 242 cost

$$C_{242,SMR} = C_{242,PWR12-BE} \times (\frac{P_{SMR}}{1144\ [MWe]})^{0.4} \qquad (39)$$

243 Switchboard (LL)

This item is estimated by scaling the cost from the PWR12-BE. The values are reduced taking into account technology modernization as performed by [24]. Therefore, value is inflated by a factor equal to 1.14 [25] and converted to EUR 01/2019 with a rate EUR/Dollar equal to 1.146 [26].

Costs are scaled adopting a factor equals to 0.4 [27]. The following equation 40 is used:

Equation 40 Acc. 243 cost

$$C_{243,SMR} = C_{243,PWR12-BE} \times (\frac{P_{SMR}}{1144\ [MWe]})^{0.4} \qquad (40)$$

244 Protective equipment (LL)

This item is estimated by scaling the inflated and converted cost of the PWR12-BE plant reported in [24].

The scaling factor adopted is equal to 0.4 [27]. Therefore, the following equation 41 is used:

Equation 41 Acc. 244 cost

$$C_{244,SMR} = C_{244,PWR12-BE} \times \left(\frac{P_{SMR}}{1144\ [MWe]}\right)^{0.4} \tag{41}$$

246 Power and control wiring (LH)

This item is estimated by scaling the cost from the PWR12-BE. The values are reduced taking into account technology modernization as performed by [24]. Therefore, cost values are inflated and converted to EUR 01/2019.

Costs are scaled adopting a factor equals to 0.4 [27]. The following equation 42 is used:

Equation 42 Acc. 246 cost

$$C_{246,SMR} = C_{246adj,PWR12-BE} \times \left(\frac{P_{SMR}}{1144\ [MWe]}\right)^{0.4} \tag{42}$$

Acc. 246 is a critical item so cost adjustments related to project performances must be considered. Analysing the data reported in [24] it emerged that between PWR12-BE and PWR12-ME labour costs increase by a factor equal to 1.93 while material plus equipment by 1.12, their weights over the total cost are respectively 56% and 44%.

251 Transportation and lifting equipment (LL)

Those items are estimated by scaling the inflated and converted Acc. 251 costs from the PWR12-BE. The cost values come from the report [24]. Note that in the report costs are reported under Acc. 261.

Costs are scaled adopting a factor equals to 0.3 [27]. The following equation 43 is used:

Equation 43 Acc. 251 cost

$$C_{251,SMR} = C_{251,PWR12-BE} \times \left(\frac{P_{SMR}}{1144\ [MWe]}\right)^{0.3} \tag{43}$$

253 Communications equipment

Those items are estimated by scaling the Acc. 256 costs from the PWR12-BE. The cost values come from the report [24]. Must be noticed that in the report communication equipment is accounted under Acc. 263. The advantages related to equipment modernization are offset by addition of broadband system, therefore no adjustments are considered over PWR12-BE cost. Values are just inflated and converted to EUR 01/2019.

Costs are scaled adopting a factor equals to 0.3 [27]. The following equation 44 is used:

Equation 44 Acc. 253 cost

$$C_{253,SMR} = C_{253,PWR12-BE} \times (\frac{P_{SMR}}{1144\ [MWe]})^{0.3} \qquad (44)$$

254 Furnishings and fixture (LL)

Those items are estimated by scaling the Acc. 254 costs from the PWR12-BE. The cost values come from the report [24]. Must be noticed that in [24] Furnishings and fixture are reported under Acc. 264. Those are inflated by a factor equal to 1.14 [25] and converted to EUR 01/2019 with a rate EUR/Dollar equal to 1.146 [26].

Costs are scaled adopting a factor equals to 0.3 [27]. The following equation 45 is used:

Equation 45 Acc. 254 cost

$$C_{254,SMR} = C_{254,PWR12-BE} \times (\frac{P_{SMR}}{1144\ [MWe]})^{0.3} \qquad (45)$$

255 Wastewater treatment equipment (LL)

Those items are estimated by scaling the inflated and converted costs of PWR12-BE Acc. 255. The values are taken from the report [24]. Note that in the document costs are reported under Acc. 265.

Costs are scaled adopting a factor equals to 0.3 [27]. The following equation 46 is used:

Equation 46 Acc. 255 cost

$$C_{255,SMR} = C_{255,PWR12-BE} \times (\frac{P_{SMR}}{1144\ [MWe]})^{0.3} \qquad (46)$$

261 Structures (LL)

Those items are estimated by scaling the Acc. 261 costs from the PWR12-BE. The cost values come from the report [24]. Must be noticed that in the report costs are accounted under Acc. 251. Therefore, cost values are inflated and converted to EUR 01/2019.

Costs are scaled adopting a factor equals to 0.8 [27]. The following equation 47 is used:

Equation 47 Acc. 261 cost

$$C_{261,SMR} = C_{261,PWR12-BE} \times \left(\frac{P_{SMR}}{1144\ [MWe]}\right)^{0.8} \qquad (47)$$

3.3.3 Modularization

Once the direct costs have identified, the impact of modularization on the distribution of costs between equipment and on-site labor costs is considered. Therefore, the same assumption stated by [28] is made: for modularized cost items 50% of labour costs move to factory at twice the productivity. Consequently, the cost of equipment increases as some of the on-site labor cost is shifted in-house. Also, considering that modularization involves moving larger parts, additional transportation costs are included as part of the equipment cost, these are added as a percentage of the component cost. Factory Equipment Cost, Site Labor Cost, and Site Material Cost items are identified by distributing the total item cost based on the composition of the PWR12-BE cost items from the EEDB estimate and the suggestions provided by the manufacturers. In addition, the cost escalation added to the NOAK cost to obtain the FOAK cost is redistributed based on the impact of each cost component, estimated from PWR12-BE and PWR12-ME. Based on the expert's judgement the following voices might be impacted from modularization:

- 212 Reactor containment building
- 213 Turbine room and heater bay
- 214 Security building
- 215 Primary auxiliary building and tunnels
- 216 Waste processing building
- 217 Fuel storage building
- 218 Other structures
- 221 Reactor equipment
- 222 Main heat transfer transport system

- 223 Safety system
- 231 Turbine generator
- 233 Condensing systems
- 234 Feedwater heating system
- 261 Structures
- 262 Mechanical equipment

4 IRIS and NuScale SMRs

This chapter describes the subjects of the estimate. Analysing the characteristics of the two reactor concepts is essential to capture the cost savings brought by the design choices and consider them in bottom-up cost estimation.

4.1 IRIS

IRIS (International Reactor Innovative and Secure) is a 335 MWe pressurized light water reactor with a modular, integrated, and integral primary system configuration. It has been under development since 1999 by an international team led by Westinghouse that includes 20 organizations from 10 countries, including MIT, California Berkeley and Politecnico di Milano [34]. The conceptual design of IRIS was completed in 2001, and the preliminary design development started in the same year. The pre-application licensing process with NRC started in October 2002, and IRIS was one of the designs considered by U.S. utilities for an Early Site Permit (ESP). After Westinghouse announced its new SMR design in January 2011, it also declared that the company would not pursue the commercialization of the IRIS project due to concerns regarding its size; considered too large to meet the needs of SMR customers [29].

Plant arrangement

The IRIS reactor can be deployed in two different plant layouts. The first option represents a multiple site layout with single units, allowing the deployment of 335MWe increments. This configuration is suitable for smaller markets Figure 32. The second option comprises the deployment of multiple twin units of 670MWe each, Figure 33. By adopting the first option, the initial front-end investment as well as the construction time is reduced. In addition, the construction of subsequent plants can benefit from learning economies and the investment can be partially supported by the cash-in generated by the previous plants. The second layout allows systems and facilities to be shared between two modules, reducing the unit electricity cost but delaying the start-up of the first couple of reactors. Obviously, if several twin-unit plants are deployed, the subsequent plants will have the same advantages as the first option.

Single unit plant

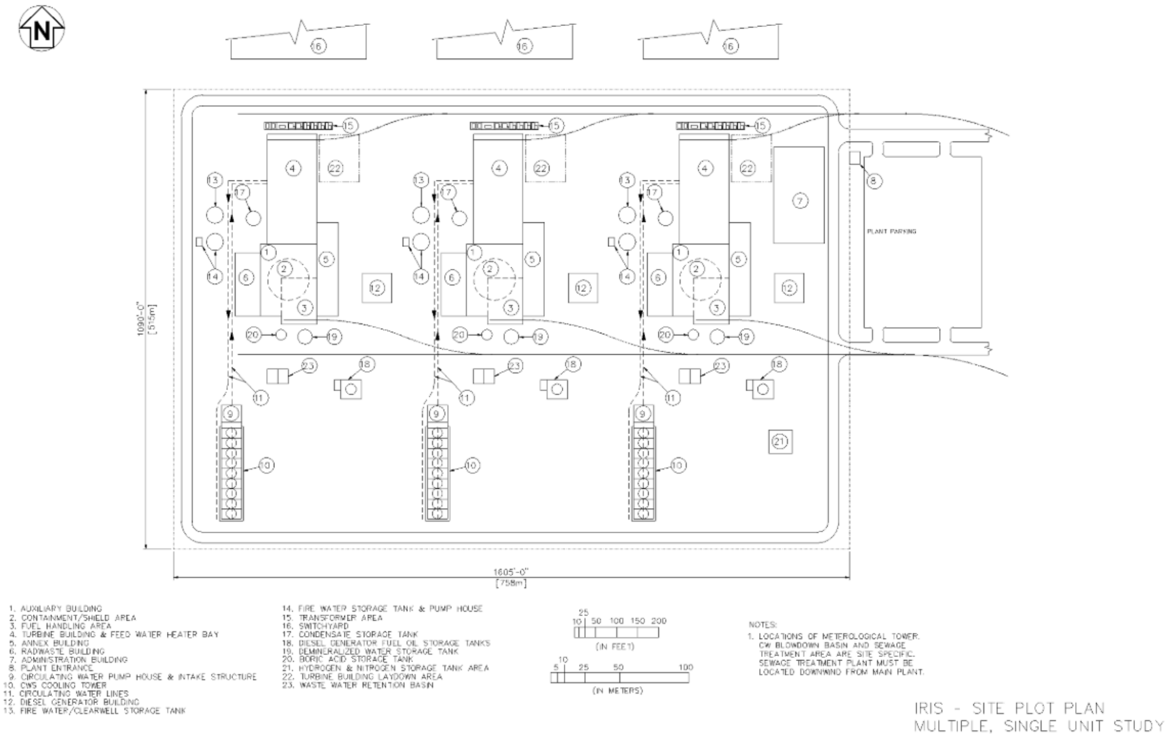

Figure 32 IRIS single unit's configuration layout

IRIS reactor is housed inside a spherical steel Containment of 25-meter diameter surrounded by a cylindrical concrete shield building (2). These are part of the auxiliary building (1) that includes the fuel handling and storage area (3), the control room the steam and feed water piping penetration area and isolation valves, safe shutdown panel, and all safety related equipment including batteries for electrical power. Adjacent to the auxiliary building are located the annex building (5) that houses access control for both the auxiliary and turbine buildings, health physics, technical support centre, and non-safety related equipment. On the opposite side of the same building is located the radwaste area (6). Finally, each module is connected to the turbine laying in its own dedicated area, that also houses all the other items related to power plant steam and feed water systems and power generation equipment (4).

Twin-units plant

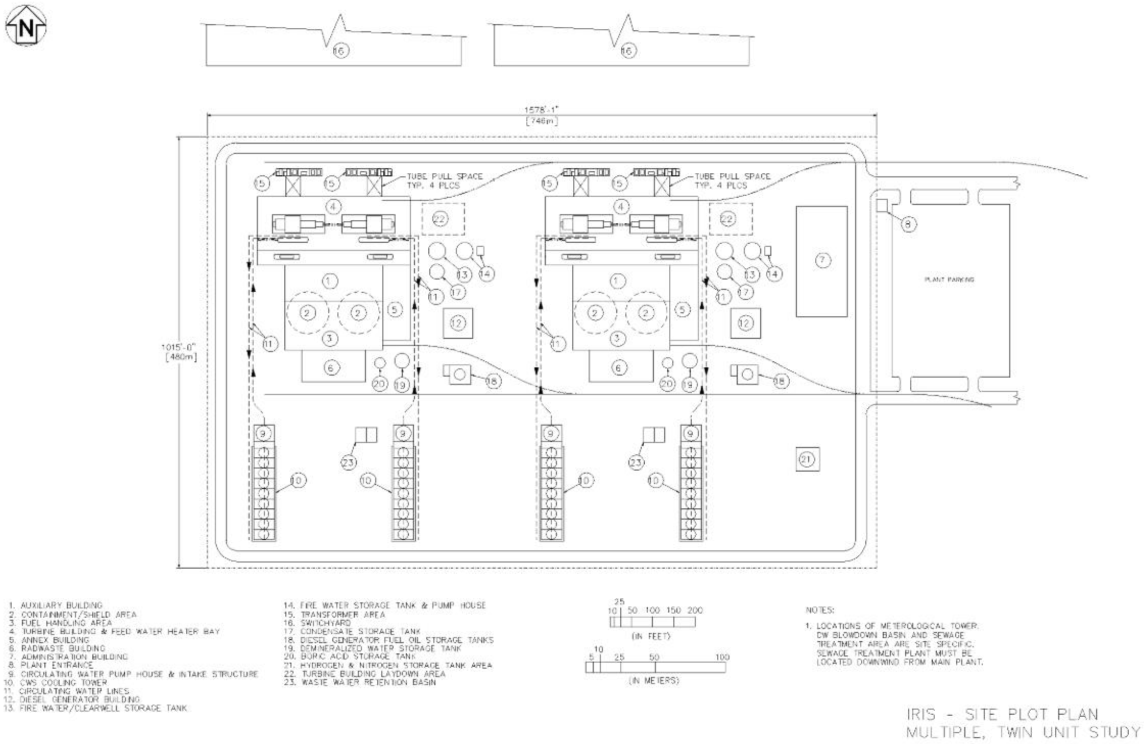

Figure 33 IRIS twin unit's configuration layout

The IRIS twin-unit auxiliary building (1) encompasses the two containment and shield buildings (2) as well as the shared fuel handling facilities and equipment (3) and is founded on a common basement. It contains typical auxiliary building features, including the shared back-to-back main control room, a steam and feed water piping penetration area and isolation valves for each reactor, safe shutdown panels, and all safety related equipment including batteries for electrical power. Separation between the safety related equipment for the two reactors is maintained throughout the building. The turbine and the other equipment associated with the power plant steam and feed water systems and power generation equipment are located under the same building (4). Nevertheless, each reactor is completely independent of each other, so all the equipment is not shared. The annex building located close to the auxiliary one is shared among the two units. [35]

Primary Circuit

IRIS integral reactor vessel has an internal diameter of 6.21 m and an overall height of 22.2 m and is housed inside a spherical steel containment that has a diameter of 25 m. RV includes the control rods with the associated drive mechanisms and all the major coolant system component comprehensive of pressurizer. Water flows upwards through the core and then through the riser region (defined by the extended core barrel). At the top of the riser, the coolant is directed into the upper part of the annular plenum between the extended core barrel and the RV inside wall, where the suction of the reactor coolant pumps is located. Eight coolant pumps are employed, and the flow from each pump is directed downward through its associated helical coil steam generator module. The primary flow path continues down through the annular downcomer region outside the core to the lower plenum and then back to the core completing the circuit, Figure 34 [34].

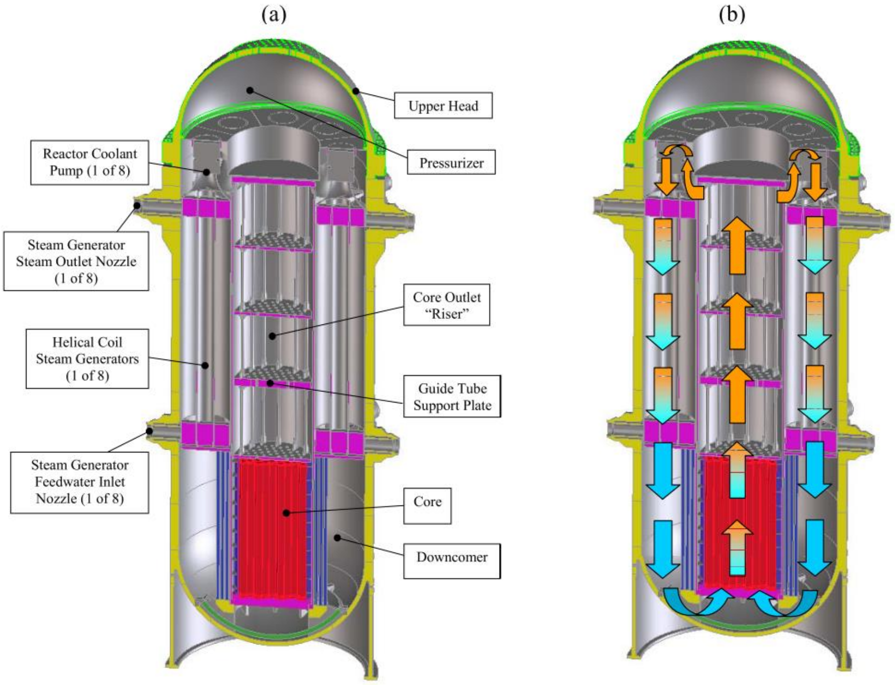

Figure 34 IRIS integral layout: (a) main components; (b) main flow path

Reactor core, fuel and refuelling operations

IRIS core configuration consists of 89 fuel assemblies, arranged in a 17×17 square array configuration, with a 4.27 m active fuel height, and a nominal thermal power of 1000 MWth. Fuel is sintered UO_2 enriched to up to 4.95%. Reactor is controlled through solid burnable absorbers, 37 control rods [35], and the use of a limited amount of soluble boron in the reactor coolant. The reduced use of soluble boron makes the temperature coefficient of the moderator more negative, thus increasing inherent safety[34].

The fuel cycle ranges from 36 up to 48 months, and the overall core fuel inventory is 48.5 tU. IRIS is equipped with a stainless-steel radial neutron reflector to lower the cost of the fuel cycle and extend the life of the reactor. Refuelling of the reactor is accomplished by removing the containment vessel closure head, installing a sealing collar between the CV and RV, and removing the RV head. The refuelling cavity above the containment and RV is then flooded, and the RV internals are removed and stored in the refuelling cavity. Fuel assemblies are vertically lifted from the RV directly into a fuel handling and storage area, using a refuelling machine located directly above the CV. Thus, no refuelling equipment is required inside containment and the single refuelling machine is used for all fuel movement activities Figure 35 [35].

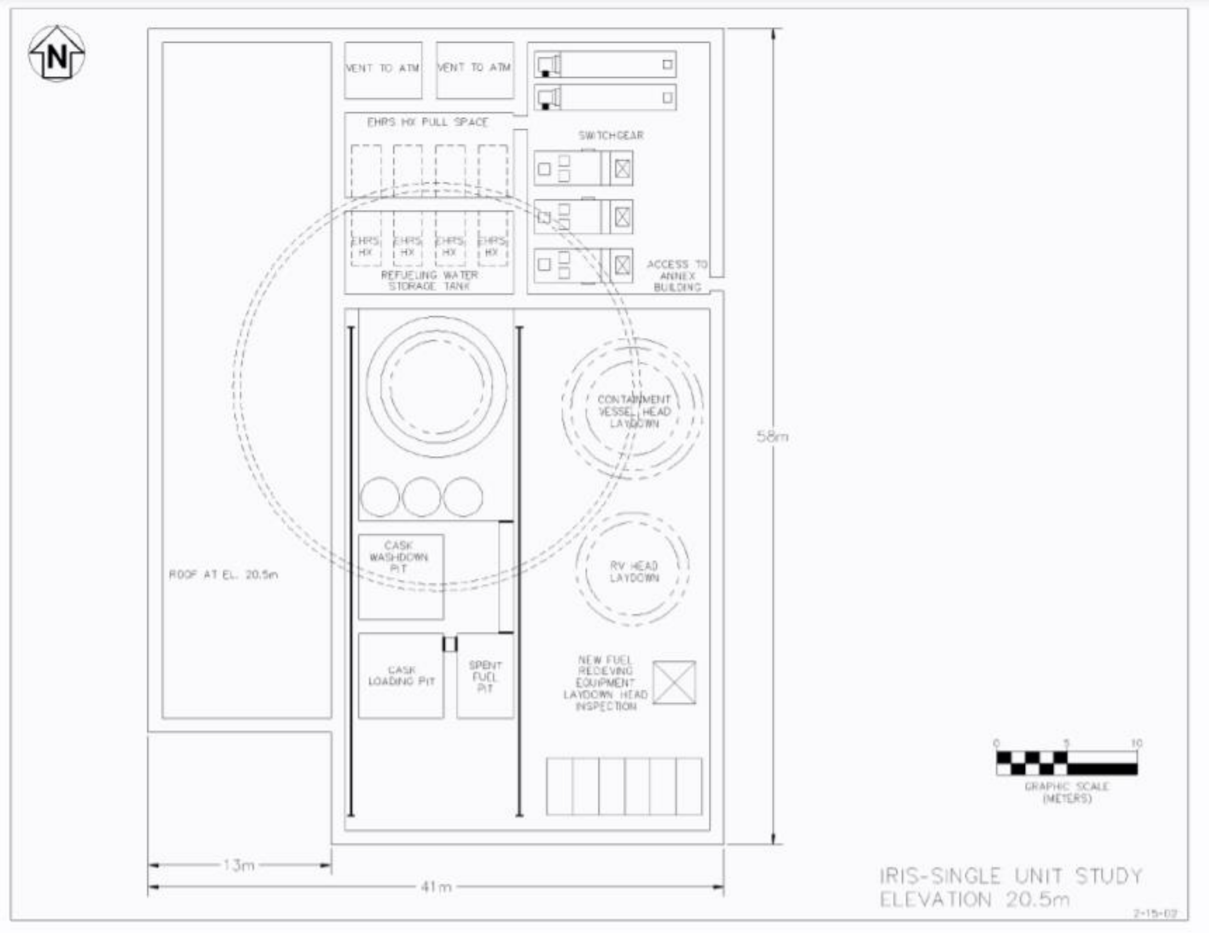

Figure 35 IRIS Auxiliary building layout at elevation +20.5 m

Secondary circuit

After conversion of the secondary coolant to steam, this is transported through pipes to the turbine. Before entering the turbine, the flow passes through the bypass system which, following a reduction in the external electrical load, has the capacity to discharge 100% of the steam generator flow into the condenser. The 335MWe turbine consists of two high-pressure and low-pressure dual-flow rotors, divided by a Moisture Separator Reheater (MSR). Exhaust steam from the high-pressure part is directed to a feedwater heating stage in the deaerator. While the condensation system collects and condenses steam from the low-pressure turbines and the turbine steam bypass and transfers it to the deaerator, passing through four stages of feedwater heating[36]. Finally, the water is pumped back into the steam generators, restarting the cycle (Figure 36).

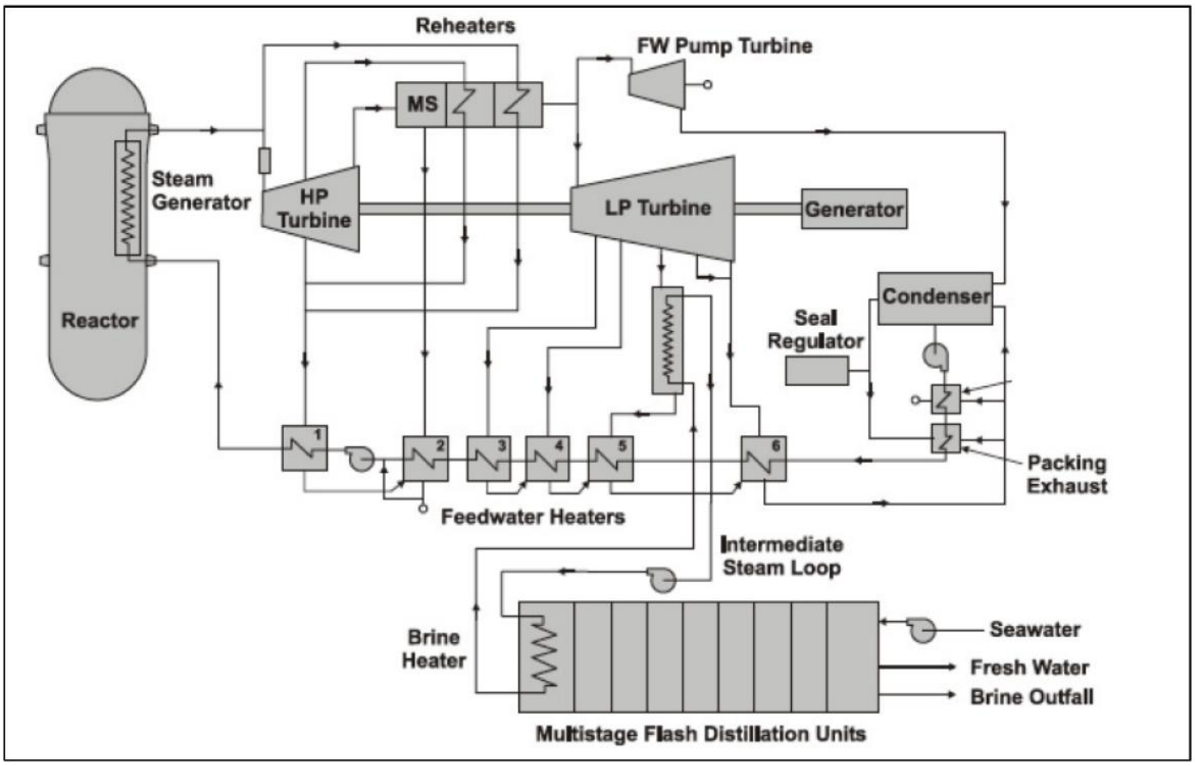

Figure 36 IRIS secondary circuit

Electrical, I&C, and Human Interface

The IRIS instrumentation and control architecture is arranged in a hierarchical manner to provide a simplified, structured design that is horizontally and vertically integrated. Information is pulled up from a data highway/monitor bus to control centres and data displays that facilitate the interaction between the plant operators and the I&C. The safety monitoring system, the plant control system, and the in-core instrumentation system operate directly from the plant sensors. The plant control system (PLS) has the function of establishing and maintaining the plant operating conditions within prescribed limits. Moreover, in case of failure, diverse actuation system (DAS) provides an alternative means of initiating the reactor trip and emergency safety features. The hardware and software used to implement the DAS are different from the hardware and software used to implement the protection and safety monitoring system. The IRIS operation and control will be provided from an advanced main control room that incorporates the latest man-machine interface features and advanced display and control technologies. In addition, IRIS will include a separate remote shutdown workstation, a waste processing control room, and a technical support centre. The on-site power system is designed to provide reliable electric power to the plant safety and non-safety equipment for normal plant operation, start-up, and normal shut down, and for accident mitigation and emergency shutdown. The on-site power systems include the main AC power system and the DC power system. The main AC power is a non-Class IE system. The DC power system consists of two independent systems, one Class IE and one non-Class IE. A key feature of the IRIS plant configuration is the stacked arrangement of the Class IE battery rooms, the dc switchgear rooms, the integrated protection system rooms, and the main control room. This stacked arrangement eliminates the need for the upper and lower cable spreading rooms that are required in the current generation of PWR plants[35].

Safety features and systems

The IRIS safety system design uses gravitational forces instead of active components such as pumps, fan coolers or sprays and their supporting systems. The main safety system involved in the IRIS safety strategy are the following.

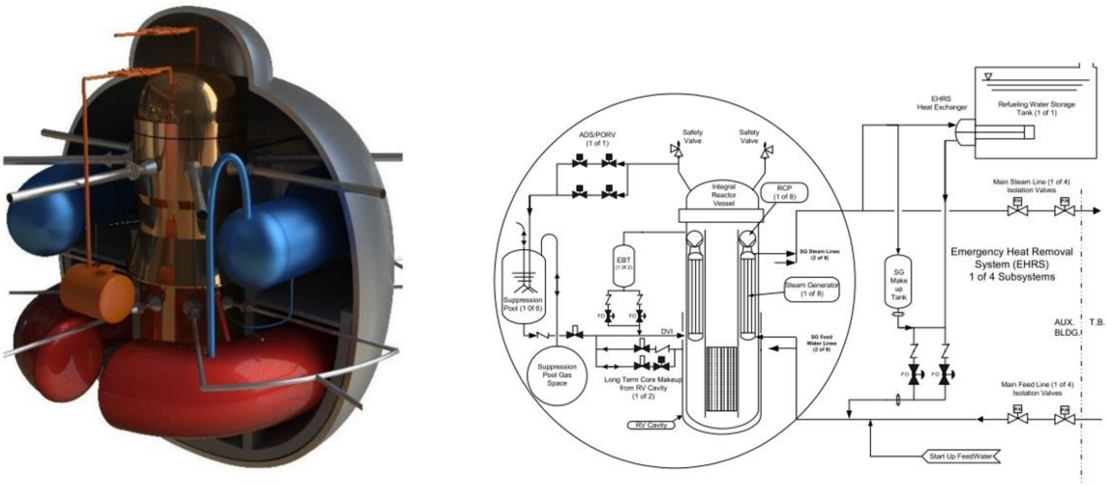

Figure 37 IRIS passive safety systems

Emergency Heat Removal System (EHRS)

A passive Emergency Heat Removal System (EHRS) consisting of four independent trains of horizontal U-tube heat exchanger located in the refuelling water storage tank (RWST). They are placed outside the containment structure and connected to the four separate SG feed/steam lines. A single train can provide decay heat removal, in case of a loss of secondary coolant. The system works by natural circulation eliminating the risk of pumps failures. The EHRS provides the main post- LOCA depressurization and coolant makeup function for IRIS [34].

Automatic Depressurization System

An Automatic Depressurization System (ADS) from the pressurizer steam space, formed by two parallel lines, each with two normally closed valves. The single ADS line discharges into the pressure suppression system pool tanks through a sparger. This ADS function ensures that the reactor vessel and containment pressures are equalized in a timely manner limiting the loss of coolant and thus preventing core uncovering following a LOCAs [34].

Emergency Boration Tanks

Two Emergency Boration Tanks (EBTs) that can deliver borated water to the Reactor Vessel through the Direct Vessel Injection (DVI) lines[34].

Pressure Suppression System

A containment Pressure Suppression System (PSS) made up of six water tanks and a common tank for non-condensable gas storage. Each suppression water tank is connected to the containment atmosphere through a vent pipe linked to a submerged sparger to condense steam released in the containment following a loss of coolant or steam/feed line break accident. The suppression system limits the peak containment pressure following a blowdown event to less than the containment design pressure and ensures an elevated source of water that is available for gravity injection into the reactor vessel [34].

Lower containment volume

A specially constructed lower containment volume that collects the liquid break flow, as well as any condensate from the containment, in a cavity where the reactor vessel is located. Following a LOCA, the cavity floods above the core level, creating a gravity head of water sufficient to provide coolant makeup to the reactor vessel through the DVI lines down the reactor vessel. It also provides a path for gravity injection to the coolant system from the CPSS [34].

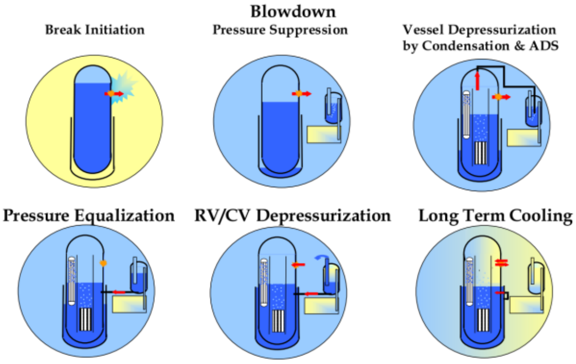

Figure 38 Overview of IRIS response to loss of coolant accidents

Key information is summarized in Table 27.

Table 27 Summary of IRIS' characteristics

IRIS		
Parameter	**Value**	**Note**
Design Life	60	Years
Lifetime Capacity Factor	N/D	%
Site footprint	285,000	m^2 (2 single units' configuration)
	202,000	m^2 (twin-units' configurations)
Plant configurations	335/1	MWe/#modules (single unit configuration)
	670/2	MWe/#modules (twin-units configuration)
Thermal capacity	1002	MWth
Electrical capacity	335	MWe
Reactor Type	PWR	
NSSS Layout	Integral	
Neutron Moderator	H_2O	
Core Coolant	H_2O	
Primary Circulation	Forced	
Thermodynamic Cycle	Rankine	
Secondary Side Fluid	H_2O	
NSSS Operating Pressure (primary/secondary)	15.5/5.8	MPa
Nominal Coolant Flow Rate (primary/secondary)	4700/503	Kg/s
Core Inlet/Outlet Coolant Temperature	292/330	°C/°C
Refuelling Cycle	48 (max)	months
Fuel Material	UO_2	
Enrichment	<4.95	%
Main Reactivity Control	Control rods, Boric acid	
Approach to safety systems	Passive	

4.2 NuScale

NuScale reactor is a 77MWe PRW developed by the start-up NuScale Power Inc. The precursor concept was developed in 2003 within the Multi-Application Small LWR—MASLWR Program [37]. In 2020, NuScale was the first ever small modular reactor (SMR) to receive NRC design approval. The NRC completed Phase 6 review, the last and final phase of NuScale's Design Certification Application (DCA) with the issuance of the Final Safety Evaluation Report (FSER) [38]. Also, in the same year, the NRC issued Standard Design Approval, which means customers can move forward with plans to develop NuScale VOYGR™ power plants. In 2027, the first commercial plant is scheduled to start up.

NuScale plant consists of 1 to 12 independent modules, so the maximum power plant output is up to 924MWe [38]. Each module includes an integral Pressurized Light Water Reactor operating under natural circulation primary flow conditions. Each reactor is housed within its own high pressure containment vessel that is immersed underwater in a concrete pool lined with stainless steel [39].

Plant arrangement

A rendering of the site layout for a 12-module NuScale plant is shown in Figure 39. All safety systems are located in the reactor building positioned in the centre of the site. The reactor building is flanked by two turbine buildings containing six turbine-generator units each, the control room building and the radioactive waste management building. Forced draught cooling towers are used to cool the condensers. The site also includes a switchyard, an administrative building, a warehouse, and a spent fuel interim storage facility. The total area within the protected boundary is nominally 140,000 m². A construction time of 36 months is estimated for NOAK plant [37].

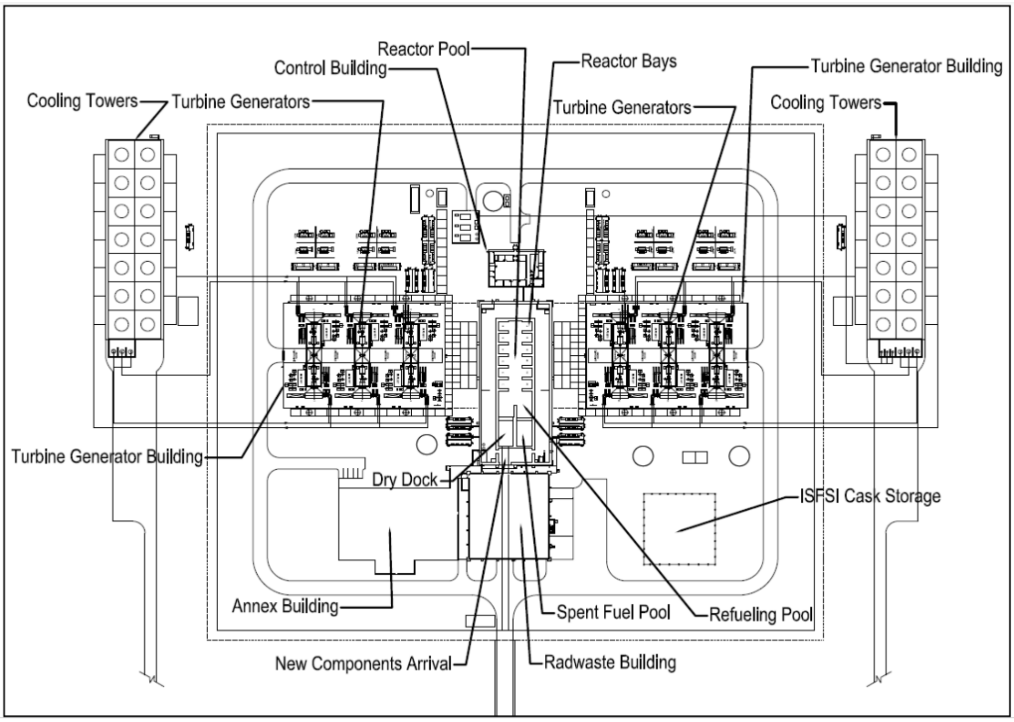

Figure 39 NuScale plant layout

Primary Circuit

The reactor pressure vessel (RPV) is approximately 19.8 m long and 2.7 m in diameter. It is housed in a steel containment vessel with a total height of about 23 m and an outer diameter of about 4.6 m, operating at a vacuum pressure and a temperature of 37 ºC [38]. The integrated design encompasses the nuclear core, two interwoven coil steam generators and a pressurizer. The reactor operates using the principles of natural circulation; therefore, no RCPs and associated valves and pipes are required. The water, heated by the core, rises due to its lower density though a riser tube, once it is at the top of the RPV, the water is cooled by passing through two helical spiral steam generators, increasing the density of the liquid which consequently falls back into the core, restarting the cycle (Figure 40). Inside the two helical coils, feed water is pumped to where it boils to generate superheated steam. Pressuriser heaters and sprayers are located in the upper head of the vessel to provide pressure control. The modules operate below ground level in a 28,000 m3 steel-lined water pool [37].

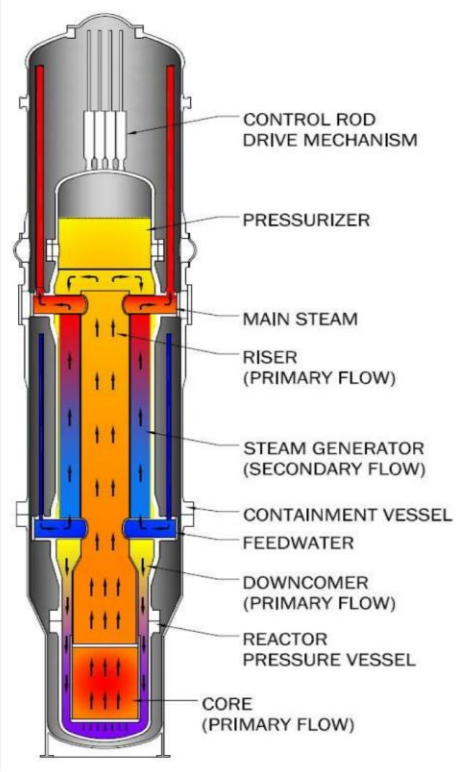

Figure 40 NuScale integral layout main components

Reactor core, fuel and refuelling operations

The reactor core within each of the modules consists of 37 fuel assemblies, arranged in a classical 17x17 square array configuration and 16 control rod assemblies. The ceramic

UO_2 pellets are enriched to up to 4.95% and are encapsulated in a M5® cladding material with an active fuel length of approximately 2 meters. Reactivity is controlled by two independent systems comprising control rods and soluble boron. The core is surrounded by a stainless-steel heavy neutron reflector to improve fuel utilization and prevent radial neutron leakage.

The refuelling cycle is 24 months. The operations are performed using an overhead crane that moves the modules from their location to the refuelling machine (Figure 41). Here the module is disassembled into the lower containment vessel, the lower reactor vessel bay, and the upper module section. While the core is being refuelled, the upper module section is moved to a partial dry-dock facility for inspection and maintenance. Refuelling of a single module is expected to require 10 days. he layout of the reactor building allows the refuelling of a single module to be completed while the other modules continue to generate power [37].

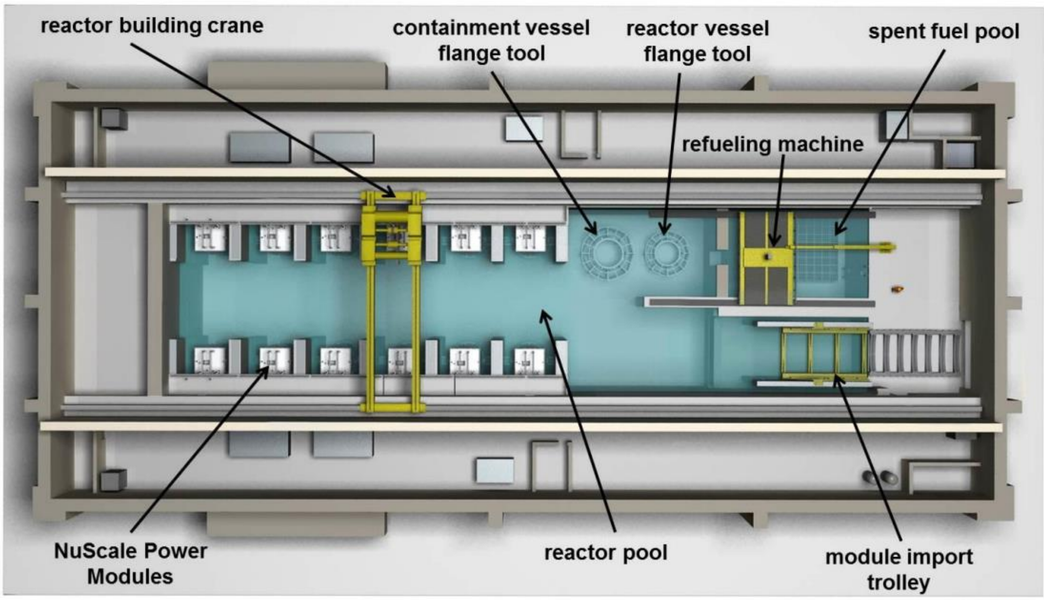

Figure 41 NuScale reactor building layout

Secondary circuit

After the conversion of the secondary coolant to steam, the steam energy is converted to electrical power in the turbine-generator system. Each module is connected to its dedicated 77 MWe conventional steam turbine-generator system (Figure 43). These are readily available and widely used in the fossil fuel power generation industry. The independence between the different modules makes it possible to avoid a complete plant shutdown due to the shutdown of a single reactor, and the plant balance can be configured differently for each module, optimising the efficiency of the cogeneration plant. Exhausted steam from the turbine passes through a condenser, a condensate polishing unit and a series of feedwater heaters before returning to the steam generator. The turbine and condenser units are designed to allow 100% steam bypass of the turbine, and the condenser can be either water- or air-cooled (to reduce plant water consumption). Due to their small size, the generators are air-cooled and the turbine-generator assembly can be skid-mounted to be easily transported and removed for maintenance [37].

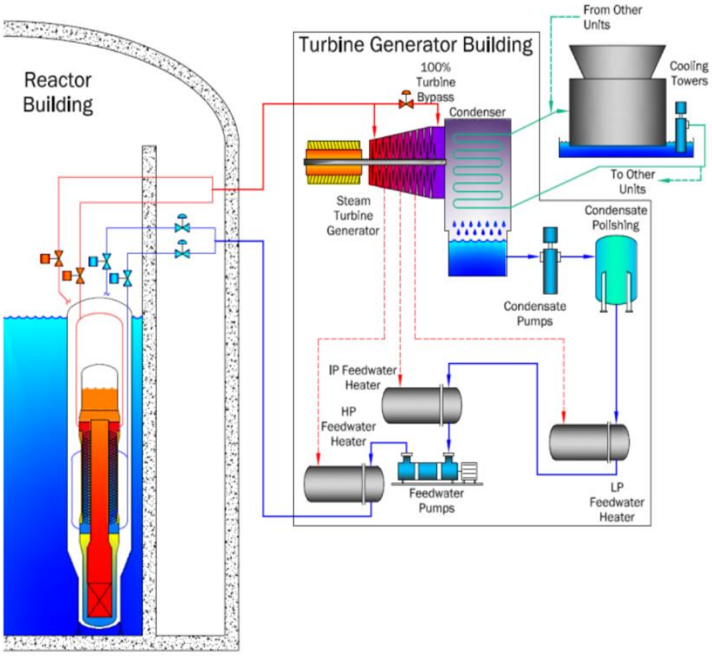

Figure 42 NuScale secondary circuit

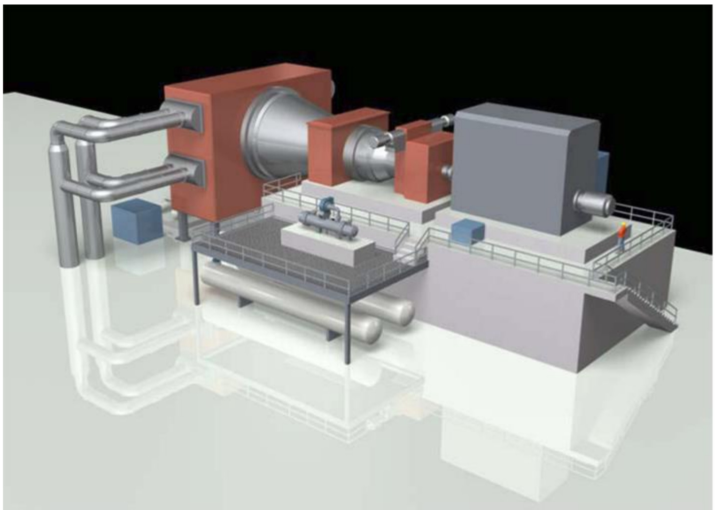

Figure 43 NuScale steam turbine-generator system

Electrical, I&C, and Human Interface

Each nuclear power module has its own dedicated monitoring and protection systems that rely on interconnection for both safety and non-safety related facility structure, systems and components. In addition, the robust design eliminates the requirement for Class 1E power systems. Class 1E is the established regulatory standard for the design of safety-related nuclear power plant electrical systems NuScale's design includes an all-digital control system based on the use of FPGA (Field Programmable Gate Array) technology, which is not vulnerable to Internet cyber-attacks. The highly integrated plant protection system (HIPS), used in the NuScale plant, consists of four types of modules that can be interconnected to implement multiple configurations to support various types of reactor security systems. A unique feature of the multi-module NuScale plant is the control room strategy. The demand of reactor operators is significantly reduced compared to conventional large reactors: only 6 operators are expected to manage the plant control functions for all 12 reactors. The result has been achieved through simplicity of design, advances in digital controls, and the fact that there are no operator-initiated safety features [37].

Figure 44 NuScale 12-Module Control Room Simulator Facility

Safety features and systems

Integral primary system

The integral primary system with natural circulation reduces the number of critical components and the challenging external piping system, eliminating the risk of a loss-of-coolant accident (LOCA).

Containment pressure vessel

The unique feature of NuScale's containment pressure vessel is that the containment atmosphere is evacuated to provide an isolation vacuum during normal operation. This avoids the risk of insulation debris interfering with the core's cooling capability. In addition, the absence of gas prevents the creation of combustible hydrogen mixtures in the unlikely event of a severe accident, thus eliminating the need for hydrogen recombiners. Finally, the containment vessel is designed for a maximum pressure of approximately 8.3 MPa. This design pressure constrains all events that lead to an increase in containment pressure (e.g., LOCA of pipe rupture), and the equilibrium pressure between the reactor vessel and the containment vessel in the event of a LOCA is reached quickly[37].

Emergency Core Cooling System

The ECCS provides a means of removing core decay heat in the event the steam generator tube bundles are not available to remove heat from the primary system. The system consists of three independent reactor vent valves, located on the rector head, that allow to transfer steam from the reactor vessel to the containment, and two independent reactor recirculation valves, that allow water to recirculate into the reactor vessel. Thus, the system removes heat and limits containment pressure through steam condensation and convective heat transfer to the inner surface of the containment vessel. The heat is then transferred by conduction through the walls of the containment vessel to the reactor pool [37] Figure 45:

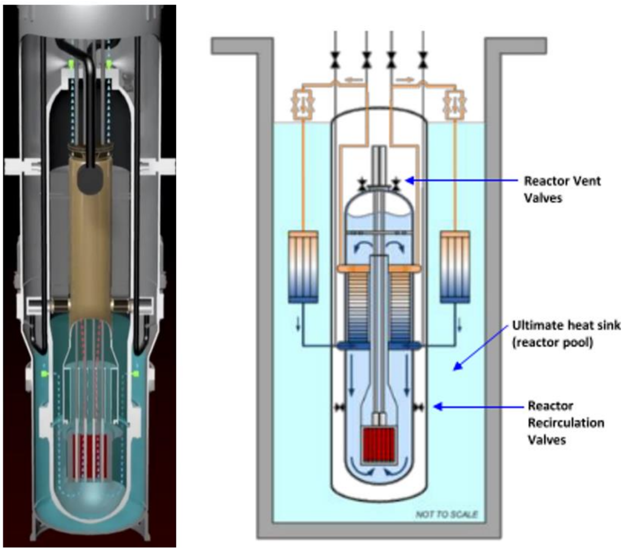

Figure 45 NuScale safety systems: ECCS

Passive Residual Heat Removal

The DHRS provides secondary-side reactor cooling for non-LOCA events when normal feedwater is not available. It is a closed-loop, two-phase natural circulation cooling system. Two redundant trains of decay heat removal equipment are provided, one attached to each steam generator loop. Each train has a passive condenser immersed in the reactor pool and is capable of removing 100 % of the decay heat load [37].

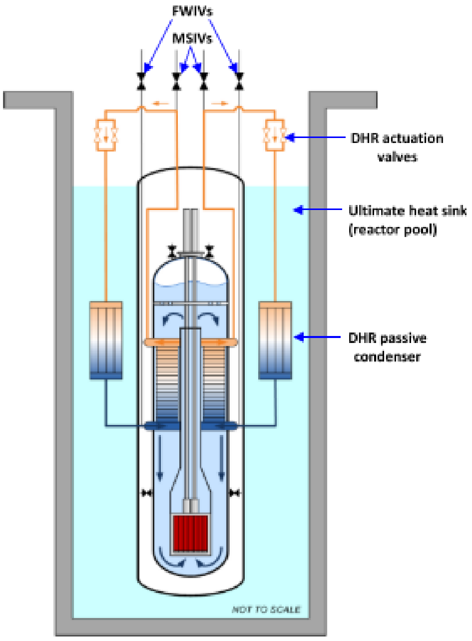

Figure 46 NuScale safety systems: Passive Residual Heat Removal circuit

The entire NSSS, including its containment, is immersed in a pool of water capable of absorbing all decay heat generated by a full complement of 12 modules for greater than 30 days followed by air cooling for an unlimited length of time, as shown in Figure 47.

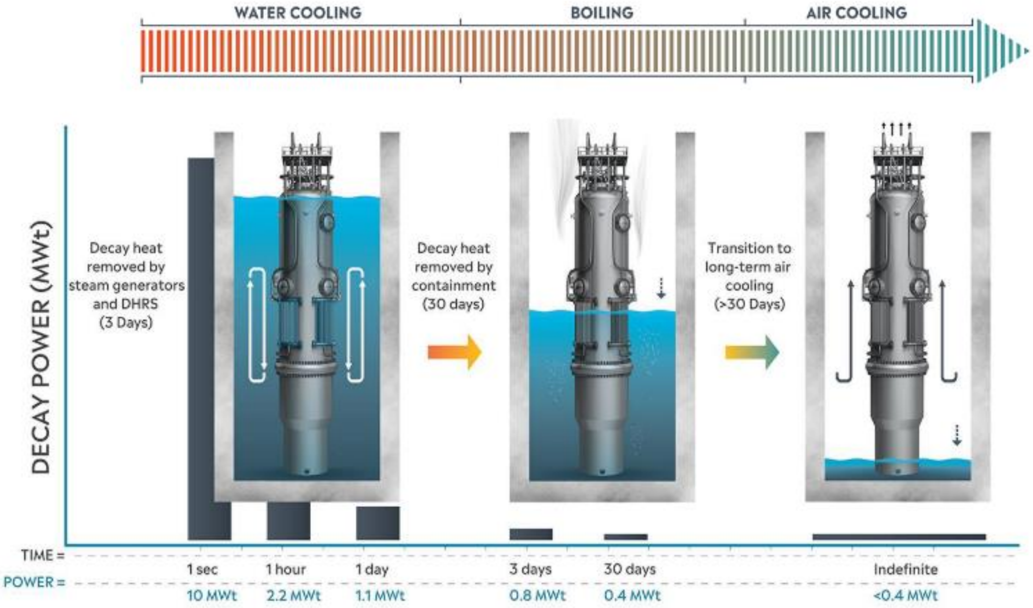

Figure 47 NuScale safety systems: Passive Residual Heat Removal phases

Key information is summarized in the Table 28.

Table 28 Summary of NuScale characteristics

NuScale		
Parameter	**Value**	**Note**
Design Life	60	Years
Lifetime Capacity Factor	>95	%
Site Footprint	140,000	m^2
Plant configurations	308/4	MWe (gross)/#modules
	462/6	MWe (gross)/#modules
	924/12	MWe (gross)/#modules
Thermal capacity	250	MWth
Electrical capacity	77	MWe (gross)
Reactor Type	PWR	
NSSS Layout	Integral	
Neutron Moderator	H_2O	
Core Coolant	H_2O	
Primary Circulation	Natural	
Thermodynamic Cycle	Rankine	
Secondary Side Fluid	H_2O	
NSSS Operating Pressure (primary/secondary)	13.8/4.4	MPa
Nominal Coolant Flow Rate (primary/secondary)	666/87	Kg/s
Core Inlet/Outlet Coolant Temperature	265/321	°C/°C
Refuelling Cycle	24	months
Fuel Material	UO_2	
Enrichment	<4.95	%
Main Reactivity Control	Control rods, Boric acid	
Approach to safety systems	Passive	

5 IRIS Cost Estimation

5.1 Direct Costs

Account 211 Site Preparation/Yard work

For this cost item, an estimate is obtained by assuming the plant footprint as the main driver and a unitary cost of 69.5 €/m^2 [29]. From [36], 285,000 m^2 are assumed as the ground footprint of a plant composed of 2 modules in single configuration, while 202,000 m^2 in the twin configuration. The resulting costs are respectively 19.81 Mln € and 14.04 Mln €.

Account 212 Reactor Island Civil Structures

Excavation work was calculated assuming that the reactor auxiliary building for a single unit plant has a rectangular shape whose area is 58x41m^2 [36] with a maximum foundation depth of 21m [29]. From this information, an excavation volume of about 50,000 m^3 per building is estimated. Considering the twin-units configuration, a total area of the building including the two reactors was assumed to be 60x70m^2 [36]. As reported in [29], a unit cost of 30 €/m^3 is considered.

As mentioned in Chapter 3, the concrete volume is estimated based on the volume of 1,000 MWe PWR using a factor of 0.50. Considering the specific case of IRIS, it is assumed to scale the quantity by the output of the single-reactor unit (335 MWe). There is no difference between twin and single plant units, in fact, although the 2 reactors are under the same building, for safety reasons they need independent concrete structures. Therefore, once the amount of concrete is scaled, the total volume is obtained by multiplying the value by two. Considering the quantity of reinforcing steel, factors of 0.26 and 0.31 are used for NOAK/FOAK cost calculations, respectively. While for the formwork, a conversion rate of 1.68 is applied on the volume of concrete. Applying the unit costs and the productivity rate, suggested in [22], on the raw material quantities, material and labor costs are estimated. Finally, to account for the impact of project performance, the FOAK cost is calculated by adjusting the labor and material plus equipment cost by a factor of 1.67 and 1.3, respectively.

The costs of plumbing and drains, HVAC, lighting, service power and elevators are directly scaled using a factor of 0.50 from the discounted cost reported in [24]. The power used to scale these cost items is 335 MWe for the single unit plant. For the twin configuration, costs are scaled to the power of 670 MWe, assuming the equipment is shared between the two reactors.

IRIS' Reactor Containment and the waterproofing pool consist of steel structures. From [29], the steel weight is estimate. Using the commodity cost, productivity and site labour cost suggested in [22] the costs are computed. No differences are shown between the single units' plant and the twin units' configuration. Both the configurations, thanks learning economies, benefit from a 10% discount on site labour cost and 6% discount on manufacturing cost.

Table 29 summarize Acc. 212 cost components:

Table 29 IRIS Acc. 212 cost components

Acc. 212 cost components	Single units' configuration		Twin-units configuration	
	NOAK	FOAK	NOAK	FOAK
Excavation work	2.997.000,00 €	2.997.000,00 €	2.646.000,00 €	2.646.000,00 €
Formwork	18.970.000,00 €	30.921.000,00 €	18.970.000,00 €	30.921.000,00 €
Concrete structures	11.388.000,00 €	16.348.000,00 €	11.388.000,00 €	16.348.000,00 €
Reinforcing steel	18.977.000,00 €	33.299.000,00 €	18.977.000,00 €	33.299.000,00 €
Plumbing and drains	1.019.000,00 €	1.019.000,00 €	721.000,00 €	721.000,00 €
Heating, ventilation, air conditioning (special)	4.688.000,00 €	4.688.000,00 €	3.315.000,00 €	3.315.000,00 €
Lighting and service power	3.306.000,00 €	3.306.000,00 €	2.338.000,00 €	2.338.000,00 €
Elevators	311.000,00 €	311.000,00 €	220.000,00 €	220.000,00 €
Reactor containment	20.337.000,00 €	20.337.000,00 €	20.337.000,00 €	20.337.000,00 €
Total	**81.990.000,00 €**	**113.222.000,00 €**	**78.910.000,00 €**	**110.142.000,00 €**

Account 213 Turbine Generator Building

The excavation volume is estimated from the information reported in [36]. For the single-unit plant, the turbine building measures 80x35m and has 10m foundations. Therefore, the volume of material removed per building is 28,000m^3. In the twin-units plant, the total area of the turbine building is 110x50m. Therefore, the volume of material removed is 55,000m^3. A unit cost of 30 €/m^3 is considered.

Following the same assumption made earlier, the volume of construction concrete of the single-unit plant is scaled by considering the single reactor power of 335 MWe and multiplying the value by 2. The same conversion factor is assumed for the formwork area, i.e. 1.68, while the ratio of steel weight to concrete volume ranges from 0.07 to 0.08. For the twin-unit configuration, the concrete volume is directly scaled to 670 MWe. The FOAK cost is calculated by adjusting the labor and material plus equipment cost by factors of 1.67 and 1.3 respectively.

The costs of plumbing and drains, HVAC, lighting, service power and elevators are directly scaled using a factor of 0.50 from the discounted cost reported in [24]. The power used to scale these cost items is 335 MWe for the single unit plant for each building. For the twin configuration, costs are scaled to 670 MWe, assuming the equipment is shared between the two reactors.

Additional concrete structures are required in the turbine buildings to support the equipment. Therefore, an additional cost item is included in the analysis. As with the building, the cost is divided into formwork, reinforcing steel, and concrete. Since this item is specific to each turbine, the concrete is scaled using the output of a single 335MWe turbine. The structure has a reinforcement weight to concrete volume ratio ranging from 0.12 to 0.14. No difference is provided for the twin configuration. The same previous adjustment factors are used to calculate the FOAK cost associated with these items.

Table 30 summarize Acc. 213 cost components:

Table 30 IRIS Acc. 213 cost components

Acc. 213 cost components	Single units' configuration		Twin-units configuration	
	NOAK	FOAK	NOAK	FOAK
Excavation work	1.680.000,00 €	1.680.000,00 €	1.673.000,00 €	1.673.000,00 €
Formwork - Building	4.257.000,00 €	6.948.000,00 €	3.010.000,00 €	4.913.000,00 €
Concrete structures - Building	2.329.000,00 €	3.377.000,00 €	1.647.000,00 €	2.388.000,00 €
Reinforcing steel - Building	986.000,00 €	1.753.000,00 €	698.000,00 €	1.239.000,00 €
Formwork - Turbine supporting structure	4.105.000,00 €	6.700.000,00 €	4.105.000,00 €	6.700.000,00 €
Concrete structures - Turbine supporting structure	2.246.000,00 €	3.256.000,00 €	2.246.000,00 €	3.256.000,00 €
Reinforcing steel - Turbine supporting structure	2.772.000,00 €	4.521.000,00 €	2.772.000,00 €	4.521.000,00 €
Plumbing and drains	3.305.000,00 €	3.305.000,00 €	2.337.000,00 €	3.305.000,00 €
Heating, ventilation, air conditioning (special)	2.691.000,00 €	2.691.000,00 €	1.903.000,00 €	2.691.000,00 €
Lighting and service power	1.385.000,00 €	1.385.000,00 €	980.000,00 €	1.385.000,00 €
Elevators	297.000,00 €	297.000,00 €	210.000,00 €	297.000,00 €
Total	**26.049.000,00 €**	**35.908.000,00 €**	**21.575.000,00 €**	**32.363.000,00 €**

Account 214 Security Building and gatehouse

Since no information about concrete are available for this building, the total cost for this facility is directly scaled by a factor of 0.50 from the discounted cost reported in [20]. It is assumed that there is no difference between the twin units and single units facilities, so the cost is scaled for both to 670 MWe. The resulting cost is about 2.49 Mln €.

Account 215 Reactor Service (Auxiliary) Building

Excavation works are included in Acc. 212.

For the single units' plant, the amount of concrete is scaled to the power of 335 MWe, then the amount of material is multiplied by two. Since most of the equipment and functions are shared between the two reactors in the twin configuration, the amount of concrete for this specific plant is scaled to a representative 670 MWe plant. This also provides savings for reinforcing steel and formwork. The scaling factor adopted is 0.5. The area of the formwork is obtained by multiplying the volume of concrete by 1.68. While the ratio between steel weight and volume of concrete ranges from 0.09 to 0.11.

As with the reactor building, the internal equipment for the single units' plant is scaled using a factor of 0.50, assuming a plant output of 335 MWe and multiplying the result by 2. While for the twin units' plant, the cost is scaled to the output of 670 MWe.

Table 31 summarize Acc. 215 cost components:

Table 31 IRIS Acc. 215 cost components

Acc. 215 cost components	Single units' configuration		Twin-units configuration	
	NOAK	FOAK	NOAK	FOAK
Formwork	11.829.000,00 €	11.829.000,00 €	8.364.000,00 €	8.364.000,00 €
Concrete structures	7.101.000,00 €	7.101.000,00 €	5.022.000,00 €	5.022.000,00 €
Reinforcing steel	4.019.000,00 €	4.775.000,00 €	2.842.000,00 €	3.377.000,00 €
Plumbing and drains	1.409.000,00 €	1.409.000,00 €	996.000,00 €	996.000,00 €
Heating, ventilation, air conditioning (special)	13.268.000,00 €	13.268.000,00 €	9.382.000,00 €	9.382.000,00 €
Lighting and service power	1.330.000,00 €	1.330.000,00 €	941.000,00 €	941.000,00 €
Elevators	489.000,00 €	489.000,00 €	346.000,00 €	346.000,00 €
Total	**39.442.000,00 €**	**40.198.000,00 €**	**27.890.000,00 €**	**28.425.000,00 €**

Account 216 Radwaste Building

From the drawing shown in [36] , the measurements of the building are estimated. In the single units' plant, the dimensions of the radioactive waste building are 45x20m, one building for each reactor is present. In contrast, a single structure serves the two reactors in the twin configuration, its measurements are 45x25m. Assuming for both cases a foundation depth of 10m the volume of excavation per building is 9,000m^3 and 11,250m^3 respectively. The unit cost assumed is 30 €/m^3.

The amount of concrete is scaled to the power of 335 MWe and multiplied by 2 for the single units' plant configuration. Due to lack of information of the 1970s PWR reference case, the amount of concrete from the 1600 MWe EPR [30] is used in the calculation. As with the other buildings, the same scaling factor (0.5) is used, and the formwork area is obtained by multiplying the concrete volume by 1.68. It is also assumed that the steel weight to concrete volume ratio is the same as in Acc. 217, ranging from 0.08 to 0.09. Considering the twin units' configuration, the civil construction cost is assumed to depend on the area ration of the buildings, estimated by [36]. Therefore, the cost of the single building is multiplied by a factor of 1.25.

The internal equipment is scaled by using a factor of 0.50 and assuming a plant capacity of 335 MWe. For the single units' plant, the value obtained is then multiplied by 2, while for the twin units' plant, the same factor as before, equal to 1.25, is used.

Table 32 summarize Acc. 216 cost components:

Table 32 IRIS Acc. 216 cost components

Acc. 216 cost components	Single units' configuration		Twin-units configuration	
	NOAK	FOAK	NOAK	FOAK
Excavation work	540.000,00 €	540.000,00 €	338.000,00 €	338.000,00 €
Formwork	8.348.000,00 €	8.348.000,00 €	5.218.000,00 €	5.218.000,00 €
Concrete structures	5.012.000,00 €	5.012.000,00 €	3.132.000,00 €	3.132.000,00 €
Reinforcing steel	2.443.000,00 €	2.902.000,00 €	1.527.000,00 €	1.814.000,00 €
Plumbing and drains	1.108.000,00 €	1.108.000,00 €	693.000,00 €	693.000,00 €
Heating, ventilation, air conditioning (special)	3.624.000,00 €	3.624.000,00 €	2.265.000,00 €	2.265.000,00 €
Lighting and service power	905.000,00 €	905.000,00 €	566.000,00 €	566.000,00 €
Elevators	496.000,00 €	496.000,00 €	310.000,00 €	310.000,00 €
Total	**22.472.000,00 €**	**22.932.000,00 €**	**14.045.000,00 €**	**14.332.000,00 €**

Account 217 Fuel Service Building

The excavation cost of the building is considered under Acc. 212.

For the single units' plant, the amount of concrete is scaled to the power of 335 MWe, then the amount of material is multiplied by two. Since most of the equipment and functions are shared between the two reactors in the twin configuration, the amount of concrete for this specific plant is scaled using a representative 670 MWe plant. This also provides savings for reinforcing steel and formwork. The scaling factor adopted is 0.5. The area of formwork is obtained by multiplying the volume of concrete by 1.68. The ratio between steel and concrete volume ranges from 0.08 to 0.09.

The internal equipment for the single-units plant is scaled by using a factor of 0.50 assuming a plant output of 335 MWe and multiplying the result by 2. While for the twin-units plant, the cost is scaled through an output of 670 MWe.

Table 33 summarize Acc. 217 cost components:

Table 33 IRIS Acc. 217 cost components

Acc. 217 cost components	Single units' configuration		Twin-units configuration	
	NOAK	FOAK	NOAK	FOAK
Formwork	8.348.000,00 €	8.348.000,00 €	5.903.000,00 €	5.903.000,00 €
Concrete structures	5.012.000,00 €	5.012.000,00 €	3.544.000,00 €	3.544.000,00 €
Reinforcing steel	2.443.000,00 €	2.902.000,00 €	1.727.000,00 €	2.052.000,00 €
Plumbing and drains	430.000,00 €	430.000,00 €	304.000,00 €	304.000,00 €
Heating, ventilation, air conditioning (special)	3.886.000,00 €	3.886.000,00 €	2.748.000,00 €	2.748.000,00 €
Lighting and service power	331.000,00 €	331.000,00 €	234.000,00 €	234.000,00 €
Total	20.447.000,00 €	20.907.000,00 €	14.458.000,00 €	14.783.000,00 €

Account 218 other building and structures

This account summarizes together all the other remaining buildings and structures, which are:

- Annex building
- Administration and training building
- Control and Diesel generators building
- Security building
- Main Steam and Feedwater Pipe Enclosure
- Fire pump house, including foundations
- Manway tunnels (RCA tunnels)
- Electrical tunnels
- Non-essential switchgear building
- Pipe tunnels
- Technical support centre
- Containment equipment hatch and missile shield
- Wastewater treatment
- Control room emergency air intake structure

The costs for these structures are directly scaled by using a factor of 0.50 from the discounted cost in reported in [24]. Adjustments for the use of passive safety systems are considered. Some differences emerge between the single-unit and the twin-units configuration. In particular, the annex building in the twin-units configuration is shared and has smaller dimensions, the cost for both configurations is taken directly from [29]. The control and diesel generator buildings are shared in the twin-units configuration so the cost is scaled based on 670 MWe, while for the single-unit configuration it is scaled based on 335 MWe and multiplied by 2. All other cost items under Acc. 218 are obtained by scaling to the power of 670 MWe without considering any difference between the two configurations. The NOAK cost value obtained are multiplied by factors of 1.68 and 1.3 to assess the FOAK value. These are applied to labour (57% of Acc. 218 cost) and material plus equipment cost (43% of Acc. 218 cost) respectively.

Table 34 summarize Acc. 218 cost components:

Table 34 IRIS Acc. 218 Structures and buildings costs

Acc. 218 Structures and buildings	**Single units' configuration**		**Twin-units configuration**	
	NOAK	**FOAK**	**NOAK**	**FOAK**
Annex building	15.725.000,00 €	23.849.000,00 €	5.616.000,00 €	5.616.000,00 €
218A Control and diesel generators building	41.411.000,00 €	62.804.000,00 €	29.282.000,00 €	50.675.000,00 €
218B Administration and training building	12.144.000,00 €	18.417.000,00 €	12.144.000,00 €	18.417.000,00 €
218J Main Steam and Feedwater Pipe Enclosure	14.374.000,00 €	21.800.000,00 €	14.374.000,00 €	21.800.000,00 €
218D Fire pump house, including foundations	780.000,00 €	1.183.000,00 €	780.000,00 €	1.183.000,00 €
218F Manway tunnels (RCA tunnels)	1.393.000,00 €	2.112.000,00 €	1.393.000,00 €	2.112.000,00 €
218G Electrical tunnels	124.000,00 €	188.000,00 €	124.000,00 €	188.000,00 €
218H non-essential switchgear building	980.000,00 €	1.485.000,00 €	980.000,00 €	1.485.000,00 €
218K Pipe tunnels	580.000,00 €	880.000,00 €	580.000,00 €	880.000,00 €
218L Technical support centre	1.443.000,00 €	2.188.000,00 €	1.443.000,00 €	2.188.000,00 €
218P Containment equipment hatch and missile shield	402.000,00 €	610.000,00 €	402.000,00 €	610.000,00 €
218S Wastewater treatment	1.402.000,00 €	2.127.000,00 €	1.402.000,00 €	2.127.000,00 €
218V Control room emergency air intake structure	163.000,00 €	247.000,00 €	163.000,00 €	247.000,00 €
Total	**90.917.000,00 €**	**137.884.000,00 €**	**68.679.000,00 €**	**107.523.000,00 €**

Account 221 Reactor equipment

Reactor vessel shell

IRIS' reactor has a total weight of about 1050 tons comprehensive of internals and shell. The weight of the shell is estimate about 900 tons. Outer diameter of cylindrical shell is about 7.1m. Given these dimensions is not reasonable to consider the possibility to integrate the nozzles into the forgings part. Assuming a cost of forged steel about 6,000 €/tons the cost of the first reactor produced is estimated through the model as 33.18Mln €.

Reactor vessel internals

Assuming that the weight of this component is about 150 tons the cost computed through the model describe in section 3 is about 42.75 Mln for first unit.

Control rods and drives

37 control rods are employed in IRIS' reactor. So, the cost of these components is estimate as 2.04 Mln €. Assuming 45 control rod drives systems the cost of these items is about 24.98 Mln €.

Summing the costs of reactor vessel shell, internals, control rods and drives, the value of manufacturing and install the two units in the FOAK NPP is about 205.89 Mln €. Considering the cost for the NOAK the previous value is discounted by 18% resulting in a total cost for the nth couple of reactors equals to 168.83 Mln €.

222 Main heat transport system

Steam generators

The parameters related to IRIS' steam generators, reported in Table 35, are used to estimate the cost of the components.

Table 35 IRIS steam generator parameters [29]

Characteristic	Value	Unit of measure
Type	8 once through helical coil	/
SG power (unit)	125	MWth
Tubes material	Inconel 690	/
# Tubes per unit	655	Units
Steam quality	5,8 - 317	MPa - C°
Steam flow	503	Kg/s
Tubes Average length	32	m
Tubes weight	18000	Kg
Collectors weight	8775	Kg
Working time collectors	860	Hours

Cost of tubes, including material and manufacturing, are estimated assuming a cost of 92 €/Kg. The resulting value of one steam generator is about 1.66 Mln €.

Collectors' material cost is evaluated taking into account 80 €/Kg, resulting into a cost equal to 0.70 Mln €. Manufacturing cost is estimated based on the working time suggested by the experts, that amount to 860 hours. Therefore assuming 110 €/h the fabrication cost of collectors is estimated around 0.095 Mln €.

Given the sum of tubes and collectors material cost, other costs are estimated a 15 % of previous values sum, resulting 0.26 Mln €.

As reported in [29], IRIS' steam generator auxiliary cost amount to 1.91 Mln € for the first unit produced. The following systems, taking advantage from non-recurring cost, are discounted by 20%. So, the auxiliary cost from the second steam generator onward is going to be about 1.53 Mln €.

Cost of installation for each steam generator is assumed to be equal to 0.48 Mln €, while site material cost about 0.045 Mln € [32].

The resulting cost for a single steam generator is obtained summing all the previous cost items. Specifically, the cost of the first unit produce is about 5.5 Mln € while from the second onward equals to 5.08 Mln €.

Given that for each reactor 8 steam generators are installed, the equipment for the first reactor is evaluated 41.05 Mln € while the second 40.62 Mln €. The total cost for two units plant results in 81.68 Mln €

Primary reactor coolant pumps

The cost for each RCP, suggested by the experts in [29], equals to 4 Mln €. Since for each reactor 8 pumps are employed, a total cost of 32 Mln € is estimated. Therefore, in 2 units NPP this equipment account for 64 Mln €.

Acc. 222 total costs for IRIS NPP is evaluated 145.68 Mln €.

Accounts 223 Safeguards system & 227 Reactor instrumentation and control

As mentioned in chapter 3, the costs of these two items are directly reported from [29]. The Table 36 summarizes the cost of each safety equipment employed in IRIS' NPP.

Table 36 IRIS' passive safety systems costs

Safety equipment	**IRIS components cost (EUR 01/2019)**
Emergency Heat Removal System (including: 4 heat exchangers, valves, control system and electrical equipment)	4.3 Mln €
EHRS and SG make-up tanks primary circuit	4 Mln €

Automatic Depressurization System and circuit (including valves and sparged)	1.1 Mln €
Emergency Boration Tanks system and circuit (2X) (Including valves)	3 Mln €
Suppression pool and Long-Term Core Makeup systems (including pumps and circuit)	2.7 Mln €
Chemical and Volume control system, Piping, water treatment, atmosphere control system and miscellaneous eq.	3.8 Mln €

The resulting NOAK cost of Acc. 223 and 227 is about 18.9 Mln €. Taking in consideration the dependency of these cost items from project execution performances, adjusting factors are applied. Specifically labour cost, representing the 19% of account cost is increased by 2.16, while equipment and site material costs are multiplied by 1.04. The FOAK cost of Acc. 223 and 227 is about 23.68 Mln €. Finally, since two reactors are installed, the resulting NOAK cost equals to 37.8 Mln €, while the value raised to 47.36 Mln € for the FOAK.

Account 224 Radwaste processing

This cost item is estimated assuming a scaling factor equal to 0.6. For the single units' configuration, the power used to scale the cost is assumed to be 335MWe. Therefore, the total cost is obtained by multiplying the value by 2, resulting in 47.86 Mln €. For the twin-units configuration the total plant power of 670MWe is used to scale the cost, the estimated value equals to 36.27 Mln €. Being a critical cost, the values are adjusted by a factor equal to 2.16 applied on the labour cost (19% of the total cost) and a factor equal to 1.04 on the material plus equipment cost (81% of the total cost). So, the FOAK costs for the single unit and twin units' configurations, respectively are, 59.96 Mln € and 45.44 Mln €.

Account 225 Fuel handling and storage

This cost item is estimated assuming a scaling factor equal to 0.6. For the single units' configuration, the power used to scale the cost is assumed to be 335MWe. Therefore, the total cost is obtained by multiplying the value by 2, resulting in a cost of 27.73 Mln €. For the twin-units configuration the total plant power of 670MWe is used to scale the cost, estimated around 21.06 Mln €.

Account 226 Other reactor plant equipment

As suggested by the experts, this cost item is estimated by scaling the PWR12-BE costs using a factor equals to 0.6. Different values are obtained for the twin-units and single plants configurations. In fact, is assumed that the reactors laying under the same building shared part of the cost associated to Acc. 226. Indeed, the cost of 2 reactors equals to 670 MWe is used to estimate the value of the twin-units configuration. On the other hand, the 2 single units are estimated by scaling the PWR12-BE cost to 335

MW and multiplying the value by two. For both the configurations FOAK costs are estimated multiplying labour cost (35% of Acc. 226 cost) by 2.16 and the equipment and site material cost by 1.04. The resulting costs for the single unit's configuration are 154.52 Mln € for the FOAK, while 107.91 Mln € for the NOAK. On the other hand, considering the twin units configuration, costs decrease to 117.12 Mln € for the FOAK and 81.78 Mln € for the NOAK.

Account 228 Reactor plant miscellaneous items

This item is estimated using a scaling factor of 0.6. The power used to scale the costs corresponds to one of a single unit i.e., 335MWe, except for the welders' qualification item where the total power of the plant is used. Therefore, the total costs are obtained by multiplying them by the number of units. No savings are foreseen for the twin configuration. No differences are account for the two plant configurations. Costs are summarized in the following Table 37:

Table 37 IRIS Acc. 228 cost components

Acc. 228 Cost items	Costs
Field painting	1.503.000,00 €
Qualification of welders	5.045.000,00 €
Pipe insulation	3.868.000,00 €
Equipment insulation	1.160.000,00 €
NSSS insulation	3.845.000,00 €
Total	**15.420.000,00 €**

Account 231 Turbine generator

As mentioned in chapter 3, the cost of this item is scaled by a factor of 0.8 from the PWR12-BE cost. Considering equipment simplification of turbine power lower than 350 MWe, the result of the scaling equation is reduced by 15%. IRIS turbine has a power of 335 MW therefore the cost for the first systems installed is estimated 102.86 Mln €. Considering the second turbine installed, experts suggested to reduce Acc. 231 equipment and site labour costs, respectively by 10% and 4%. Therefore, the cost for the second turbine is estimated around 92.93 Mln €. The total Acc. 231 cost is about 195.8 Mln €.

Account 233 Condensing systems

To estimate Acc. 233 cost voice the same factors used for Acc. 231 are assumed. Therefore, costs are scaled based on the system heat rejection power with a factor equal to 0.8. Then the output is reduced by 15%. The heat rejected by IRIS' condensing system amount to 667 MWth. Therefore, the cost obtained for the first unit installed equals to 22.18 Mln €. Considering the second produced system, a learning factor of 4% is applied over site labour cost. Moreover, a discount of 10% over equipment's purchasing is assumed. Resulting in a cost of 20.33 Mln €. Given that 2 systems are installed, the NOAK estimated cost is 42.51 Mln €. To obtain the FOAK value, site labour cost (28%) is multiplied by 1.82, while equipment plus site material cost is multiplied by 1.05. FOAK cost is evaluated 53.94 Mln €.

Account 234 Feedwater heating system

In line with Acc. 231 and 233 the same factors are used to adjust and discount the scaled PWR12-BE cost. The thermal output of IRIS (1002 MWth) is used to represents the size of the SMR system in the equation. After being reduced by 15%, the cost of the first system installed is estimated 18 Mln €. Appling the saving factors previously described the cost for the second system equals to 16.60 Mln €. Being IRIS NPP composed by 2 turbines the total cost of Acc. 234 results 34.66 Mln €.

Account 235 Other turbine plant equipment

As mention in chapter 3 the same model proposed by [32] is adopted to estimate Acc. 235 cost voice. In Table 38 is reported the Acc. 231 previously computed cost and the factors used to estimate Acc. 235.

Table 38 IRIS Acc. 235/231 cost relations

	Factory equipment	Site labor	Site material	Total
IRIS Acc. 231 costs	182.26 Mln €	11.48 Mln €	2.05 Mln €	195.79 Mln €
Account 235/account 231 cost	8.9%	130.3%	85.8%	16.7%

Therefore, NOAK cost related to Acc. 235 is estimated 32.89 Mln €. The cost of the FOAK is determined multiplying labour and equipment plus material costs respectively by 1.82 and 1.05. The resulting value is around 46.03 Mln €.

Account 236 Instrumentation and control

Assuming the equipment is not shared between the turbines, the costs are scaled based on the 335MWe output. Then, the total cost is calculated by multiplying the value obtained by the number of units. An adjustment to the PWR12-BE costs is made to account for the digitisation of the instruments, so the cost is reduced by 10%. No differences are considered for the two configurations.

Costs are summarized in Table 39:

Table 39 IRIS Acc. 236 cost components

Acc. 236 Cost items	Costs
Process instrumentation and control equipment	4.534.000,00 €
Turbine plant instrumentation and control tubing	6.494.000,00 €
Total	**11.027.000,00 €**

Account 237 Turbine plant miscellaneous items

This item is estimated using a scaling factor of 0.8. The power used to scale the costs corresponds to that of a single unit i.e., 335MWe, except for the welders' qualification item where the total power of the plant is used. Therefore, the final costs are obtained by multiplying them by the number of units. No differences are considered for the two configurations.

Table 40 reported the estimated cost:

Table 40 IRIS Acc. 237 cost components

Acc. 237 Cost items	Costs
Field painting	2.370.000,00 €
Qualification of welders	2.720.000,00 €
Turbine plant insulation	8.890.000,00 €
Total	**13.979.000,00 €**

Account 241 Switchgear

This cost item is estimated assuming a scaling factor of 0.4 and reducing by 10% PWR12-BE cost related to class 1E electrical systems. For the single plant configuration, the power of 335MWe is used in the scaling equation. The total cost is then multiplied by 2, i.e., by the number of reactors, resulting in a cost of 33.66 Mln €. For the twin units' configuration, the total plant output of 670MWe is used to scale the cost obtaining a value about 22.21 Mln €.

Account 242 Station service equipment

This cost item is estimated assuming a scaling factor of 0.4 and the single unit power of 335MWe. The total cost is then multiplied by 2, i.e., by the number of reactors. For the twin units' configuration, the total plant power of 670MWe is used. Some cost adjustments are made considering the specific characteristics of IRIS' NPP. As reported in [24], the cost of PWR12-BE for class 1E load centres, transformers and battery systems are reduced by 10%. In addition, since emergency power is not a safety-related function, the costs for diesel generators are reduced by $10 Mln (2011 USD). For the twin units' configuration, a total cost of 30.48 Mln € is obtained, while for the single units' plants, the value raised to 46.21 Mln €.

Account 243 Switchboard

This cost item is estimated assuming a scaling factor of 0.4 and a single unit power of 335MWe. The total cost is then multiplied by 2. For the twin configuration, the total plant power of 670MWe is used. A reduction of 25% is assumed for Class 1E AC systems as reported in [24]. No reduction is considered for the DC system. The resulting cost for the single and twin units' configurations respectively are: 5.95 Mln € and 3.93 Mln €.

Account 244 Protective equipment

This cost item is estimated assuming a scaling factor of 0.4 and a single unit power of 335MWe. The total cost is then multiplied by 2, resulting in 12.45 Mln €. For the twin units' configuration, the total plant power of 670MWe is used, therefore the cost is estimated around 8.21 Mln €.

Account 245 Electric structure and wiring

As suggested by the expert costs related to Acc. 245 are scaled from the actualized cost of the PWR12-BE. Considering the escalation of systems complexity over the years, partially balanced by the adoption of passive safety systems, PWR12-BE costs are increased by 15%. Acc. 245 material cost is estimated considering the power of a single reactor equals to 335 MWe and adopting a scaling factor of 0.4. On the other hand, if the reactors lay under the same building, labour cost taking advantages from commons activities, are accounted considering the power of a couple of reactors. Therefore, for the twin-units configuration the total power of 670 MWe is used to estimate that cost. The resulting NOAK cost for the twin-units configuration is about 49.70 Mln €, while the value increases to 67.76 Mln € for the single units' plant. FOAK costs are estimated multiplying labour and material cost respectively by 1.93 and 1.12. For the twin-units the value raises to 84.2 Mln € while for the single configuration it escalates up to 118.89 Mln €.

Account 246 Power and control wiring

This cost item is estimated by assuming a scale factor of 0.4 and the unit power of 335MWe. The cost is then multiplied by 2 obtaining the total plant cost of 40.71 Mln €. For the twin units' configuration, the total plant power of 670MWe is used, resulting in 26.86 Mln €. Being a critical cost, the FOAK cost value is obtained by multiplying the cost of site labour (56% of the total cost of the item) by 1.93 and the cost of equipment plus materials (44% of the total cost of the item) by a factor of 1.12.

Therefore, the values obtained for the FOAK of the single and twin units' configuration respectively are 64.01 Mln € and 42.26 Mln €

Account 251 Transportation and lifting equipment

This cost item is estimated assuming a scaling factor of 0.3 and a single unit power of 335MWe. The total cost is then multiplied by 2, i.e. the number of reactors, resulting in a cost of 19.80 Mln €. For the twin configuration, the total plant power of 670MWe is used to scale the costs assuming that the equipment is shared between the units. The value obtained equals to 12.19 Mln €.

Account 252 Air water and steam service systems

The service systems are estimated by scaling the PWR12-BE cost through a factor of 0.4. For the single units plant the power used in the equation correspond to the one of single reactor. Instead, assuming that part of the equipment and work is common for the 2 modules in the twin-units configuration, costs are scaled to the power of a couple of reactors. The resulting value for the NOAKs are: 84.80 Mln € for the single units' plant and 55.95 Mln € for the twin-units plant. Being Acc. 252 dependents on project execution performances, the FOAK costs are estimated escalating site labour cost (54% of Acc. 252 cost) by a factor equals to 1.94 and material and equipment cost by 1.11. The resulting value for the single units' plant is 132.30 Mln €, while for twin-units configuration is about 87.28 Mln €.

Account 253 Communications Equipment

In the single units' configuration, the costs of fire detection and safety system are estimated assuming the power of a single unit to be 335MWe. The total cost is then multiplied by 2 (i.e., the number of reactors) the cost obtained is about 20.10 Mln €. For the other cost items and for the twin units, the total plant power of 670MWe is used. The twin units' configuration cost equals to 13.04 Mln €. The scaling factor used is 0.3.

Account 254 Furnishings and Fixtures

These cost items are estimated by assuming a scale factor of 0.3 and a total plant capacity of 670MWe. There are no differences between the two configurations. Therefore, the Acc. 254 cost is estimated 5.56 Mln €.

Account 255 Wastewater Treatment Equipment

This cost item is estimated by assuming a scale factor of 0.3 and a total plant capacity of 670MWe. There are no differences between the two configurations. Therefore, the Acc. 254 cost is estimated 5.76 Mln €.

Account 261 Structures

The facilities are not shared between the different units in both the configurations. Therefore, the power of a single reactor (335MWe) is used to scale the costs and the resulting value is multiplied by the number of units. The scaling factor is 0.8.

Costs are summarized in the following Table 41:

Table 41 IRIS Acc. 261 cost components

Acc. 261 Cost items	Costs
Makeup water intake structure	1.824.000,00 €
Circulating water pump house structure	3.366.000,00 €
Circulating water pump house services	375.000,00 €
Makeup water pre-treatment building	1.795.000,00 €
Makeup water pre-treatment building services	387.000,00 €
Total	**7.747.000,00 €**

Account 262 Mechanical equipment

Being this equipment strictly correlated with Acc. 23 voices, the same adjusting factors of Acc. 231, 233 and 234 are adopted. Therefore, the cost of the PWR-BE is scaled based on heat rejection power of the system. For the IRIS's case this amount to 667 MWth. Therefore, after being discounted of 15%, the cost of the first installed equipment is equal to 34.17 Mln €. Taking advantage of 10% discount on the equipment and 4% on site labour cost, the second system installed is estimated 31.33 Mln €. Considering the installation of two systems the resulting cost for Acc. 262 is 65.50 Mln €.

In Table 42 are reported the costs of all the previous voices for the IRIS single units' configurations.

Table 42 IRIS single units' configuration direct costs

COA	Single units' configuration 670 MWe								
	NOAK				FOAK -NOAK	FOAK			
	Total	Factory cost	Site labor cost	Site material cost		Total	Factory cost	Site labor cost	Site material cost
211	19.808.000 €	226.000 €	11.496.000 €	8.087.000 €	0 €	19.808.000 €	226.000 €	11.496.000 €	8.087.000 €
212	81.990.000 €	18.046.000 €	45.053.000 €	18.892.000 €	31.233.000 €	113.222.000 €	18.311.000 €	68.371.000 €	26.542.000 €
213	26.049.000 €	700.000 €	12.571.000 €	12.780.000 €	9.860.000 €	35.908.000 €	783.000 €	19.931.000 €	15.194.000 €
214	2.489.000 €	95.000 €	1.723.000 €	672.000 €	0 €	2.489.000 €	95.000 €	1.723.000 €	672.000 €
215	39.442.000 €	6.710.000 €	22.462.000 €	10.271.000 €	757.000 €	40.198.000 €	6.716.000 €	23.027.000 €	10.456.000 €
216	22.472.000 €	1.019.000 €	14.114.000 €	7.340.000 €	460.000 €	22.932.000 €	1.023.000 €	14.457.000 €	7.453.000 €
217	20.447.000 €	2.065.000 €	9.324.000 €	9.059.000 €	460.000 €	20.907.000 €	2.069.000 €	9.668.000 €	9.171.000 €
218	90.917.000 €	5.226.000 €	56.650.000 €	29.042.000 €	46.968.000 €	137.884.000 €	5.625.000 €	91.715.000 €	40.545.000 €
21	**303.610.000 €**	**34.083.000 €**	**173.389.000 €**	**96.139.000 €**	**89.734.000 €**	**393.344.000 €**	**34.844.000 €**	**240.384.000 €**	**118.117.000 €**
221	168.830.000 €	148.965.000 €	7.726.000 €	12.141.000 €	37.061.000 €	205.890.000 €	151.968.000 €	38.854.000 €	15.070.000 €
222	145.678.000 €	129.675.000 €	14.563.000 €	1.441.000 €	0 €	145.678.000 €	129.675.000 €	14.563.000 €	1.441.000 €
223	37.800.000 €	30.240.000 €	7.182.000 €	378.000 €	9.556.000 €	47.356.000 €	31.450.000 €	15.514.000 €	394.000 €
224	47.859.000 €	36.931.000 €	9.171.000 €	1.758.000 €	12.099.000 €	59.958.000 €	37.912.000 €	19.333.000 €	2.714.000 €
225	27.730.000 €	25.528.000 €	1.961.000 €	242.000 €	0 €	27.730.000 €	25.528.000 €	1.961.000 €	242.000 €
226	107.909.000 €	64.746.000 €	37.768.000 €	5.396.000 €	46.617.000 €	154.525.000 €	67.335.000 €	81.579.000 €	5.612.000 €
227	Incl. in 223	Incl. in 223	Incl. in 223	Incl. in 223		Incl. in 223	Incl. in 223	Incl. in 223	Incl. in 223
228	15.419.000 €	0 €	8.841.000 €	6.578.000 €	0 €	15.419.000 €	0 €	8.841.000 €	6.578.000 €
22	**551.223.000 €**	**436.082.000 €**	**87.210.000 €**	**27.932.000 €**	**105.332.000 €**	**656.554.000 €**	**443.865.000 €**	**180.643.000 €**	**32.048.000 €**
231	195.792.000 €	182.261.000 €	11.484.000 €	2.047.000 €	0 €	195.792.000 €	182.261.000 €	11.484.000 €	2.047.000 €

233	42.509.000 €	28.749.000 €	12.088.000 €	1.673.000 €	11.434.000 €	53.942.000 €	30.186.000 €	22.001.000 €	1.757.000 €
234	34.662.000 €	22.923.000 €	10.707.000 €	1.034.000 €	0 €	34.662.000 €	22.923.000 €	10.707.000 €	1.034.000 €
235	32.890.000 €	16.222.000 €	14.930.000 €	1.740.000 €	13.140.000 €	46.030.000 €	17.033.000 €	27.171.000 €	1.827.000 €
236	11.027.000 €	3.006.000 €	7.387.000 €	635.000 €	0 €	11.027.000 €	3.006.000 €	7.387.000 €	635.000 €
237	13.979.000 €	0 €	8.006.000 €	5.973.000 €	0 €	13.979.000 €	0 €	8.006.000 €	5.973.000 €
23	**330.857.000 €**	**253.158.000 €**	**64.600.000 €**	**13.100.000 €**	**24.574.000 €**	**355.430.000 €**	**255.407.000 €**	**86.754.000 €**	**13.270.000 €**
241	33.664.000 €	31.713.000 €	1.702.000 €	249.000 €	0 €	33.664.000 €	31.713.000 €	1.702.000 €	249.000 €
242	46.207.000 €	40.839.000 €	4.508.000 €	862.000 €	0 €	46.207.000 €	40.839.000 €	4.508.000 €	862.000 €
243	5.955.000 €	4.568.000 €	1.026.000 €	363.000 €	0 €	5.955.000 €	4.568.000 €	1.026.000 €	363.000 €
244	12.450.000 €	0 €	7.283.000 €	5.168.000 €	0 €	12.450.000 €	0 €	7.283.000 €	5.168.000 €
245	67.756.000 €	0 €	53.088.000 €	14.668.000 €	51.132.000 €	118.888.000 €	0 €	102.460.000 €	16.428.000 €
246	40.710.000 €	4.626.000 €	22.595.000 €	13.491.000 €	23.352.000 €	64.061.000 €	4.688.000 €	42.571.000 €	16.803.000 €
24	**206.741.000 €**	**81.744.000 €**	**90.200.000 €**	**34.798.000 €**	**74.483.000 €**	**281.224.000 €**	**81.807.000 €**	**159.547.000 €**	**39.871.000 €**
251	19.800.000 €	16.713.000 €	2.806.000 €	281.000 €	0 €	19.800.000 €	16.713.000 €	2.806.000 €	281.000 €
252	84.809.000 €	25.769.000 €	45.975.000 €	13.066.000 €	47.489.000 €	132.297.000 €	28.603.000 €	89.192.000 €	14.503.000 €
253	20.099.000 €	6.106.000 €	12.135.000 €	1.859.000 €	0 €	20.099.000 €	6.106.000 €	12.135.000 €	1.859.000 €
254	5.564.000 €	4.412.000 €	1.022.000 €	130.000 €	0 €	5.564.000 €	4.412.000 €	1.022.000 €	130.000 €
255	5.762.000 €	1.526.000 €	3.813.000 €	424.000 €	0 €	5.762.000 €	1.526.000 €	3.813.000 €	424.000 €
25	**136.031.000 €**	**54.524.000 €**	**65.750.000 €**	**15.758.000 €**	**47.489.000 €**	**183.519.000 €**	**57.358.000 €**	**108.967.000 €**	**17.195.000 €**
261	7.745.000 €	314.000 €	4.795.000 €	2.638.000 €	0 €	7.745.000 €	314.000 €	4.795.000 €	2.638.000 €
262	65.496.000 €	44.299.000 €	18.896.000 €	2.302.000 €	0 €	65.496.000 €	44.299.000 €	18.896.000 €	2.302.000 €
26	**73.240.000 €**	**44.612.000 €**	**23.690.000 €**	**4.939.000 €**	**0 €**	**73.240.000 €**	**44.612.000 €**	**23.690.000 €**	**4.939.000 €**
Total direct	**1.601.700.000 €**	**904.200.000 €**	**504.837.000 €**	**192.664.000 €**	**341.610.000 €**	**1.943.310.000 €**	**917.890.000 €**	**799.983.000 €**	**225.438.000 €**

In Table 43 are reported the costs of all the previous voices for the IRIS twin units' configuration.

Table 43 IRIS twin units' configuration direct costs

COA	Twin units' configuration 670 MWe								
	NOAK				FOAK - NOAK	FOAK			
	Total	Factory cost	Site labor cost	Site material cost		Total	Factory cost	Site labor cost	Site material cost
211	14.039.000 €	160.000 €	8.148.000 €	5.732.000 €	0 €	14.039.000 €	160.000 €	8.148.000 €	5.732.000 €
212	78.910.000 €	17.368.000 €	43.360.000 €	18.182.000 €	31.233.000 €	110.142.000 €	17.633.000 €	66.678.000 €	25.832.000 €
213	21.575.000 €	580.000 €	10.412.000 €	10.585.000 €	10.789.000 €	32.363.000 €	671.000 €	18.466.000 €	13.227.000 €
214	2.489.000 €	95.000 €	1.723.000 €	672.000 €	0 €	2.489.000 €	95.000 €	1.723.000 €	672.000 €
215	27.890.000 €	4.745.000 €	15.883.000 €	7.263.000 €	535.000 €	28.425.000 €	4.749.000 €	16.283.000 €	7.394.000 €
216	14.045.000 €	637.000 €	8.822.000 €	4.588.000 €	288.000 €	14.332.000 €	639.000 €	9.036.000 €	4.658.000 €
217	14.458.000 €	1.460.000 €	6.594.000 €	6.406.000 €	325.000 €	14.783.000 €	1.463.000 €	6.836.000 €	6.485.000 €
218	68.679.000 €	3.948.000 €	42.793.000 €	21.938.000 €	38.844.000 €	107.523.000 €	4.278.000 €	71.794.000 €	31.452.000 €
21	**242.082.000 €**	**28.990.000 €**	**137.732.000 €**	**75.362.000 €**	**82.011.000 €**	**324.093.000 €**	**29.685.000 €**	**198.960.000 €**	**95.449.000 €**
221	168.830.000 €	148.965.000 €	7.726.000 €	12.141.000 €	37.061.000 €	205.890.000 €	151.968.000 €	38.854.000 €	15.070.000 €
222	145.678.000 €	129.675.000 €	14.563.000 €	1.441.000 €	0 €	145.678.000 €	129.675.000 €	14.563.000 €	1.441.000 €
223	37.800.000 €	30.240.000 €	7.182.000 €	378.000 €	9.556.000 €	47.356.000 €	31.450.000 €	15.514.000 €	394.000 €
224	36.270.000 €	27.989.000 €	6.950.000 €	1.332.000 €	9.170.000 €	45.440.000 €	28.732.000 €	14.652.000 €	2.057.000 €
225	21.016.000 €	19.347.000 €	1.486.000 €	184.000 €	0 €	21.016.000 €	19.347.000 €	1.486.000 €	184.000 €
226	81.780.000 €	49.068.000 €	28.623.000 €	4.089.000 €	35.329.000 €	117.109.000 €	51.031.000 €	61.826.000 €	4.253.000 €
227	Incl. in 223	Incl. in 223	Incl. in 223	Incl. in 223		Incl. in 223	Incl. in 223	Incl. in 223	Incl. in 223
228	15.419.000 €	0 €	8.841.000 €	6.578.000 €	0 €	15.419.000 €	0 €	8.841.000 €	6.578.000 €
22	**506.791.000 €**	**405.281.000 €**	**75.369.000 €**	**26.142.000 €**	**91.114.000 €**	**597.905.000 €**	**412.199.000 €**	**155.733.000 €**	**29.973.000 €**
231	195.792.000 €	182.261.000 €	11.484.000 €	2.047.000 €	0 €	195.792.000 €	182.261.000 €	11.484.000 €	2.047.000 €
233	42.509.000 €	28.749.000 €	12.088.000 €	1.673.000 €	11.434.000 €	53.942.000 €	30.186.000 €	22.001.000 €	1.757.000 €
234	34.662.000 €	22.923.000 €	10.707.000 €	1.034.000 €	0 €	34.662.000 €	22.923.000 €	10.707.000 €	1.034.000 €
235	32.890.000 €	16.222.000 €	14.930.000 €	1.740.000 €	13.140.000 €	46.030.000 €	17.033.000 €	27.171.000 €	1.827.000 €
236	11.027.000 €	3.006.000 €	7.387.000 €	635.000 €	0 €	11.027.000 €	3.006.000 €	7.387.000 €	635.000 €
237	13.979.000 €	0 €	8.006.000 €	5.973.000 €	0 €	13.979.000 €	0 €	8.006.000 €	5.973.000 €
23	**330.857.000 €**	**253.158.000 €**	**64.600.000 €**	**13.100.000 €**	**24.574.000 €**	**355.430.000 €**	**255.407.000 €**	**86.754.000 €**	**13.270.000 €**
241	22.210.000 €	20.923.000 €	1.123.000 €	165.000 €	0 €	22.210.000 €	20.923.000 €	1.123.000 €	165.000 €
242	30.486.000 €	26.944.000 €	2.974.000 €	569.000 €	0 €	30.486.000 €	26.944.000 €	2.974.000 €	569.000 €
243	3.929.000 €	3.014.000 €	677.000 €	239.000 €	0 €	3.929.000 €	3.014.000 €	677.000 €	239.000 €
244	8.214.000 €	0 €	4.805.000 €	3.410.000 €	0 €	8.214.000 €	0 €	4.805.000 €	3.410.000 €
245	49.693.000 €	0 €	35.025.000 €	14.668.000 €	34.334.000 €	84.027.000 €	0 €	67.599.000 €	16.428.000 €
246	26.859.000 €	3.052.000 €	14.907.000 €	8.901.000 €	15.406.000 €	42.265.000 €	3.093.000 €	28.087.000 €	11.086.000 €
24	**141.389.000 €**	**53.931.000 €**	**59.510.000 €**	**27.949.000 €**	**49.740.000 €**	**191.128.000 €**	**53.972.000 €**	**105.262.000 €**	**31.895.000 €**
251	12.188.000 €	10.288.000 €	1.728.000 €	173.000 €	0 €	12.188.000 €	10.288.000 €	1.728.000 €	173.000 €
252	55.953.000 €	17.001.000 €	30.333.000 €	8.620.000 €	31.331.000 €	87.284.000 €	18.871.000 €	58.845.000 €	9.569.000 €

253	13.045.000 €	3.963.000 €	7.876.000 €	1.207.000 €	0 €	13.045.000 €	3.963.000 €	7.876.000 €	1.207.000 €
254	5.564.000 €	4.412.000 €	1.022.000 €	130.000 €	0 €	5.564.000 €	4.412.000 €	1.022.000 €	130.000 €
255	5.762.000 €	1.526.000 €	3.813.000 €	424.000 €	0 €	5.762.000 €	1.526.000 €	3.813.000 €	424.000 €
25	**92.510.000 €**	**37.189.000 €**	**44.770.000 €**	**10.553.000 €**	**31.331.000 €**	**123.841.000 €**	**39.059.000 €**	**73.282.000 €**	**11.501.000 €**
261	7.745.000 €	314.000 €	4.795.000 €	2.638.000 €	0 €	7.745.000 €	314.000 €	4.795.000 €	2.638.000 €
262	65.496.000 €	44.299.000 €	18.896.000 €	2.302.000 €	0 €	65.496.000 €	44.299.000 €	18.896.000 €	2.302.000 €
26	**73.240.000 €**	**44.612.000 €**	**23.690.000 €**	**4.939.000 €**	**0 €**	**73.240.000 €**	**44.612.000 €**	**23.690.000 €**	**4.939.000 €**
Total direct	**1.386.867.000 €**	**823.157.000 €**	**405.668.000 €**	**158.042.000 €**	**278.768.000 €**	**1.665.635.000 €**	**834.931.000 €**	**643.680.000 €**	**187.025.000 €**

5.1.1 Modularization

Having obtained the direct cost for each cost item, the modularisation effect is applied over the previously mentioned voices (section 3.3.3). Therefore, for these COA items, 50% of site labour costs is move to factory at twice the productivity. In order to account the impact of moving larger parts for IRIS NPPs is assumed that transportation represents 2% of the total items cost and that modularization are going to raise this by 5%.

For the single unit's plant configuration, a total savings of 61.71 Mln € is estimated for the NOAK plant, while for the FOAK the value amounts to 90.80 Mln €. A bigger saving was expected for the first NPP employed given the higher impact of labor over total direct cost. Therefore, it can be stated that modularization become particularly interesting to control inefficiencies during the construction of the FOAK. Considering the twin unit's configuration, savings result 53.64 Mln € for the NOAK and 81.28 Mln € for the FOAK. These values are in line with what previously said. Since part of site labour cost is shared among the two units in the twin configuration, the expected savings from modularization are reduced, but still remaining consistent.

A detailed view of the results is reported in Table 44 (single units' configuration) and Table 45 (twin units' configuration).

Table 44 IRIS single units' configuration modularization savings

COA	Single units' configuration - Modularization savings			
	NOAK		FOAK	
	Cost	Modul. Savings	Cost	Modul. Savings
211	19.808.000,00 €	0,00 €	19.808.000,00 €	0,00 €
212	70.745.000,00 €	11.246.000,00 €	96.148.000,00 €	17.075.000,00 €
213	22.907.000,00 €	3.142.000,00 €	30.926.000,00 €	4.982.000,00 €
214	2.058.000,00 €	431.000,00 €	2.058.000,00 €	431.000,00 €
215	33.833.000,00 €	5.609.000,00 €	34.449.000,00 €	5.750.000,00 €
216	18.945.000,00 €	3.528.000,00 €	19.318.000,00 €	3.614.000,00 €
217	18.118.000,00 €	2.329.000,00 €	18.492.000,00 €	2.415.000,00 €

218	76.760.000,00 €	14.158.000,00 €	114.961.000,00 €	22.924.000,00 €
21	**263.171.000,00 €**	**40.440.000,00 €**	**336.157.000,00 €**	**57.188.000,00 €**
221	167.048.000,00 €	1.783.000,00 €	196.329.000,00 €	9.562.000,00 €
222	142.167.000,00 €	3.511.000,00 €	142.167.000,00 €	3.511.000,00 €
223	36.035.000,00 €	1.766.000,00 €	43.510.000,00 €	3.847.000,00 €
224	47.859.000,00 €	0,00 €	59.958.000,00 €	0,00 €
225	27.730.000,00 €	0,00 €	27.730.000,00 €	0,00 €
226	107.909.000,00 €	0,00 €	154.525.000,00 €	0,00 €
227	incl. in 223	incl. in 223	incl. in 223	incl. in 223
228	15.419.000,00 €	0,00 €	15.419.000,00 €	0,00 €
22	**544.165.000,00 €**	**7.059.000,00 €**	**639.635.000,00 €**	**16.920.000,00 €**
231	193.103.000,00 €	2.689.000,00 €	193.103.000,00 €	2.689.000,00 €
233	39.516.000,00 €	2.994.000,00 €	48.472.000,00 €	5.470.000,00 €
234	32.009.000,00 €	2.654.000,00 €	32.009.000,00 €	2.654.000,00 €
235	32.890.000,00 €	0,00 €	46.030.000,00 €	0,00 €
236	11.027.000,00 €	0,00 €	11.027.000,00 €	0,00 €
237	13.979.000,00 €	0,00 €	13.979.000,00 €	0,00 €
23	**322.521.000,00 €**	**8.336.000,00 €**	**344.618.000,00 €**	**10.813.000,00 €**
241	33.664.000,00 €	0,00 €	33.664.000,00 €	0,00 €
242	46.207.000,00 €	0,00 €	46.207.000,00 €	0,00 €
243	5.955.000,00 €	0,00 €	5.955.000,00 €	0,00 €
244	12.450.000,00 €	0,00 €	12.450.000,00 €	0,00 €
245	67.756.000,00 €	0,00 €	118.888.000,00 €	0,00 €
246	40.710.000,00 €	0,00 €	64.061.000,00 €	0,00 €
24	**206.741.000,00 €**	**0,00 €**	**281.224.000,00 €**	**0,00 €**
251	19.800.000,00 €	0,00 €	19.800.000,00 €	0,00 €
252	84.809.000,00 €	0,00 €	132.297.000,00 €	0,00 €
253	20.099.000,00 €	0,00 €	20.099.000,00 €	0,00 €
254	5.564.000,00 €	0,00 €	5.564.000,00 €	0,00 €
255	5.762.000,00 €	0,00 €	5.762.000,00 €	0,00 €
25	**136.031.000,00 €**	**0,00 €**	**183.519.000,00 €**	**0,00 €**
261	6.547.000,00 €	1.199.000,00 €	6.547.000,00 €	1.199.000,00 €
262	60.816.000,00 €	4.680.000,00 €	60.816.000,00 €	4.680.000,00 €
26	**67.363.000,00 €**	**5.878.000,00 €**	**67.363.000,00 €**	**5.878.000,00 €**
Total	**1.539.989.000,00 €**	**61.712.000,00 €**	**1.852.513.000,00 €**	**90.797.000,00 €**

Table 45 IRIS twin units' configuration modularization savings

COA	Twin units' configuration - Modularization savings			
	NOAK		FOAK	
	Cost	Modul. Savings	Cost	Modul. Savings
211	14.039.000,00 €	- €	14.039.000,00 €	- €
212	68.087.000,00 €	10.823.000,00 €	93.490.000,00 €	16.652.000,00 €

213	18.973.000,00 €	2.603.000,00 €	27.748.000,00 €	4.616.000,00 €
214	2.058.000,00 €	431.000,00 €	2.058.000,00 €	431.000,00 €
215	23.924.000,00 €	3.966.000,00 €	24.359.000,00 €	4.066.000,00 €
216	11.841.000,00 €	2.205.000,00 €	12.074.000,00 €	2.259.000,00 €
217	12.812.000,00 €	1.647.000,00 €	13.076.000,00 €	1.708.000,00 €
218	57.985.000,00 €	10.695.000,00 €	89.579.000,00 €	17.945.000,00 €
21	**209.715.000,00 €**	**32.368.000,00 €**	**276.420.000,00 €**	**47.674.000,00 €**
221	167.048.000,00 €	1.783.000,00 €	196.329.000,00 €	9.562.000,00 €
222	142.167.000,00 €	3.511.000,00 €	142.167.000,00 €	3.511.000,00 €
223	36.035.000,00 €	1.766.000,00 €	43.510.000,00 €	3.847.000,00 €
224	36.270.000,00 €	- €	45.440.000,00 €	- €
225	21.016.000,00 €	- €	21.016.000,00 €	- €
226	81.780.000,00 €	- €	117.109.000,00 €	- €
227	incl. in 223	incl. in 223	incl. in 223	incl. in 223
228	15.419.000,00 €	- €	15.419.000,00 €	- €
22	**499.732.000,00 €**	**7.059.000,00 €**	**580.985.000,00 €**	**16.920.000,00 €**
231	193.103.000,00 €	2.689.000,00 €	193.103.000,00 €	2.689.000,00 €
233	39.516.000,00 €	2.994.000,00 €	48.472.000,00 €	5.470.000,00 €
234	32.009.000,00 €	2.654.000,00 €	32.009.000,00 €	2.654.000,00 €
235	32.890.000,00 €	- €	46.030.000,00 €	- €
236	11.027.000,00 €	- €	11.027.000,00 €	- €
237	13.979.000,00 €	- €	13.979.000,00 €	- €
23	**322.521.000,00 €**	**8.336.000,00 €**	**344.618.000,00 €**	**10.813.000,00 €**
241	22.210.000,00 €	- €	22.210.000,00 €	- €
242	30.486.000,00 €	- €	30.486.000,00 €	- €
243	3.929.000,00 €	- €	3.929.000,00 €	- €
244	8.214.000,00 €	- €	8.214.000,00 €	- €
245	49.693.000,00 €	- €	84.027.000,00 €	- €
246	26.859.000,00 €	- €	42.265.000,00 €	- €
24	**141.389.000,00 €**	**- €**	**191.128.000,00 €**	**- €**
251	12.188.000,00 €	- €	12.188.000,00 €	- €
252	55.953.000,00 €	- €	87.284.000,00 €	- €
253	13.045.000,00 €	- €	13.045.000,00 €	- €
254	5.564.000,00 €	- €	5.564.000,00 €	- €
255	5.762.000,00 €	- €	5.762.000,00 €	- €
25	**92.510.000,00 €**	**- €**	**123.841.000,00 €**	**- €**
261	6.547.000,00 €	1.199.000,00 €	6.547.000,00 €	1.199.000,00 €
262	60.816.000,00 €	4.680.000,00 €	60.816.000,00 €	4.680.000,00 €
26	**67.363.000,00 €**	**5.878.000,00 €**	**67.363.000,00 €**	**5.878.000,00 €**
Total	**1.333.228.000,00 €**	**53.639.000,00 €**	**1.584.352.000,00 €**	**81.283.000,00 €**

5.2 Indirect Costs

As declared in section 3.2.3 indirect costs are computed through the model proposed by [28]. Therefore, assumptions about construction duration and average number of workers in site are made. Table 46 summarize these values for the NOAK and the FOAK plants relative to the two configurations of IRIS' NPP and the reference case. These are estimated thanks to the experts' judgments.

Table 46 IRIS construction duration and average number of workers in site

Adjusting factors	PWR12-BE	Single units' configuration		Twin units' configuration	
		NOAK	FAOK	NOAK	FAOK
Average number of workers	3000	1200	1500	1500	1800
Construction time [months]	72	36	48	42	54

The resulting estimation factors and values of the single units' configuration are reported in Table 47.

Table 47 IRIS single units' configuration indirect cost factors and values

			Single units' configuration			
Cost item	Scaling relation	Base scaling value	Escalation relation (NOAK)	Escalation relation (FOAK)	NOAK	FAOK
Site labour cost	Indirect Site Labor Cost/Direct Site Labor Cost	36%			136.862.000,00 €	222.169.000,00 €
Site Material Cost	Indirect Site Material Cost/ Direct Site Material Cost	79%	40%	50%	60.497.000,00 €	88.485.000,00 €
Factory Equipment cost	Indirect Factory Cost/Direct Site Labor cost	132%	50%	67%	250.913.000,00 €	543.078.000,00 €
			Total indirect costs		448.271.000,00 €	853.730.000,00 €

The resulting estimation factors and values of the twin units' configuration are reported in Table 48.

Table 48 IRIS twin units' configuration indirect cost estimation factors and values

			Twin units' configuration			
Cost item	Scaling relation	PWR12-BE	Scaling relation Value (NOAK)	Scaling relation Value (FOAK)	NOAK	FAOK

Site labour cost	Indirect Site Labor Cost/Direct Site Labor Cost	36%			106.977.000,00 €	172.753.000,00 €
Site Material Cost	Indirect Site Material Cost/ Direct Site Material Cost	79%	50%	60%	62.032.000,00 €	88.089.000,00 €
Factory Equipment cost	Indirect Factory Cost/Direct Site Labor cost	132%	58%	75%	228.812.000,00 €	475.070.000,00 €
			Total indirect costs		**397.820.000,00 €**	**735.912.000,00 €**

Comparing the two results it seems that, despite the twin-units' configuration is penalized by a higher number of workers in site and a longer project duration, it performs better respect to the single units' configuration. Analysing in detail the results, this is true for the cost items that depends by site labour costs. Therefore, the sharing of common activities, resulting in a reduced amount of work to be managed, is going to benefit construction indirect costs.

5.3 Contingency, Owner's costs, and IDC

Contingencies

Following the guidelines reported in section 3.1.3, contingencies are estimated as 25% of the innovative items cost and 15% of standard and well-known systems costs. The riskier cost items considered are all the ones inside Acc. 21. Whereby, the resulting contingency cost for IRIS FOAK single units' configuration amount to 341.84 Mln €. While for the twin units' configuration the value equals to 295.75 Mln €. By definition for the NOAK the contingency cost is estimated as 15% of all cost voices. Therefore, the cost for the single units' configuration is estimated around 231.00 Mln € while for the other about 199.98 Mln €.

Owner's costs

As reported by [33], owner's costs consists in: "*development costs, preliminary feasibility and engineering studies, environmental studies and permitting, legal fees, insurance costs, property taxes during construction, and the electrical interconnection costs, including a tie-in to a nearby electrical transmission system*". The most authoritative references seem to converge on an estimate of the owner's costs of around 15-20% of the Overnight Capital Cost. The lower range boundary is adopted for the NOAK while the higher value for the FOAK NPPs. The resulting NOAK and FOAK costs for the single unit's configuration amount respectively to 332.89 Mln € and 609.61 Mln €. Instead, considering the twin units' configuration, the values are 289.65 Mln € and 523.20 Mln €.

Interest during construction

Since high detail information about project execution and financing are required to estimate the cash flows along the years, this cost is estimated as percentage of the Overnight capital costs. As suggested by [17], different values are estimated depending on the cost of capital and construction duration, Table 49.

Table 49 Relations among IDC, capital cost and construction duration

Cost of capital	Construction period		
	3 years	5 years	10 years
3%	5.8%	8.6%	15.3%
7%	12.8%	18.7%	32.4%
10%	17.6%	25.5%	43.0%

For the FOAKs a capital cost of 10% is assumed while for the NOAKs the value lower to 7%. Therefore, given the estimated project duration the IDC are extrapolated for the different configuration as reported in Table 50.

Table 50 IRIS: IDC/OCC values

	Single units' configuration		Twin units' configuration	
	NOAK	FAOK	NOAK	FAOK
Construction time [months]	36	48	42	54
Cost of capital	7%	10%	7%	10%
IDC/OCC	12.8%	21.5%	14.3%	23.3%
IDC	284.06 Mln €	655.33 Mln €	276.14 Mln €	609.53 Mln €

Finally in Tables 51 and 52 are reported a summary of the cost estimations respectively for the single units' and twin units' configuration. (Contingencies are included in Acc. 2x Voices).

Table 51 IRIS single units' configuration Capital Cost

670 Mwe	Single units' configuration			
	NOAK	Cost Items/OCC	FAOK	Cost Items/OCC
Acc. 21 - Structures and improvements	302.646.000,00 €	14%	386.580.000,00 €	13%
Acc. 22 - Reactor plant equipment	625.789.000,00 €	28%	799.544.000,00 €	26%
Acc. 23 - Turbine plant equipment	370.900.000,00 €	17%	396.310.000,00 €	13%

Acc. 24 - Electric plant equipment	237.752.000,00 €	11%	323.407.000,00 €	11%
Acc. 25 - Miscellaneous plant equipment	156.436.000,00 €	7%	211.047.000,00 €	7%
Acc. 26 - Main condenser heat rejection system	77.467.000,00 €	3%	77.467.000,00 €	3%
Total direct cost	**1.770.987.000,00 €**	**80%**	**2.194.353.000,00 €**	**72%**
Indirect - Site labour cost	136.862.000,00 €	6%	222.169.000,00 €	7%
Indirect Site Material Cost	60.497.000,00 €	3%	88.485.000,00 €	3%
Indirect - Factory Equipment cost	250.913.000,00 €	11%	543.078.000,00 €	18%
Total Indirect costs	**448.271.000,00 €**	**20%**	**853.730.000,00 €**	**28%**
Overnight Capital cost	**2.219.258.000,00 €**	**100%**	**3.048.083.000,00 €**	**100%**
Interest during construction	284.065.000,00 €		655.338.000,00 €	
Owner's costs	332.889.000,00 €		609.617.000,00 €	
Total capital cost	**2.836.212.000,00 €**		**4.313.037.000,00 €**	
€/kW	**4.240,00 €**		**6.440,00 €**	

Table 52 IRIS twin units' configuration Capital Cost

670 Mwe	Twin units' configuration			
	NOAK	Cost Items/OCC	FAOK	Cost Items/OCC
Acc. 21 - Structures and improvements	241.172.000,00 €	12%	317.883.000,00 €	12%
Acc. 22 - Reactor plant equipment	574.692.000,00 €	30%	726.232.000,00 €	28%
Acc. 23 - Turbine plant equipment	370.900.000,00 €	19%	396.310.000,00 €	15%
Acc. 24 - Electric plant equipment	162.597.000,00 €	8%	219.797.000,00 €	8%
Acc. 25 - Miscellaneous plant equipment	106.387.000,00 €	6%	142.417.000,00 €	5%
Acc. 26 - Main condenser heat rejection system	77.467.000,00 €	4%	77.467.000,00 €	3%
Total direct cost	**1.533.212.000,00 €**	**79%**	**1.880.103.000,00 €**	**72%**
Indirect - Site labour cost	106.977.000,00 €	6%	172.753.000,00 €	7%
Indirect Site Material Cost	62.032.000,00 €	3%	88.089.000,00 €	3%
Indirect - Factory Equipment cost	228.812.000,00 €	12%	475.070.000,00 €	18%
Total Indirect costs	**397.820.000,00 €**	**21%**	**735.912.000,00 €**	**28%**

Overnight Capital cost	**1.931.032.000,00 €**	**100%**	**2.616.014.000,00 €**	**100%**
Interest during construction	276.138.000,00 €		609.532.000,00 €	
Owner's costs	289.655.000,00 €		523.203.000,00 €	
Total capital cost	**2.496.824.000,00 €**		**3.748.748.000,00 €**	
€/kW	**3.730,00 €**		**5.600,00 €**	

6 NuScale Cost Estimation

6.1 Direct Costs

Account 211 Site Preparation/Yard work

As reported in chapter 3, this cost item is estimated by assuming the site footprint as the main driver and a total cost of 69.5 €/m^2. From [37] 140,000 m^2 are assumed as the site footprint of a 12-module plant, resulting in a total cost of 9.73 Mln €.

Account 212 Reactor Island Civil Structures

The excavation works were calculated assuming that the reactor building has a rectangular shape whose area is 107x46 m^2 [37] with a maximum foundation depth of 21 m [29]. From this information an excavation volume of 103,362 m^3 is estimated. Multiplying this by a unitary cost of 30 €/m^3 the total cost is computed.

Concrete volume is estimated by scaling the volume from a 1,000 MWe PWR using a factor of 0.50. Considering NuScale case, it is assumed that the quantity is not scaled to the total plant capacity of 924 MWe, but to the capacity of two reactor units (77 × 2 MWe). In fact, being all reactors located under the same building, it is reasonable to consider the sharing of concrete structures. Considering the amount of reinforcing steel, factors of 0.26 and 0.31 are used for the calculation of NOAK/FOAK costs respectively. While for the formwork a conversion rate of 1.68 is applied on the concrete volume. Then, the quantities of commodities are multiplied by the unitary costs and productivity rates suggested in [22]. Finally, all the values obtained are multiplied by 12, i.e., the number of units. The FOAK cost is calculated by adjusting the labour and material plus equipment cost by a factor of 1.67 and 1.3 respectively.

The costs of piping and drains, HVAC, lighting and service power, and lifts are obtained by scaling the discounted cost reported in [24] to the power of 924 MWe with a factor of 0.50.

A total area of 5,129 m^2 is estimated for the reactor spent fuel pool [40]. Then assuming that the stainless steel thickness ranges from 3 to 5 mm [41], and its density is about

7,5 tons/m^3, a weight that around 1,192 to 1,987 tons is assumed. Therefore by using the unitary costs and productivity rates suggested in [22], the cost of the component is estimated.

The cost of all the previously described items are summarize in Table 53.

Table 53 NuScale Acc. 212 cost components

Acc. 212 cost components	NuScale 12 modules plant	
	NOAK	FOAK
Excavation work	3.101.000,00 €	3.101.000,00 €
Formwork	38.585.000,00 €	63.247.000,00 €
Concrete structures	23.164.000,00 €	33.340.000,00 €
Reinforcing steel	38.600.000,00 €	67.955.000,00 €
Plumbing and drains	846.000,00 €	846.000,00 €
Heating, ventilation, air conditioning (special)	3.893.000,00 €	3.893.000,00 €
Lighting and service power	2.745.000,00 €	2.745.000,00 €
Elevators	258.000,00 €	258.000,00 €
Reactors pool and spent fuel pool	9.148.000,00 €	15.250.000,00 €
Total	**120.338.000,00 €**	**190.633.000,00 €**

Account 213 Turbine Generator Building

NuScale's plant configuration comprises two turbine buildings containing six turbines each, located close to the reactor building.

The excavation volume is estimated from the information reported in [37]. Each turbine building measures 105x65m and has foundations ranging from 8 to 10 metres. Thus, the volume of material removed varies from 54,600 to 68,250m^3 for each turbine building. A unit cost of 30 €/m^3 is considered.

The concrete volume of the building is scaled considering the power of 77 MWe x 6 turbines. The conversion factor 1.68 is assumed to calculate the formwork area from the concrete volume. While the ratio between steel weight and volume of concrete varies from 0.07 to 0.08. The total cost of these items is then calculated multiplying the value by 2. To take into account, the impact of project execution performances, the FOAK cost is calculated adjusting the labour and materials plus equipment cost respectively by a factor of 1.67 and 1.3.

The costs of plumbing and drains, HVAC, lighting, and service power and elevators are obtained by scaling the discounted cost reported in [24] to the power of 462 MWe with a factor of 0.50. Finally, the costs are multiplied by 2 to obtain the total cost.

In turbine buildings, concrete structures are required to support the equipment. Therefore, an additional cost item is included in the analysis. This is divided into formwork, reinforcing steel and concrete. Since the item is specific to each turbine, the concrete is scaled to the power of 77MWe. The structure presents a steel weight - volume of concrete ratio that varies from 0.12 to 0.14. The same factors as above are used to calculate the FOAK cost associated with these items.

In the following Table 54 a summary of the cost computations is reported.

Table 54 NuScale Acc. 213 cost components

Acc. 213 cost components	**NuScale 12 modules plant**	
	NOAK	FOAK
Excavation work	3.276.000,00 €	4.095.000,00 €
Formwork - Building	4.774.000,00 €	7.784.000,00 €
Concrete structures - Building	2.680.000,00 €	3.873.000,00 €
Reinforcing steel - Building	1.128.000,00 €	1.997.000,00 €
Formwork - Turbine supporting structure	8.876.000,00 €	14.379.000,00 €
Concrete structures - Turbine supporting structure	5.739.000,00 €	8.160.000,00 €
Reinforcing steel - Turbine supporting structure	7.539.000,00 €	12.144.000,00 €
Plumbing and drains	3.687.000,00 €	3.726.000,00 €
Heating, ventilation, air conditioning (special)	3.002.000,00 €	3.034.000,00 €
Lighting and service power	1.546.000,00 €	1.562.000,00 €
Elevators	331.000,00 €	335.000,00 €
Total	**42.574.000,00 €**	**61.084.000,00 €**

Account 214 Security Building and gatehouse

Since no information about concrete are available for this building, the total cost of this facility is directly scaled by a factor of 0.50 from the discounted cost reported in [20]. In the equation, it is assumed the total NPP power of 924 MWe. The cost is estimated 2.92 Mln €.

Account 215 Reactor Service (Auxiliary) Building

Excavation costs are under Acc. 212.

The amount of concrete is scaled to the total power of 924 MWe by using a scaling factor of 0.5. The area of the formwork is obtained multiplying the volume of concrete by 1,68. While, steel weight - volume of concrete ratio varies from 0.09 to 0.11.

As for the reactor building, the internal equipment is scaled by using a factor of 0.50 and assuming the plant power of 924 MWe.

The Table 55 summarizes the cost computations.

Table 55 NuScale Acc. 215 cost components

Acc. 215 cost components	NuScale 12 modules plant	
	NOAK	FOAK
Formwork	9.822.000,00 €	9.822.000,00 €
Concrete structures	5.897.000,00 €	5.897.000,00 €
Reinforcing steel	3.338.000,00 €	3.966.000,00 €
Plumbing and drains	1.170.000,00 €	1.170.000,00 €
Heating, ventilation, air conditioning (special)	11.018.000,00 €	11.018.000,00 €
Lighting and service power	1.104.000,00 €	1.104.000,00 €
Elevators	406.000,00 €	406.000,00 €
Total	**32.753.000,00 €**	**33.381.000,00 €**

Account 216 Radwaste Building

From the information reported in [37], a building size of 55x60m, and a foundation depth that range from 8 and 10 m, it is assumed. Therefore, the removed material varies from 26,400 to 33,000m^3.

The structure is shared between all the units, so concrete amount is scaled by using the overall power output equals to 924 MWe. Due to lack of information in the 1970s PWR reference case, 1,600 MWe EPR concrete quantity [30] is used in the computation. As for the other buildings the same scaling factor is used, and the formwork area is obtained multiplying the concrete volume by 1.68. It is also assumed that rebar weight - concrete volume ratio is the same of Acc. 217.

Internal equipment is scaled assuming a factor of 0.50 and the power of 924 MWe.

The cost estimations are reported in Table 56.

Table 56 NuScale Acc. 216 cost components

Acc. 216 cost components	NuScale 12 modules plant	
	NOAK	FOAK
Excavation work	792.000,00 €	990.000,00 €
Formwork	6.932.000,00 €	6.932.000,00 €
Concrete structures	4.162.000,00 €	4.162.000,00 €
Reinforcing steel	2.028.000,00 €	2.410.000,00 €
Plumbing and drains	920.000,00 €	920.000,00 €

Heating, ventilation, air conditioning (special)	3.009.000,00 €	3.009.000,00 €
Lighting and service power	752.000,00 €	752.000,00 €
Elevators	412.000,00 €	412.000,00 €
Total	**19.004.000,00 €**	**19.584.000,00 €**

Account 217 Fuel Service Building

Excavation costs are included in Acc. 212.

Being a building shared among all the 12 units, concrete amount is scaled using the overall power output of 924 MWe. As for the other buildings a scaling factor of 0.5 is used. The formwork area is obtained multiplying the concrete volume by 1.68. Rebar weight - concrete volume ratio range from 0.08 to 0.09.

Considering the internal equipment, it is scaled using a factor of 0.50 and assuming a plant power of 924 MWe.

Table 57 reported in detail the results.

Table 57 NuScale Acc. 217 cost components

Acc. 217 cost components	NuScale 12 modules plant	
	NOAK	FOAK
Formwork	6.952.000,00 €	6.952.000,00 €
Concrete structures	4.174.000,00 €	4.174.000,00 €
Reinforcing steel	2.034.000,00 €	2.417.000,00 €
Plumbing and drains	357.000,00 €	357.000,00 €
Heating, ventilation, air conditioning (special)	3.227.000,00 €	3.227.000,00 €
Lighting and service power	275.000,00 €	275.000,00 €
Total	**17.017.000,00 €**	**17.400.000,00 €**

Account 218 other building and structures

This account summarizes together all the remaining buildings and structures, which are:

- Administration and training building
- Annex building
- Control building
- Security building
- Main Steam and Feedwater Pipe Enclosure
- Fire pump house, including foundations

- Manway tunnels (RCA tunnels)
- Electrical tunnels
- Non-essential switchgear building
- Pipe tunnels
- Technical support centre
- Containment equipment hatch and missile shield
- Wastewater treatment
- Control room emergency air intake structure

The costs for these structures are obtained by scaling the discounted cost reported in[24] to the power of 924 MWe using a factor of 0.50. Annex building cost is taken from [29]. Adjustments for the use of passive safety systems are considered. To determine the FOAK value, factors equal to 1.68 and 1.3 are respectively applied over labor (57% of the Acc. 218 cost) and material plus equipment (43% of the Acc. 218 cost) costs.

Table 58 summarize Acc. 218 cost components:

Table 58 NuScale Acc. 218 Structures and buildings costs

Acc. 218 Structures and buildings	NuScale 12 modules plant	
	NOAK	FOAK
Annex building	20.280.000,00 €	30.757.000,00 €
218A Control and diesel generators building	34.388.000,00 €	52.152.000,00 €
218B Administration and training building	14.261.000,00 €	21.628.000,00 €
218J Main Steam and Feedwater Pipe Enclosure	16.881.000,00 €	25.601.000,00 €
218D Fire pump house, including foundations	916.000,00 €	1.389.000,00 €
218F Manway tunnels (RCA tunnels)	1.635.000,00 €	2.480.000,00 €
218G Electrical tunnels	146.000,00 €	221.000,00 €
218H non-essential switchgear building	1.150.000,00 €	1.744.000,00 €
218K Pipe tunnels	681.000,00 €	1.033.000,00 €
218L Technical support centre	1.694.000,00 €	2.569.000,00 €
218P Containment equipment hatch and missile shield	472.000,00 €	716.000,00 €
218S Wastewater treatment	1.647.000,00 €	2.497.000,00 €
218V Control room emergency air intake structure	192.000,00 €	291.000,00 €
Total	**94.338.000,00 €**	**143.073.000,00 €**

Account 221 Reactor equipment

Reactor containment

NuScale reactor containment concept is quite different from the traditional PRWs, in fact it is considered as part of the reactor equipment. For this reason, it is included in Acc. 221 instead of 212. Assuming that its fabrication is quite similar to the one of reactor pressure vessel shell, the same model developed is used. A forged steel weight of 110 tons and an external diameter of 4.6 m is considered for the component. Given the cost of forged steel equals to 6,000 €/ton, the cost obtained for the is about 3.66 Mln €

Reactor vessel shell

NuScale reactor pressure vessel has a total weight of around 590 tons, comprehensive of internals and shell. The weight of the shell is estimate about 500 tons. Outer diameter is 2.83 m. Given these dimensions is reasonable to consider the possibility to integrate the nozzles into the forgings part. Assuming a cost of forged steel about 6000 €/tons the cost of the first reactor produced is estimated 15.47 Mln €.

Reactor vessel internals

Assuming the component weight about 90 tons the cost computed, through the model describe in Chapter 3, is about 25.65 Mln for 1 unit.

Control rods and drives

The number of control rods employed in NuScale reactor is 16; 4 in regulating bank and 12 in shutdown bank. So, the cost of these components is estimated 0.88 Mln €. Assuming 20 control rod drives systems their cost is evaluated 11.1 Mln €.

Summing the costs of reactor containment, pressure vessel shell, internals, control rods and drives, the resulting cost of manufacturing and install the first unit is about 56.76 Mln €. Being NuScale's NPP, composed by 12 units a discount of 11% is applied on the 2nd and 3rd couples installed, while a saving of 18% respect to the first couple, is considered for the remaining units. As result, the FOAK cost of Acc. 221 is about 455,21 Mln €. For the NOAK a discount of 18% is applied over all the 12 modules resulting in a cost equal to 279,26 Mln €.

Account 222 Main steam transport system

The parameters related to NuScale steam generators are reported in Table 59.

Table 59 NuScale steam generator parameters[29]

Characteristic	Value	Unit of measure
Type	2 once through helical coil	/
SG power (unit)	150	MWth
Tubes material	Inconel 690	/
# Tubes per unit	740	Units
Steam quality	4.4 - 321	MPa - C°
Steam flow	87	Kg/s
Tubes Average length	30	m
Tubes weight	10996	Kg
Collectors weight	4214.9	Kg
Working time collectors	766	Hours

Cost of tubes, including material and manufacturing are estimated assuming a cost of 92 €/Kg. The resulting value for one steam generator is about 1.01 Mln €.

Collectors' material is evaluated assuming a cost of 80 €/Kg, resulting into 0.34 Mln €. Manufacturing cost is estimated based on the working time suggested by the experts, which amount to 740 hours. Assuming a fabrication cost of 110 €/h, collectors are estimated about 0.084 Mln €.

Other costs are estimated 15 % of the sum of tubes and collectors' material cost, resulting in 0.20 Mln €.

As reported in [29], NuScale steam generator auxiliary cost amount to 1.05 Mln € for the first unit produced. The successive units are discounted by 20%, considering uninfluencing the non-recurring costs. So, the auxiliary cost from the second steam generator onward is going to be about 0.84 Mln €.

Cost of installation for each steam generator is assumed to be 0.48 Mln €, this value is reduced for the following units installed by 10%. Site material cost is assumed to be about 0.045 Mln € [32].

The total cost of the first unit produced is about 3.50 Mln € while from the second onward it equals to 3.25 Mln €.

Given that for each reactor 2 steam generators are installed, the equipment for the first reactor is evaluated 6.75 Mln € while for the second 6.50 Mln €. The total cost for twelve units plant results in 78.20 Mln €.

Being the primary cooling system based on natural circulation, no reactor coolant pumps are present.

Accounts 223 Safeguards system & 227 Reactor instrumentation and control

As mentioned in chapter 3, the costs of these two items are estimated adjusting the cost of IRIS' components reported in [29]. The Table 60 summarize the cost of each safety system employed in IRIS' NPP and the adjusting factors used to obtain the corresponding cost of NuScale equipment. The discounts were suggested by experts of the sector.

Table 60 NuScale' passive safety systems cost and adjusting factors

Safety equipment	IRIS components cost (EUR 01/2019)	Cost reduction NuScale components	NuScale components cost (EUR 01/2019)
Emergency Heat Removal System (including: 4 heat exchangers, valves, control system and electrical equipment)	4.3 Mln €	100%	0 €
EHRS and SG make-up tanks primary circuit	4 Mln €	50%	2 Mln €
Automatic Depressurization System and circuit (including valves and sparged)	1.1 Mln €	50%	0.55 Mln €
Emergency Boratian Tanks system and circuit (2X) (Including valves)	3 Mln €	50%	1.5 Mln €
Suppression pool and Long-Term Core Makeup systems (including pumps and circuit)	2.7 Mln €	0%	2.7 Mln €
Chemical and Volume control system, Piping, water treatment, atmosphere control system and miscellaneous eq.	3.8 Mln €	60%	1.52 Mln €

The resulting NOAK cost of Acc. 223 and 227 is about 8.27 Mln €. Taking in consideration the dependency of these cost items from project execution performances, adjusting factors are applied. Specifically labour cost, representing the 19% of account cost is increased by 2.16, while equipment and site material costs are multiplied by 1.04. The FOAK cost of Acc. 223 and 227 is about 10.27 Mln €. Taking in consideration the deployment of 12 reactors, experts suggested to consider an additional saving of 10%. This accounts for possible saving coming from the sharing of common activities and/or equipment. Therefore, the resulting cost for the NOAK is estimated 89.32 Mln €, while for the FOAK 111.90 Mln €.

Account 224 Radwaste processing

This cost item is estimated assuming a scaling factor of 0.6 and a total plant capacity of 924MWe. The FOAK value is obtained by adjusting the cost with a factor of 2.16

applied on 19% of the total cost (labour cost) and a factor of 1.04 on the remaining 81% (equipment plus materials cost). The estimated costs of Acc. 224 are 43.99 Mln € for the NOAK and 55.10 Mln € for the FOAK.

Account 225 Fuel handling and storage

This cost item is estimated by assuming a scaling factor of 0.6 and the total plant capacity of 924MWe. The resulting cost amounts to 25.48 Mln €.

Account 226 Other reactor plant equipment

As suggested by the experts, this cost item is estimated by scaling the PWR12-BE costs using a factor equals to 0.6. It is assumed that reactors laying under the same building shared part of the cost associated to Acc. 226. Indeed, the power of a couple of reactors (154 MWe) is used to scale cost related to components included in Acc. 226. Therefore, the output of the equation is multiplied by 6 to account the deployment of 12 modules. FOAK costs are estimated multiplying labour cost (35% of Acc. 226 cost) by 2.16, while equipment and site material cost by 1.04. The resulting costs are 187.40 Mln € for the FOAK and 130.86 Mln € for the NOAK.

Account 228 Reactor plant miscellaneous items

This item is estimated using a scaling factor of 0.6. The power used to scale the costs corresponds to that of a single unit i.e., 77MWe, except for the welders' qualification item where the total power of the plant is used. Therefore, the total costs are obtained by multiplying them by the number of units. Table 61 summarizes the cost computations.

Table 61 NuScale Acc. 228 cost components

Acc. 228 Cost items	Costs
Field painting	3.731.000,00 €
Qualification of welders	6.118.000,00 €
Pipe insulation	9.606.000,00 €
Equipment insulation	2.880.000,00 €
NSSS insulation	9.548.000,00 €
Total	**31.880.000,00 €**

Account 231 Turbine generator

As mentioned in chapter 3, the cost of this items is scaled by a factor equal to 0.8 from the PWR12-BE cost. Considering equipment simplification of turbine power lower than 350 MWe, the result of the scaling equation is reduced by 15%. NuScale turbines have a power of 77 MWe, therefore, the cost for the first system installed is estimated 31.72 Mln €. Considering the second turbine installed, experts suggested to reduce Acc. 231 equipment and site labour costs, respectively by 10% and 4%. Therefore, the cost of the second and the nth turbine is estimated 26.63 Mln €. Since 12 turbines are installed in NuScale NPP a total of 347 Mln € is estimated for Acc. 231.

Account 233 Condensing systems

To estimate Acc. 233 cost voice the same factors used for Acc. 231 are assumed. Therefore, costs are scaled based on the system heat rejection power with a factor equal to 0.8. Then the output is reduced by 15%. The heat rejected by NuScale' s condensing system amount to 173 MWth. Therefore, the cost obtained for the first unit installed equals to 7.53 Mln €. Considering the second, a learning factor of 4% is applied over site labour cost. Moreover, a discount of 10% over equipment's purchasing is assumed. Resulting in a cost for the systems of 6.9 Mln €. Given that 12 systems are installed in NuScale's NPP, the NOAK cost is estimated 83.51 Mln €. To obtain the FOAK cost, site labour cost (29%) is raised by 1.82, while equipment plus site material cost by 1.05. FOAK cost is evaluated 106.34 Mln €.

Account 234 Feedwater heating system

In line with Acc. 231 and 233 the same factors are used to adjust and discount the scaled PWR12-BE cost. The thermal output of NuScale module (250 MWth) is used to represents the size of the system in the equation. After being reduce of 15% the cost of the first system installed is estimated 5.95 Mln €. Appling the saving factors previously described the cost of the second system equals to 5.46 Mln €. Being NuScale's NPP composed by12 turbines the total cost of Acc. 234 results 66.06 Mln €.

Account 235 Other turbine plant equipment

As mention in Chapter 3 the same model proposed by [32] is adopted to estimate Acc. 235 cost voice. In Table 62 is reported the Acc. 231 previously computed cost and the factors used to estimate Acc. 235.

Table 62 NuScale Acc. 235/231 cost relations

	Factory equipment	Site labor	Site material	Total
NuScale Acc. 231 costs	322.49 Mln €	20.89 Mln €	3.62 Mln €	347.00 Mln €
Account 235/account 231 cost	8.9%	130.3%	85.8%	16.7%

Therefore, NOAK cost related to Acc. 235 is estimated 58.93 Mln €. The cost of the FOAK is determined multiplying labour cost and equipment plus material cost respectively by 1.82 and 1.05. The resulting value is about 82.80 Mln €.

Account 236 Instrumentation and control

Assuming the equipment is not shared between the turbines, the costs are scaled to the power of 77 MWe by using a scaling factor of 0.8. Then, the total cost is calculated by multiplying the value obtained by the number of units. To account for technological innovations and digitisation of instruments, the costs for PWR12-BE are reduced by 10% before to be scaled. The estimation obtain for NuScale's NPP equals to 20.41 Mln €.

Account 237 Turbine plant miscellaneous items

This item is estimated using a scaling factor of 0.8. The power used to scale the costs corresponds to that of a single unit i.e., 77MWe, except for the welders' qualification item where the total power of the plant is used. Therefore, the final cost is obtained by multiplying them by the number of units. Results are reported in Table 63.

Table 63 NuScale Acc. 237 cost components

Acc. 237 Cost items	Costs
Field painting	4.385.000,00 €
Qualification of welders	3.517.000,00 €
Turbine plant insulation	16.451.000,00 €
Total	**24.352.000,00 €**

Account 241 Switchgear

This cost item is estimated assuming a scaling factor of 0.4 and the total plant capacity of 924MWe. Cost adjustments are made to consider the specific characteristics of the NuScale's NPP. In particular, as reported [24], PWR12-BE costs for class 1E electrical systems are reduced by 25%. The cost obtained amount to 23.86 Mln €.

Account 242 Station service equipment

This cost item is estimated assuming a scaling factor of 0.4 and the total plant capacity of 924MWe. Some cost adjustments are made to consider the specific characteristics of the NuScale's NPP. As reported in [24], the cost of PWR12-BE for class 1E load centres, transformers and battery systems are reduced by 25%. In addition, since emergency power is not a safety-related function, the costs for diesel generators are reduced by $10 Mln (2011 USD). The resulting cost for NuScale power plant is 34.07 Mln €.

Account 243 Switchboards

This cost item is estimated assuming a scaling factor of 0.4 and the total plant capacity of 924MWe. As reported in [24], PWR12-BE costs for class 1E electrical systems are reduced by 25%. The cost estimated is about 4.37 Mln €.

Account 244 Protective equipment

This cost item is estimated assuming a scaling factor of 0.4 and the total plant capacity of 924MWe, resulting in 9.34 Mln €.

Account 245 Electric structure and wiring

As suggested by the expert costs related to Acc. 245 are scaled from the actualized cost of the PWR12-BE. Considering the escalation of systems complexity over the years, partially balanced by the adoption of passive safety systems, PWR12-BE costs are increased by 15%. Acc. 245 material cost is estimated considering the power of a single reactor equals to 77 MWe and adopting a scaling factor of 0.4. On the other hand, considering site labour cost, advantages from common activities are accounted considering the power of a couple of reactors in the scaling equation. Therefore, the power of 154 MWe is assumed to estimate site labour cost. The resulting NOAK cost for the 12-modules plant is around 165.59 Mln €. FOAK costs are estimated multiplying labour and material cost respectively by 1.93 and 1.12. The value obtained for the FOAK is 279.99 Mln €.

Account 246 Power and control wiring

This cost item is estimated assuming a scale factor of 0.4 and the total plant capacity of 924MWe. The cost for the NOAK NPP amount to 30.54 Mln €. The FOAK cost is estimated by multiplying 56% of the previous value by 1.93 (site labour cost), and the remaining 44% by 1.12 (Site material plus equipment costs). The resulting cost equals to 48.06 Mln €.

Account 251 Transportation and lifting equipment

The crane of the turbine building, and the crane of the heater bay are estimated using the power of 6 units equal to 462MWe. The total cost is then obtained by multiplying the results by 2, i.e. the number of turbine buildings. The other items are estimated using the total plant capacity of 924MWe. The scaling factor used is 0.3. The resulting cost amounts to 16.23 Mln €.

Account 252 Air water and steam service systems

The service systems are estimated by scaling the PWR12-BE cost through a factor of 0.4. For the 12-modules plant of NuScale is assumed that equipment and installation work is common for 6 of the 12 units. Therefore, costs are scaled to the power of six reactors (462 MWe). The resulting cost of the NOAK NPP is 96.44 Mln €. Being Acc. 252 dependents on project execution performances, the FOAK costs are estimated escalating site labour cost (54% of Acc. 252 cost) by a factor equals to 1.94 and material and equipment cost by 1.11. The resulting value for the NuScale's NPP is 150.45 Mln €.

Account 253 Communications Equipment

This cost item is estimated assuming a scale factor of 0.3 and the total plant capacity of 924MWe, the resulting value is 14.36 Mln €.

Account 254 Furnishings and Fixtures

This cost item is estimated assuming a scale factor of 0.3 and the total plant capacity of 924MWe, the resulting value is 6.13Mln €.

Account 255 Wastewater Treatment Equipment

This cost item is estimated assuming a scale factor of 0.3 and the total plant capacity of 924MWe, the resulting value is 6.34Mln €.

Account 261 Structures

The facilities are not shared between the different units. Therefore, the power of a single reactor (77MWe) is used to scale the costs. Finally, the value obtained is multiplied by the number of reactors. The scaling factor adopted is 0.8. The cost for each component is reported in Table 64.

Table 64 NuScale Acc. 261 cost components

Acc. 261 Cost items	Costs
Makeup water intake structure	3.376.000,00 €
Circulating water pump house structure	6.228.000,00 €
Circulating water pump house services	694.000,00 €
Makeup water pre-treatment building	3.321.000,00 €
Makeup water pre-treatment building services	716.000,00 €
Total	**14.333.000,00 €**

Account 262 Mechanical equipment

Being this equipment strictly correlated with Acc. 23 voices, the same adjusting factors of Acc. 231, 233 and 234 are adopted. Therefore, the cost of the PWR-BE is scaled based on heat rejection power of the system. For the NuScale this amount to 173 MWth. Therefore, after being discounted of 15%, the cost of the first installed equipment is equal to 11.61 Mln €. Taking advantage of 10% discount on equipment and 4% on site labour cost, the second and the nth system installed is estimated 10.64 Mln €.

Considering the installation of twelve systems the resulting cost for Acc. 262 is 128.68 Mln €.

In Table 65 are reported the costs of all the previous voices for the NuScale 12 modules NPP.

Table 65 NuScale direct costs

COA	NuScale 12 modules plant 924 Mwe								
	NOAK				Difference FOAK/NOAK	FOAK			
	Total	Factory cost	Site labor cost	Site material cost		Total	Factory cost	Site labor cost	Site material cost
211	9.730.000 €	111.000 €	5.647.000 €	3.973.000 €	0 €	9.730.000 €	111.000 €	5.647.000 €	3.973.000 €
212	120.338.000 €	26.486.000 €	66.125.000 €	27.728.000 €	70.295.000 €	190.633.000 €	27.082.000 €	118.606.000 €	44.945.000 €
213	42.574.000 €	1.143.000 €	20.545.000 €	20.887.000 €	18.511.000 €	61.084.000 €	1.300.000 €	34.365.000 €	25.420.000 €
214	2.923.000 €	112.000 €	2.023.000 €	789.000 €	0 €	2.923.000 €	112.000 €	2.023.000 €	789.000 €
215	32.753.000 €	5.572.000 €	18.653.000 €	8.529.000 €	628.000 €	33.381.000 €	5.577.000 €	19.122.000 €	8.683.000 €
216	19.004.000 €	862.000 €	11.936.000 €	6.207.000 €	580.000 €	19.584.000 €	867.000 €	12.369.000 €	6.349.000 €
217	17.017.000 €	1.719.000 €	7.760.000 €	7.539.000 €	383.000 €	17.400.000 €	1.722.000 €	8.046.000 €	7.633.000 €
218	94.338.000 €	5.423.000 €	58.781.000 €	30.135.000 €	48.735.000 €	143.073.000 €	5.836.000 €	95.167.000 €	42.071.000 €
21	**338.674.000 €**	**41.424.000 €**	**191.468.000 €**	**105.783.000 €**	**139.131.000 €**	**477.804.000 €**	**42.604.000 €**	**295.341.000 €**	**139.860.000 €**
221	279.260.000 €	246.400.000 €	12.778.000 €	20.082.000 €	175.956.000 €	455.216.000 €	260.657.000 €	160.573.000 €	33.986.000 €
222	78.203.000 €	69.612.000 €	7.818.000 €	774.000 €	0 €	78.203.000 €	69.612.000 €	7.818.000 €	774.000 €
223	89.316.000 €	71.453.000 €	16.971.000 €	894.000 €	22.580.000 €	111.896.000 €	74.311.000 €	36.656.000 €	929.000 €
224	43.986.000 €	33.942.000 €	8.429.000 €	1.616.000 €	11.120.000 €	55.105.000 €	34.843.000 €	17.769.000 €	2.494.000 €
225	25.486.000 €	23.462.000 €	1.802.000 €	223.000 €	0 €	25.486.000 €	23.462.000 €	1.802.000 €	223.000 €
226	130.863.000 €	78.518.000 €	45.802.000 €	6.544.000 €	56.533.000 €	187.395.000 €	81.658.000 €	98.932.000 €	6.805.000 €
227	Incl. in 223	Incl. in 223	Incl. in 223	Incl. in 223	Incl. in 223	Incl. in 223	Incl. in 223	Incl. in 223	Incl. in 223
228	31.880.000 €	0 €	18.280.000 €	13.601.000 €	0 €	31.880.000 €	0 €	18.280.000 €	13.601.000 €
22	**678.990.000 €**	**523.385.000 €**	**111.877.000 €**	**43.729.000 €**	**266.187.000 €**	**945.177.000 €**	**544.542.000 €**	**341.827.000 €**	**58.809.000 €**
231	347.007.000 €	322.495.000 €	20.891.000 €	3.622.000 €	0 €	347.007.000 €	323.607.000 €	19.766.000 €	3.634.000 €
233	83.511.000 €	56.030.000 €	24.221.000 €	3.260.000 €	22.826.000 €	106.336.000 €	58.832.000 €	44.083.000 €	3.423.000 €
234	66.060.000 €	43.311.000 €	20.797.000 €	1.952.000 €	0 €	66.060.000 €	43.311.000 €	20.797.000 €	1.952.000 €
235	58.938.000 €	28.702.000 €	27.158.000 €	3.079.000 €	23.859.000 €	82.797.000 €	30.138.000 €	49.427.000 €	3.233.000 €
236	20.407.000 €	5.562.000 €	13.671.000 €	1.175.000 €	0 €	20.407.000 €	5.562.000 €	13.671.000 €	1.175.000 €
237	24.352.000 €	0 €	13.948.000 €	10.405.000 €	0 €	24.352.000 €	0 €	13.948.000 €	10.405.000 €
23	**600.273.000 €**	**456.099.000 €**	**120.684.000 €**	**23.491.000 €**	**46.684.000 €**	**646.956.000 €**	**461.448.000 €**	**161.689.000 €**	**23.821.000 €**
241	23.864.000 €	22.481.000 €	1.207.000 €	177.000 €	0 €	23.864.000 €	22.481.000 €	1.207.000 €	177.000 €
242	34.075.000 €	30.116.000 €	3.324.000 €	636.000 €	0 €	34.075.000 €	30.116.000 €	3.324.000 €	636.000 €
243	4.377.000 €	3.357.000 €	754.000 €	267.000 €	0 €	4.377.000 €	3.357.000 €	754.000 €	267.000 €
244	9.341.000 €	0 €	5.464.000 €	3.877.000 €	0 €	9.341.000 €	0 €	5.464.000 €	3.877.000 €
245	165.586.000 €	0 €	116.710.000 €	48.876.000 €	114.406.000 €	279.991.000 €	0 €	225.250.000 €	54.742.000 €
246	30.544.000 €	3.471.000 €	16.953.000 €	10.122.000 €	17.520.000 €	48.064.000 €	3.518.000 €	31.940.000 €	12.607.000 €
24	**267.784.000 €**	**59.423.000 €**	**144.410.000 €**	**63.953.000 €**	**131.925.000 €**	**399.709.000 €**	**59.470.000 €**	**267.937.000 €**	**72.303.000 €**
251	16.232.000 €	13.702.000 €	2.301.000 €	231.000 €	0 €	16.232.000 €	13.702.000 €	2.301.000 €	231.000 €
252	96.445.000 €	29.304.000 €	52.283.000 €	14.858.000 €	54.004.000 €	150.449.000 €	32.528.000 €	101.429.000 €	16.493.000 €
253	14.365.000 €	4.364.000 €	8.673.000 €	1.329.000 €	0 €	14.365.000 €	4.364.000 €	8.673.000 €	1.329.000 €
254	6.127.000 €	4.859.000 €	1.126.000 €	144.000 €	0 €	6.127.000 €	4.859.000 €	1.126.000 €	144.000 €
255	6.345.000 €	1.680.000 €	4.199.000 €	467.000 €	0 €	6.345.000 €	1.680.000 €	4.199.000 €	467.000 €
25	**139.512.000 €**	**53.907.000 €**	**68.581.000 €**	**17.026.000 €**	**54.004.000 €**	**193.516.000 €**	**57.130.000 €**	**117.726.000 €**	**18.661.000 €**
261	14.333.000 €	580.000 €	8.873.000 €	4.881.000 €	0 €	14.333.000 €	580.000 €	8.873.000 €	4.881.000 €
262	128.684.000 €	86.337.000 €	37.861.000 €	4.486.000 €	0 €	128.684.000 €	86.337.000 €	37.861.000 €	4.486.000 €
26	**143.016.000 €**	**86.916.000 €**	**46.734.000 €**	**9.367.000 €**	**0 €**	**143.016.000 €**	**86.916.000 €**	**46.734.000 €**	**9.367.000 €**
Total direct	**2.168.247.000 €**	**1.221.151.000 €**	**683.750.000 €**	**263.347.000 €**	**637.930.000 €**	**2.806.176.000 €**	**1.252.108.000 €**	**1.231.252.000 €**	**322.817.000 €**

6.1.1 Modularization

Having obtained the direct cost for each cost item, the modularisation effect is applied over the previously mentioned voices (section 3.3.3). Therefore, for these COA items, 50% of site labour costs is move to factory at twice the productivity. In order to account the impact of moving larger parts for NuScale's NPP is assumed that transportation represents 2% of the total items cost and that modularization are going to raise this by 3%. This last value is lower than the one considered for IRIS (5%) due to the reduced size of the components.

For NuScale's 12 modules NPP, a total savings of 112.62 Mln € is estimated for the NOAK plant, while for the FOAK the value amounts to 212.27 Mln €. A bigger saving was expected for the first NPP employed given the higher impact of labor over total direct cost.

A detailed view of the results is reported in Table 66.

Table 66 NuScale modularization savings

COA	NuScale 12 modules plant 924 Mwe - Modularization savings			
	NOAK		FOAK	
	Cost	Modul. Savings	Cost	Modul. Savings
211	9.730.000,00 €	0,00 €	9.730.000,00 €	0,00 €
212	103.823.000,00 €	16.516.000,00 €	160.997.000,00 €	29.636.000,00 €
213	37.438.000,00 €	5.136.000,00 €	52.494.000,00 €	8.591.000,00 €
214	2.417.000,00 €	506.000,00 €	2.417.000,00 €	506.000,00 €
215	28.093.000,00 €	4.660.000,00 €	28.604.000,00 €	4.777.000,00 €
216	16.021.000,00 €	2.984.000,00 €	16.492.000,00 €	3.092.000,00 €
217	15.078.000,00 €	1.939.000,00 €	15.390.000,00 €	2.011.000,00 €
218	79.646.000,00 €	14.692.000,00 €	119.285.000,00 €	23.788.000,00 €
21	**292.243.000,00 €**	**46.431.000,00 €**	**405.406.000,00 €**	**72.399.000,00 €**
221	276.213.000,00 €	3.047.000,00 €	415.229.000,00 €	39.987.000,00 €
222	76.291.000,00 €	1.913.000,00 €	76.291.000,00 €	1.913.000,00 €
223	85.117.000,00 €	4.200.000,00 €	102.776.000,00 €	9.120.000,00 €
224	43.986.000,00 €	0,00 €	55.105.000,00 €	0,00 €
225	25.486.000,00 €	0,00 €	25.486.000,00 €	0,00 €
226	130.863.000,00 €	0,00 €	187.395.000,00 €	0,00 €
227	incl. in 223	incl. in 223	incl. in 223	incl. in 223
228	31.880.000,00 €	0,00 €	31.880.000,00 €	0,00 €
22	**669.831.000,00 €**	**9.159.000,00 €**	**894.159.000,00 €**	**51.019.000,00 €**
231	341.978.000,00 €	5.030.000,00 €	342.260.000,00 €	4.748.000,00 €
233	77.489.000,00 €	6.022.000,00 €	95.351.000,00 €	10.986.000,00 €
234	60.887.000,00 €	5.174.000,00 €	60.887.000,00 €	5.174.000,00 €
235	58.938.000,00 €	0,00 €	82.797.000,00 €	0,00 €
236	20.407.000,00 €	0,00 €	20.407.000,00 €	0,00 €
237	24.352.000,00 €	0,00 €	24.352.000,00 €	0,00 €
23	**584.049.000,00 €**	**16.224.000,00 €**	**626.051.000,00 €**	**20.906.000,00 €**
241	23.864.000,00 €	0,00 €	23.864.000,00 €	0,00 €
242	34.075.000,00 €	0,00 €	34.075.000,00 €	0,00 €

243	4.377.000,00 €	0,00 €	4.377.000,00 €	0,00 €
244	9.341.000,00 €	0,00 €	9.341.000,00 €	0,00 €
245	136.409.000,00 €	29.178.000,00 €	223.679.000,00 €	56.313.000,00 €
246	30.544.000,00 €	0,00 €	48.064.000,00 €	0,00 €
24	**238.607.000,00 €**	**29.178.000,00 €**	**343.396.000,00 €**	**56.313.000,00 €**
251	16.232.000,00 €	0,00 €	16.232.000,00 €	0,00 €
252	96.445.000,00 €	0,00 €	150.449.000,00 €	0,00 €
253	14.365.000,00 €	0,00 €	14.365.000,00 €	0,00 €
254	6.127.000,00 €	0,00 €	6.127.000,00 €	0,00 €
255	6.345.000,00 €	0,00 €	6.345.000,00 €	0,00 €
25	**139.512.000,00 €**	**0,00 €**	**193.516.000,00 €**	**0,00 €**
261	12.115.000,00 €	2.218.000,00 €	12.115.000,00 €	2.218.000,00 €
262	119.270.000,00 €	9.414.000,00 €	119.270.000,00 €	9.414.000,00 €
26	**131.385.000,00 €**	**11.632.000,00 €**	**131.385.000,00 €**	**11.632.000,00 €**
Total	**2.055.625.000,00 €**	**112.622.000,00 €**	**2.593.911.000,00 €**	**212.266.000,00 €**

6.2 Indirect Costs

As declared in section 3.2.3 indirect costs are computed through the model proposed by [28]. Therefore, assumptions about construction duration and average number of workers in site are made. Table 67 summarizes these values for the NOAK and the FOAK NuScale's NPP and the reference case. These are estimated thanks to the experts' judgments.

Table 67 NuScale construction duration and average number of workers in site

Adjusting factors	PWR12 BE	NuScale 12 modules plant	
		NOAK	FAOK
Average number of workers	3000	1000	1200
Construction time [months]	72	48	60

The resulting estimation factors and values use to estimate the NuScale's 12 modules NPP indirect costs are reported in Table 68.

Table 68 NuScale indirect cost factors and values

			NuScale 12 modules plant			
Cost item	**Scaling relation**	**Base scaling value**	**Escalation relation (NOAK)**	**Escalation relation (FOAK)**	**NOAK**	**FAOK**
Site labour cost	Indirect Site Labor Cost/Direct Site Labor Cost	36%			164.658.000,00 €	290.005.000,00 €
Site Material Cost	Indirect Site Material Cost/ Direct Site Material Cost	79%	40%	50%	68.909.000,00 €	101.365.000,00 €
Factory Equipment cost	Indirect Factory Cost/Direct Site Labor cost	132%	50%	67%	402.496.000,00 €	886.126.000,00 €
			Total indirect costs		**636.062.000,00 €**	**1.277.495.000,00 €**

6.3 Contingency, Owner's costs, and IDC

Contingencies

Following the guidelines reported in section 3.1.3, contingencies are estimated as 25% of the innovative items cost and 15% of standard and well-known systems costs. The riskier cost items considered are all the ones inside Acc. 21. The resulting contingency cost for NuScale's FOAK NPP amounts to 478.50 Mln €. By definition for the NOAK the contingency cost is estimated as 15% of all the cost voices. Therefore, the cost is estimated 308.34 Mln €.

Owner's costs

As previously mentioned, owner's costs are estimated as percentage of Overnight Capital Cost. A value of 15% is adopted for the NOAK, while 20 % for the FOAK NPP. The resulting NOAK and FOAK costs of NuScale's NPP amount respectively to 450 Mln € and 869.98 Mln €.

Interest during construction

Taking as reference the values reported in [17] (Table 49), IDC are extrapolated based on construction duration. For the FOAK a capital cost of 10% is assumed while for the NOAK the value lower to 7%. Table 69 summarised the assumptions and factors used to compute NuScale IDC:

Table 69 NuScale: IDC/OCC values

	NuScale 12 modules plant	
	NOAK	FAOK
Construction time [months]	48	60
Cost of capital	7%	10%
IDC/OCC	15.7%	25.5%
IDC	471.00 Mln €	1,109.23 Mln €

Finally in Table 70 is reported a summary of NuScale's NPP cost estimations (Contingencies are included in Acc. 2x Voices).

Table 70 NuScale Capital Cost

924 MWe	NuScale 12 modules plant			
	NOAK	Cost Items/OCC	FAOK	Cost Items/OCC
Acc. 21 - Structures and improvements	336.080.000,00 €	11%	466.217.000,00 €	11%
Acc. 22 - Reactor plant equipment	770.306.000,00 €	26%	1.117.698.000,00 €	26%
Acc. 23 - Turbine plant equipment	671.656.000,00 €	22%	719.958.000,00 €	17%
Acc. 24 - Electric plant equipment	274.398.000,00 €	9%	394.906.000,00 €	9%
Acc. 25 - Miscellaneous plant equipment	160.439.000,00 €	5%	222.543.000,00 €	5%
Acc. 26 - Main condenser heat rejection system	151.093.000,00 €	5%	151.093.000,00 €	3%
Total direct cost	**2.363.969.000,00 €**	**79%**	**3.072.413.000,00 €**	**71%**
Indirect - Site labour cost	164.658.000,00 €	5%	290.005.000,00 €	7%
Indirect Site Material Cost	68.909.000,00 €	2%	101.365.000,00 €	2%
Indirect - Factory Equipment cost	402.496.000,00 €	13%	886.126.000,00 €	20%
Total Indirect costs	**636.062.000,00 €**	**21%**	**1.277.495.000,00 €**	**29%**
Overnight Capital cost	**3.000.030.000,00 €**	**100%**	**4.349.907.000,00 €**	**100%**
Interest during construction	471.005.000,00 €		1.109.227.000,00 €	
Owner's costs	450.005.000,00 €		869.982.000,00 €	
Total capital cost	**3.921.039.000,00 €**		**6.329.115.000,00 €**	
€/kW	**4.250,00 €**		**6.850,00 €**	

7 Results

7.1 Results accuracy

The cost estimation model incorporates different methodologies used for different items. The type of model developed depends on the availability of information and the relevance of the cost items on the total direct cost. Thus, as mentioned in Chapter 3, the most important items are estimated by collecting primary information from the industry. On the other hand, less important costs are scaled from the 1,144 MWe PWR. Moreover, a third category is present, this refers to the relevant cost items on which it was not possible to collect information from producers. For those voices a model was built based on secondary sources of information gathered from the literature.

Given the nature of the information and the model adopted for estimation, it is possible to associate different ranges of uncertainty to different items. Following the guidelines in [42], the cost associated with different items can fall into different estimation classes. Given the high uncertainty related to the nuclear sector and the unavailability of design specifications, the widest range of values for each class is considered. In detail:

- Less relevant cost items under LL and LH are estimated by means of secondary source information without or with few cost adjustments. These are associated with the class 5 estimate and the expected accuracy range is -50% for the lower bound and +100% for the upper bound.
- The most relevant cost items below HL and HH that are estimated through models built on secondary information, are associated with the class 4 estimate and the expected accuracy range is -30% for the lower bound and +50% for the upper bound.
- The most relevant cost items below the HL and HH category, which are estimated through models built on primary information, are associated with estimation class 3 and the expected accuracy range is -20% for the lower bound and +30% for the upper bound.

In order to assess the overall model accuracy, the weighted average of the uncertainty boundaries associated to the accounts is performed. Therefore, an overall accuracy of -30% for the lower bound and +50% for the upper bound is associated to the model. Details about the class of each item are reported in Table 71:

Table 71 Cost items accuracy classes

EEDB Account No.	Account descriptions	Weight over direct cost (PWR12-BE)	Accuracy class	Lower value	Higher value
231	Turbine generator	14,81%	3	-20%	+30%
221	Reactor equipment	9,09%	3/4	-25%	+40%
212	Reactor containment building	7,17%	4	-30%	+50%
222	Main heat transfer transport system	7,04%	3	-20%	+30%
226	Other reactor plant equipment	5,17%	5	-50%	+100%
262	Mechanical equipment	4,94%	3	-20%	+30%
218	Other structures	4,83%	5	-50%	+100%
223	Safeguards system	4,35%	3	-20%	+30%
227	Reactor instrumentation and control	3,37%	3	-20%	+30%
233	Condensing systems	3,20%	3	-20%	+30%
252	Air water and steam service systems	3,18%	3	-20%	+30%
211	Yard work	2,76%	3	-20%	+30%
234	Feedwater heating system	2,61%	3	-20%	+30%
213	Turbine room and heater bay	2,56%	4	-30%	+50%
235	Other turbine plant equipment	2,47%	4	-30%	+50%
245	Electric structure and wiring	2,47%	3	-20%	+30%
224	Radwaste processing	2,32%	5	-50%	+100%
246	Power and control wiring	2,28%	5	-50%	+100%
242	Station service equipment	2,23%	5	-50%	+100%
215	Primary auxiliary building and tunnels	2,04%	4	-30%	+50%
216	Waste processing building	1,59%	4	-30%	+50%
225	Fuel handling and storage	1,34%	5	-50%	+100%
241	Switchgear	1,32%	5	-50%	+100%
217	Fuel storage building	1,09%	4	-30%	+50%
237	Turbine plant miscellaneous items	0,89%	5	-50%	+100%
228	Reactor plant miscellaneous items	0,82%	5	-50%	+100%
236	Instrumentation and control	0,76%	5	-50%	+100%
253	Communications equipment	0,71%	5	-50%	+100%
251	Transportation and lifting equipment	0,66%	5	-50%	+100%
261	Structures	0,48%	5	-50%	+100%
244	Protective equipment	0,47%	5	-50%	+100%
255	Wastewater treatment equipment	0,31%	5	-50%	+100%
254	Furnishings and fixture	0,30%	5	-50%	+100%
243	Switchboard	0,23%	5	-50%	+100%
214	Security building	0,15%	5	-50%	+100%

7.2 Results benchmark

In order to do some "benchmarking" of the costs estimated in this Thesis, the model outputs are evaluated comparing them with other models or public information related to nuclear cost estimating.

7.2.1 IRIS NPPs

IRIS NOAK (2x335 MWe) has been compared taking as reference an upper level cost structure related to the construction of 2 AP1000s (2x1078 MWe) [43]. In Table 72 are summarized the values:

Table 72 AP1000, PWR12-BE and IRIS NOAKs cost structures

	AP1000 (1078 MWe)	**PWR12-BE (1144MWe)**	**IRIS single conf. (2x335 MWe)**	**IRIS twin conf. (2x335 MWe)**
Civil/Structural/Architectural Subtotal	24%	22%	17%	16%
Mechanical Subtotal	65%	69%	69%	74%
Electrical Subtotal	11%	9%	13%	11%
Direct costs	**100%**	**100%**	**100%**	**100%**

Civil/Structural/Architectural item consist of Acc. 21, Mechanical cost is the sum of Acc. 22, 23, 25 and 26 while Electrical voice represents Acc. 24. The relative percentage values that were obtained in this cost structure are quite similar except for the Civil construction category that is higher for the AP1000 and PWR12-BE NPPs. This might be associated to a consistent reduction of reactor building size due to the adoption of an integral reactor in the IRIS design concept. As a consequence, this less incidence of Civil gives more emphasis to Mechanical systems. Regarding the relation among direct and indirect costs, for both configurations the model is in line with the values reported in [43], respectively representing the 80% and 20% of OCCs. Considering the FOAKs, the impact of indirect cost increase up to 30%, which is in line with the cost analysis performed in [14]. This reflects the optimization by applying the maturity of design, standardization, achieved licensing and regulatory approvals, and effective project management techniques.

[44] reports that for the AP1000's NOAK an Overnight Capital Cost equal to $ 2,900/KWe is predicted, excluding the Owner's costs. By scaling this value to power of 335 MWe with a factor equal to 0.6, an OCC of $ 4,600/KWe is obtained. Comparing

this value with the one reported in Table 73, it appears evident that the loss of economy of scale is partially compensated by IRIS design simplifications, modularization and other cost savings. The latter aspect is particularly relevant for the twin units' configuration.

Table 73 OCC NOAKs comparison [USD 2019, USD/EUR = 1.14]

	AP1000	PWR12-BE	IRIS single configuration	IRIS twin configuration
OCC/KWe	$ 2.900,00	$ 3.500,00	$ 3.800,00	$ 3.300,00

7.2.2 NuScale NPP

NuScale NOAK (12x77 MWe) is compared taking as reference the cost structure of 12 units SMR based NPP with a power of 50 MWe each [43]. Table 74 summarizes these values:

Table 74 General 12-Modules SMR and NuScale NOAKs cost structures

Costs include contingency	Small Modular Reactor (12x50MWe)	PWR12-BE (1144MWe)	NuScale (12x77 MWe)
Civil/Structural/Architectural Subtotal	25%	22%	14%
Mechanical Subtotal	63%	69%	74%
Electrical Subtotal	11%	9%	12%
Direct costs	**100%**	**100%**	**100%**

As for the IRIS case, the main difference among the reference consists in Civil and Mechanical equipment cost categories. This might depend on differences in the plant's configurations (e.g., the rector containment structure of NuScale is accounted under Acc. 221 instead of 212). However, since the same deviation appear in the two estimations, a revision of the Acc. 21 model is suggested. Regarding the relation among direct and indirect costs the model is in line with the values reported in [43], respectively representing the 80% and 20% of OCCs. Considering the FOAKs, the impact of indirect cost increases up to 30%. This reflects the optimization by applying the maturity of design, standardization, achieved licensing and regulatory approvals, and effective project management techniques.

[28] estimates a cost for a NOAK 12 units NPP of 57 MWe each equals to $ 3,856/KWe. The cost model estimates a value of $ 3,700/KWe, referring to a power of 77 MWe per reactor. On the other hand, NuScale has declared a target OCC equals to $ 3,600/KWe for a 12 units NPP of 60 MWe each. The result obtained seems to be in line with the strategy adopted from NuScale to reduce the electricity cost of its NPP. In fact, the

company over the years increased the power of its reactor to distribute the cost of the 12 units plant on more power.

7.3 Analysis

In this section an analysis of the main results obtained is provided.

As shown in Figures 48 and 49, the main component of the capital cost consists of direct costs. For NOAK IRIS configurations, the costs of labour, equipment and materials are valued at about 60% of the total. When considering FOAK, the weight of direct costs decreases to about 50%, in fact a higher impact of indirect costs and IDC is expected. This means that the longer duration of the construction as well as the increased labour hours do not only affect the direct cost but have a greater impact on these other items. In particular, direct costs increase by a factor of 1.2 while indirect costs by 1.9 and IDC by 2.3. The sum of IDC and indirect costs increases from 26% to 35% of the cost of capital. This result is in line with the analysis carried out in [14]. An Overall Capital Cost saving of about 35% is estimated by switching from FOAK to NOAK, this is valid for both configurations.

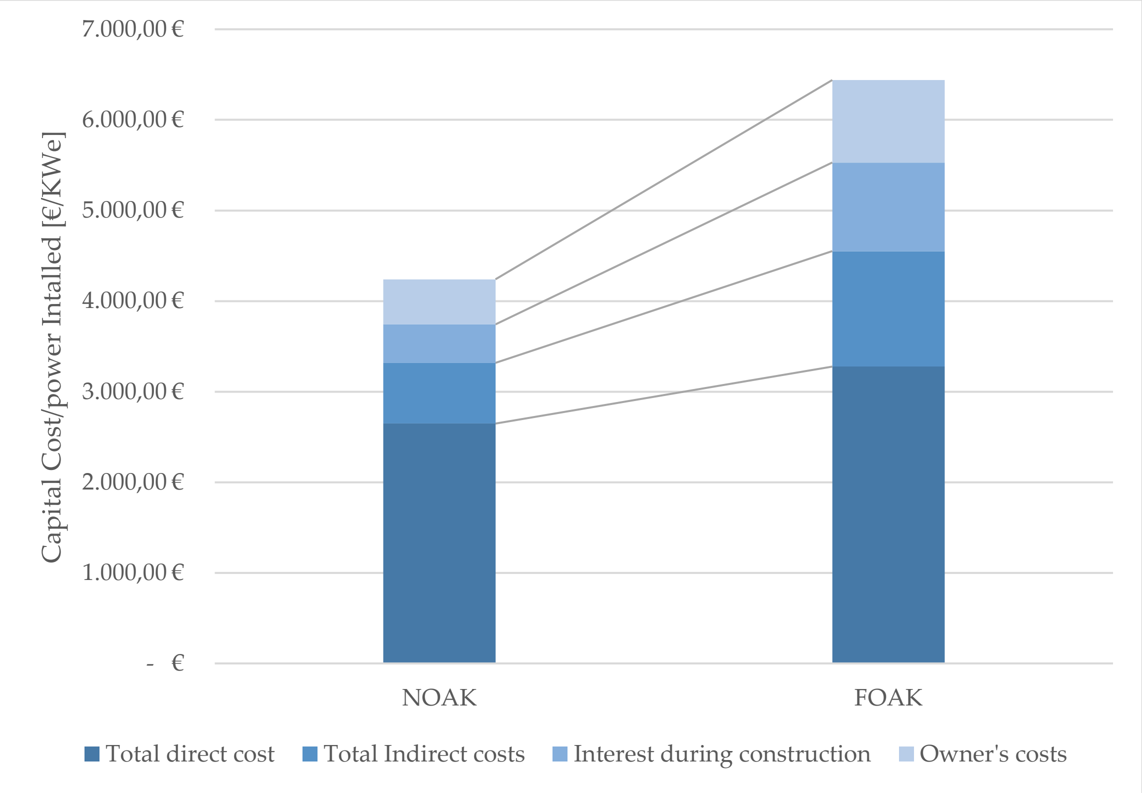

Figure 48 IRIS single units’ configuration Capital cost (670 MWe)

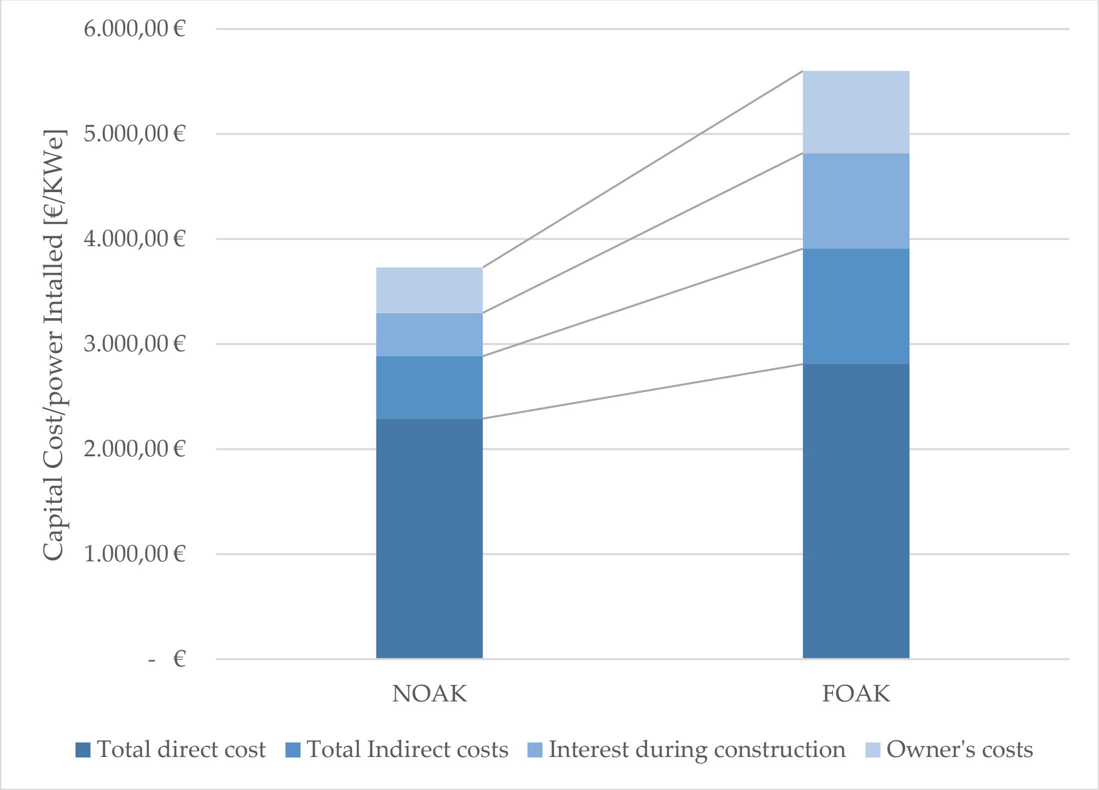

Figure 49 IRIS twin units' configuration Capital cost (670 MWe)

Although the increase of the items is not proportional, the direct cost, being the highest value, represents the main contributor to the increase, about 30% of the total variation. Therefore, analysing its composition (Figure 50) it is evident that the most sensitive item is the cost of site work. Of the 312 Mln € variation related to the single units' configuration, and 251 Mln € for the twin units' configuration, about 75% is due to the escalation of working hours. This result is consistent with the analysis made in Chapter 2. The second main contributor is the cost of equipment, around 15%, this reflects design optimisations and the impact of learning from equipment manufacturers. For the single units IRIS plant configuration, the distribution of direct costs for NOAK is: factory cost 63%, on-site labour cost 25% and on-site material cost 13%. The values for FOAK become respectively: 55%, 33% and 12%. For IRIS twin units' configuration, the distribution of NOAK direct costs consists of: factory cost 66%, on-site labour cost 22% and on-site material cost 12%. The value for FOAK changes respectively to 58%, 30% and 12%. As expected, in both cases, site labour cost has less impact in the twin units' configuration due to the sharing of working activities during construction.

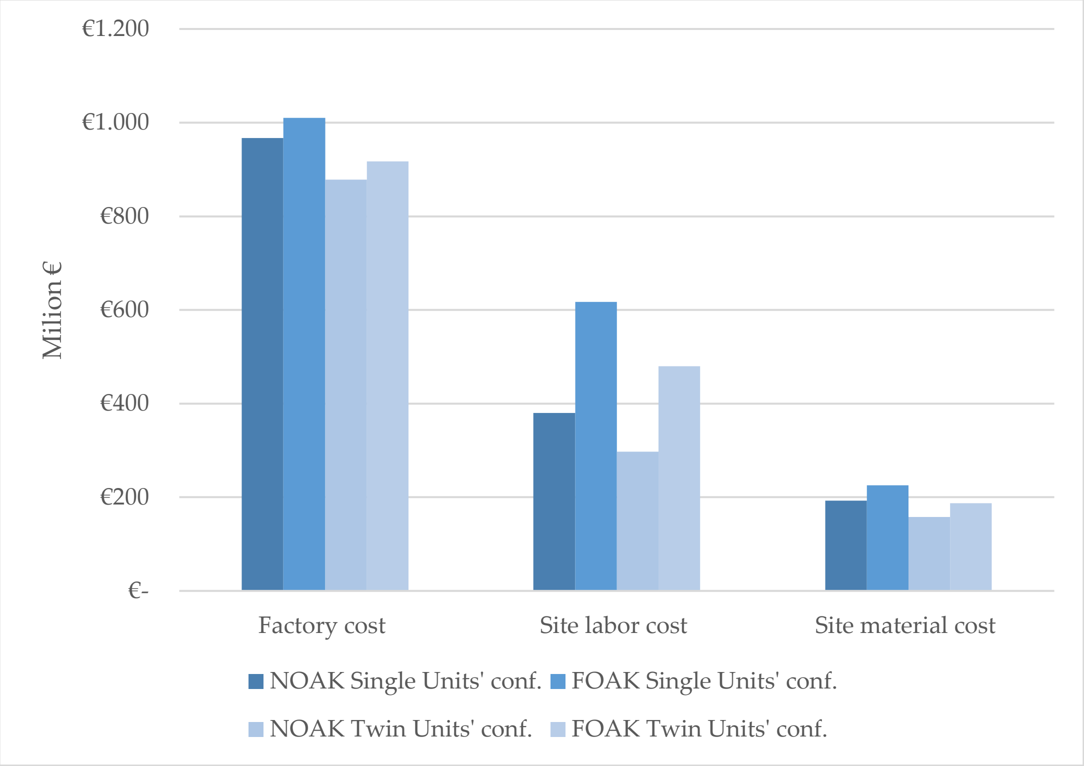

Figure 50 IRIS direct costs distribution

When analysing the impact of the different accounts on direct costs (Figure 51), Acc. 22 seems to be predominant (35% of the direct costs related to NOAK of the single units' configuration and 37% of those related to the twin-units configuration). As mentioned in the previous section, this is in line with the reference [43], although a greater impact of Acc. 21 is expected. Considering the two configurations and different construction experiences, Civil construction value varies from 16% to 18%. Being the heaviest component, the reactor plant equipment is also the main contributor of variation between FOAK and NOAK. Acc. 22 represents 41% of the single unit s' configuration cost variation and 44% for the other. The lower cost variation impact of Acc. 21 (around 21% for both configurations) is not in line with other estimates and the reference PWR12. This could be related to a lower estimated weight for structures and construction cost components. Particularly interesting is the Acc. 24 associated cost variation; although its weight varies from 11% to 15% (considering the two configurations and the different construction experience), the impact on the cost variation is respectively about 20% and 16% for single and twin unit configurations.

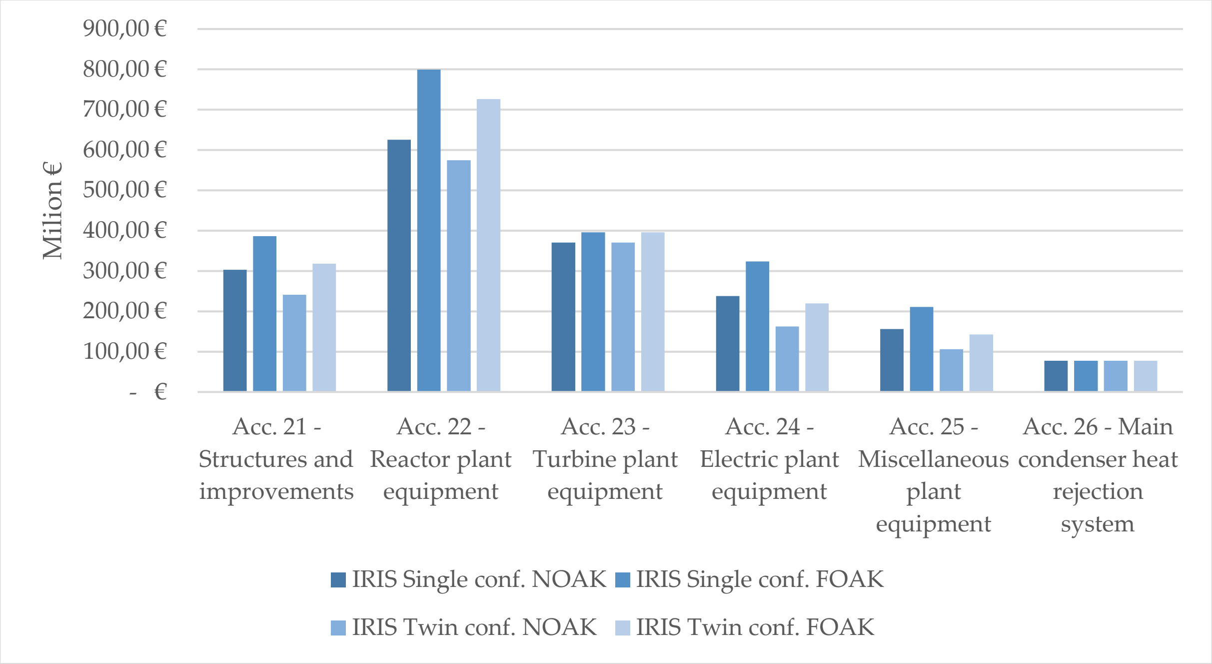

Figure 51 IRIS COAs direct cost distribution

The results of NuScale's cost estimation reflect those obtained for the IRIS NPPs. The direct cost represents for NOAK and FOAK respectively 60% and 49% of the total Capital Cost. The IDC and indirect cost increase from 28% for NOAK to about 38% for the construction of the first NPP. The direct cost is increased by a factor of 1.3, the indirect cost by 2 and the IDC by 2.3. The NOAK/FOAK ration is about 62%, similar to the result obtained for the IRIS NPP, Figure 52.

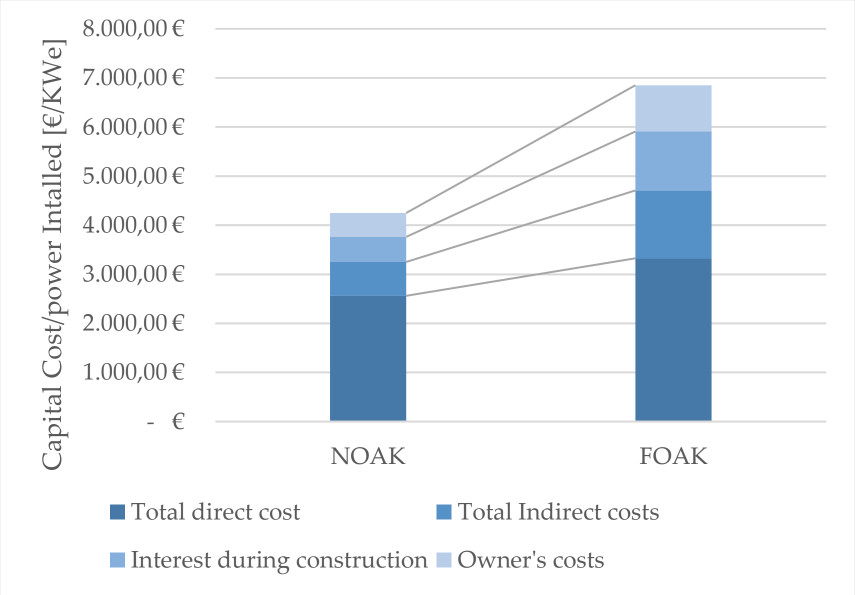

Figure 52 NuScale Capital Cost (924 MWe)

The main contribution to the cost variation is due to the site labour cost, which accounts for about 65% of the cost difference (Figure 53). The second main component is the factory cost, about 24%. This value is higher than for IRIS, which can be justified by an attractive use of learning economies from buying and installing the same equipment several times at the same site. As with the twin-unit configuration of IRIS, the distribution of direct costs, for NOAK, consists of: Factory cost 65%, on-site labour cost 22% and on-site material cost 13%. The value for FOAK becomes respectively: 57%, 31% and 12%.

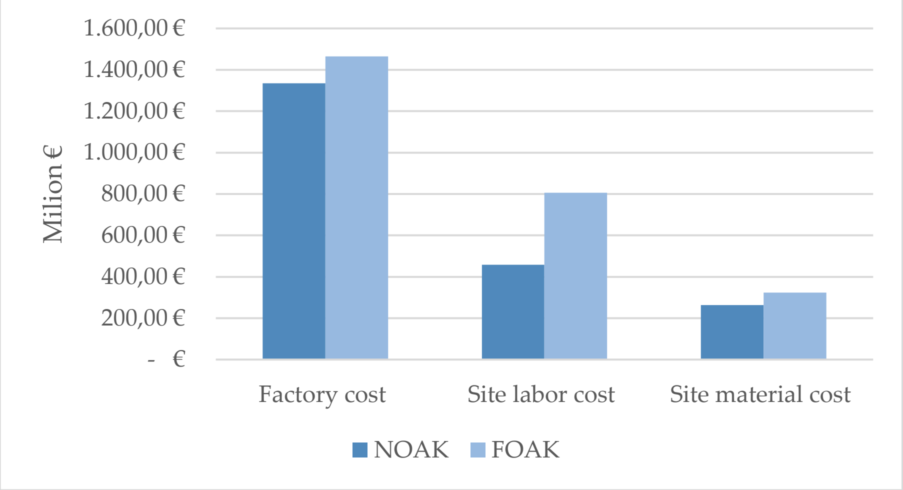

Figure 53 NuScale direct cost distribution

A similar cost structure to IRIS is obtained for NuScale NPP. Therefore, the same consideration can be extrapolated from Figure 54. Acc. 22 appears to be predominant over the other cost items (NOAK: 33%; FOAK: 36% of total direct costs) and it is the main contributor to cost variation, about 49%. Acc. 21 has a weight of 14% and 15% for NOAK and FOAK respectively and contributes 18% of the cost variation. In this case a lower weight of Acc. 21 components can be justified by the fact that the reactor containment structure, due to its characteristics, is included in the reactor equipment item. Another reason is that all the 12 NuScale's modules are installed within the same reactor building. But, as reported in the previous section, this only partially justifies the different cost impact. The other main cost contributor is Acc. 24 which, despite representing only 12% (NOAK) and 13% (FOAK) of direct costs, generates a 17% variation in direct costs between the first construction and the umpteenth construction.

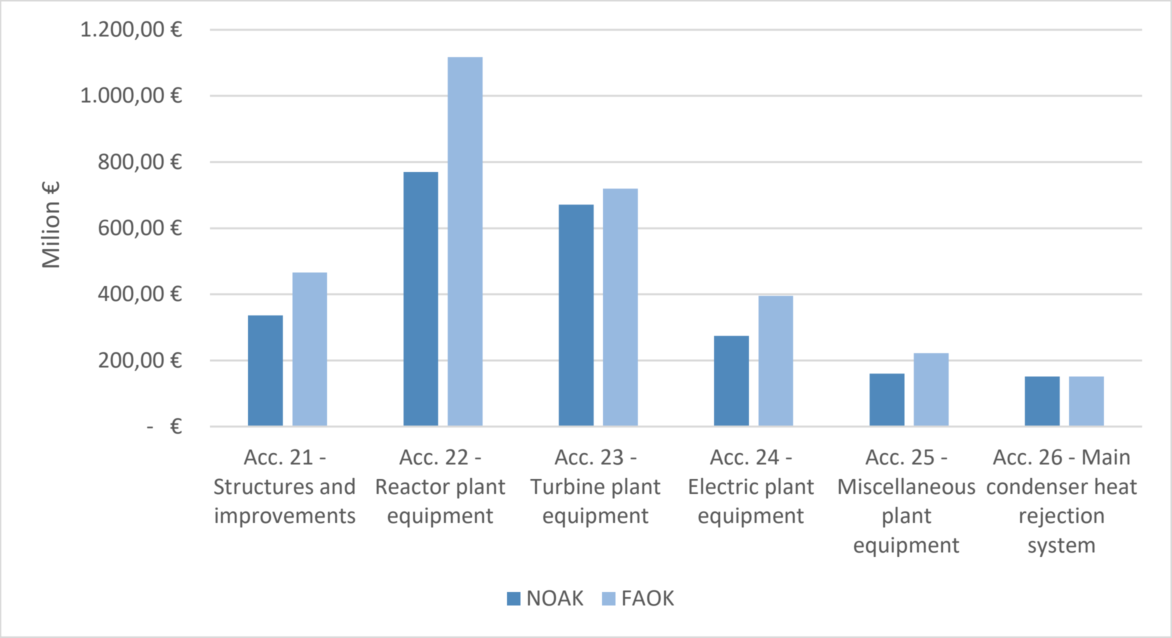

Figure 54 NuScale COAs direct cost distribution

Finally, a comparison is made between the results obtained for different SMR based NPPs. Table 75 shows the OCC normalised to reactor power and the estimated capital costs.

Table 75 OCC and Capital Cost SMRs and PWR12 [2019 EUR]

EUR/KWe	Overnight Capital Cost				Capital Cost		
	IRIS single conf.	IRIS twin conf.	NuScale	PWR12	IRIS single conf.	IRIS twin conf.	NuScale
FOAK	4.550 €	3.900 €	4.700 €	5.350 €	6.440 €	5.600 €	6.850 €
NOAK	3.310 €	2.880 €	3.250 €	3.080 €	4.240 €	3.730 €	4.250 €

Looking at the results in the long term, even though the SMRs characteristics have limited the impact of economies of scale this factor remains decisive. This is true except for the IRIS twin units' configuration, in fact the adoption of a larger SMR (335MWe), combined with plant design optimisation, simplification and modularization seems to fully compensate the loss of economies of scale. If attention shifts to the cost of FOAKs, a quite different situation can be observed. Indeed, the cost associated with PWR12 appears to be particularly high. Therefore, the reduced complexity of the SMRs based NPPs, reflected in a more streamlined project execution, seems to mitigate the onerous cost escalation related to LRs. Comparing the results between the SMRs, the loss of economy of scale between NuScale and IRIS seems to be compensated by a high degree of sharing between facilities and equipment. In support of this hypothesis, when comparing the cost of NuScale and the twin units' configuration of IRIS, the latter is cheaper as it uses the same savings factor, which is not true for the single configuration. Another advantage of NuScale is its design features, e.g., the size of the reactor containment is drastically reduced, and since the primary coolant circulation is based on the natural principle, there are no RCPs.

As a conclusion, it must be stressed that the law of "bigger is better" is still valid for SMRs. The right trade-off between reactor size and simplification of plant construction must be found in order to achieve a competitive electricity cost. In addition, as the cost estimate shows, special attention must be paid to finding additional sources of savings when designing smaller reactors. This last aspect emphasises the necessity of estimating costs since the reactor development stage.

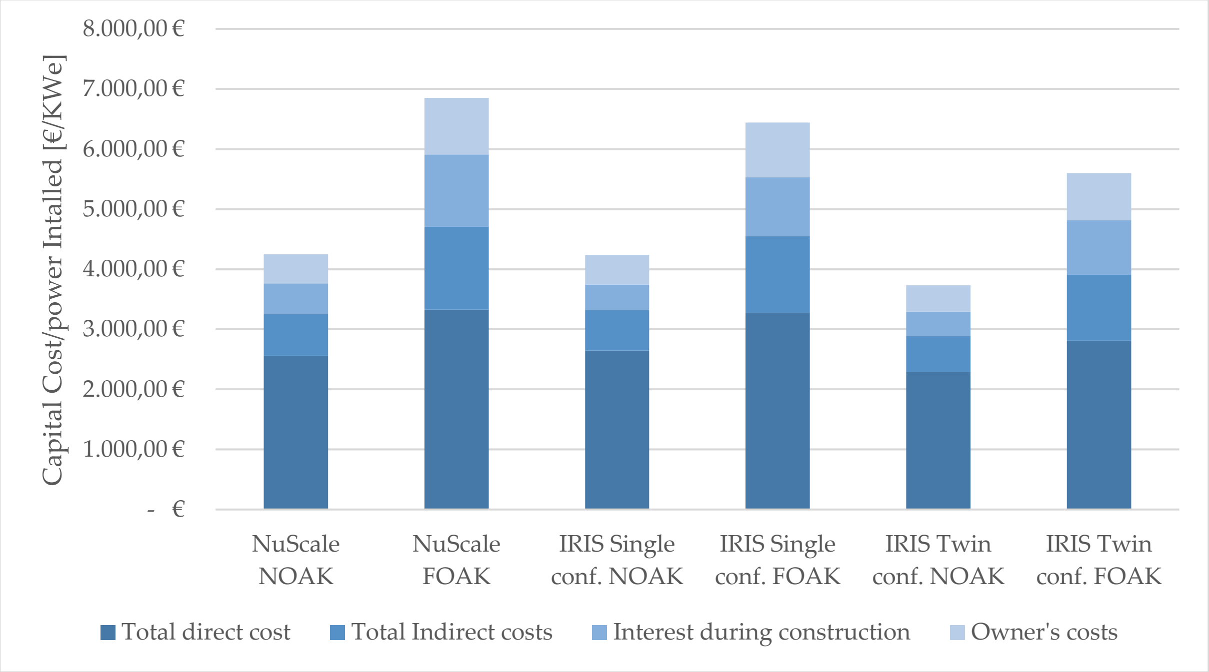

Figure 55 SMRs Capital cost

8 Conclusion

The bottom-up cost estimation model proposed in this Thesis aims to provide a tool for estimating the costs of SMR-based nuclear power plants by taking into account all the advantages of building a smaller, simplified reactor. After discriminating the most relevant cost items, a specific model was developed for each COA cost item. Thanks to this approach, it was possible to identify the impact of several factors that could compensate for the loss of economies of scale. Those identified are:

- Modularization
- Use of passive safety systems
- Reduced size
- Sharing economies
- Learning
- Construction project simplification

Considering the case of the IRIS twin units' NPP, where all these aspects are present, the impact of savings factors can be identified. Therefore, taking the cost of PWR12-BE as a reference, the OCC of the IRIS plant is calculated by scaling the value with a factor of 0.6. The result obtained is about 5034 €/MWe, which can be interpreted as the cost of the IRIS plant without the application of any savings lever. Therefore, through the relationship between OCCs of the single units' configuration of IRIS and the twin units' configuration, it was possible to isolate the impact of sharing economies estimated as 9% of scaled OCC of IRIS (5034 €/MWe). A modularization saving of 5% was estimated from the model. By comparing the cost of PWR12-BE with that of AP1000 (NOAK) and excluding the impact of modularization, the impact of using passive safety systems could be estimated as 6% of the OCC. Moving on, project simplification savings were obtained assuming a project duration and average number of workers equal to that of PWR12-BE. This leverage allows for a 7% reduction in IRIS' OCC. Finally, other cost savings related to smaller equipment sizes and site learning are estimated to be around 16% of the scaled IRIS OCC. Figure 56 graphically shows the results obtained.

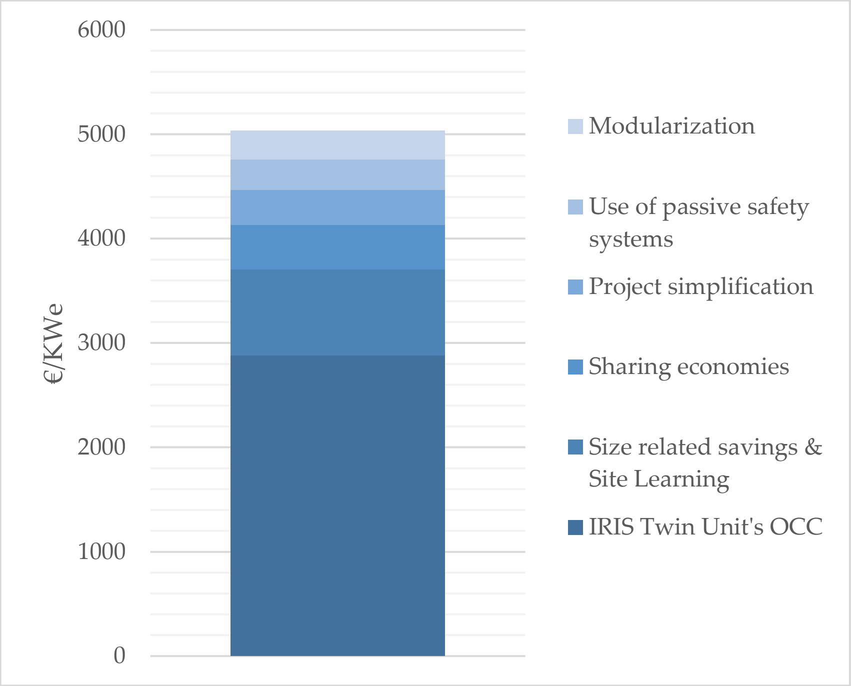

Figure 56 IRIS twin units' configuration Savings factors impact

As a conclusion, the model results showed that SMRs seem to be able to overcome the loss of economies of scale by leveraging different savings factors. However, the smaller the reactor size, the higher the savings that must be achieved to compensate for the loss. In this light, NuScale's reactor compared to IRIS's has several design simplifications (e.g., reactor containment, RCPs) that make their 12-module plant competitive with other SMRs and LRs, Figure 57.

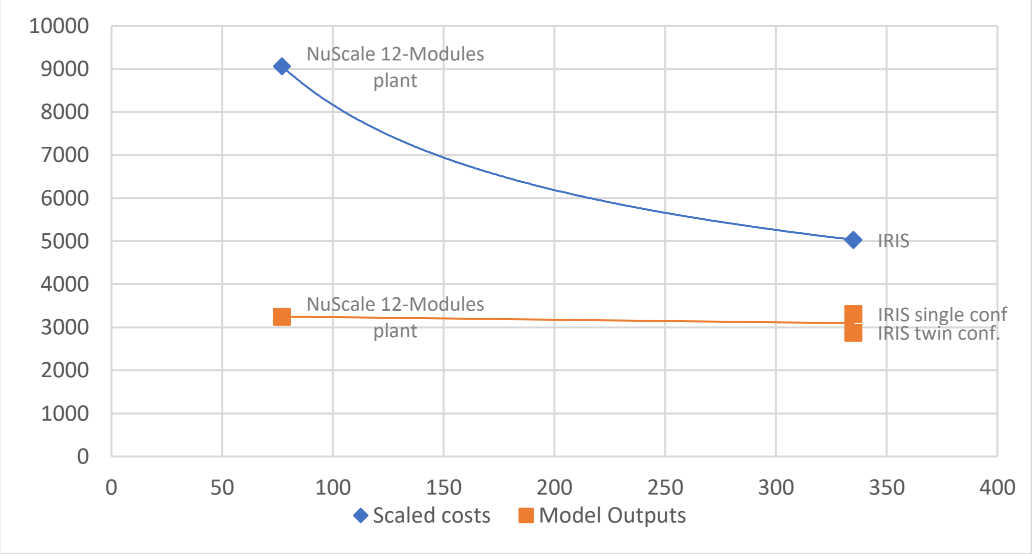

Figure 57 Comparison between scaling relation costs and model output

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A. Appendix A

PWR12-BE costs value and composition, expressed in 2011 USD and 2019 EUR.

EEDB Account No.	Account descriptions	PWR12-BE (2011 $)	PWR12-BE (2019 €)	Factory cost %	Site labor cost %	Site material cost %
211	Yard work	$ 59.982.046,00	59.668.003,87 €	1%	58%	41%
212	Reactor containment building	$ 155.606.498,00	154.791.804,29 €	22%	55%	23%
213	Turbine room and heater bay	$ 55.565.592,00	55.274.672,67 €	3%	48%	49%
214	Security building	$ 3.268.692,00	3.251.578,43 €	4%	69%	27%
215	Primary auxiliary building and tunnels	$ 44.333.148,00	44.101.037,28 €	17%	57%	26%
216	Waste processing building	$ 34.481.563,00	34.301.031,26 €	5%	63%	33%
217	Fuel storage building	$ 23.709.847,00	23.585.711,68 €	10%	46%	44%
218	Other structures	$ 104.838.449,00	104.289.556,60 €	6%	62%	32%
21	**Structures and improvements subtotal**	**$ 481.785.835,00**	**479.263.396,07 €**	**11%**	**57%**	**32%**
221	Reactor equipment	$ 197.406.910,00	196.373.365,97 €	88%	5%	7%
222	Main heat transfer transport system	$ 152.881.006,00	152.080.581,88 €	89%	10%	1%
223	Safety systems	$ 94.361.424,00	93.867.385,13 €	84%	14%	2%
224	Radwaste processing	$ 50.261.788,00	49.998.637,28 €	77%	19%	4%
225	Fuel handling and storage	$ 29.121.985,00	28.969.513,87 €	92%	7%	1%
226	Other reactor plant equipment	$ 112.143.626,00	111.556.486,60 €	59%	35%	5%
227	Reactor instrumentation and control	$ 73.253.448,00	72.869.922,09 €	73%	25%	2%
228	Reactor plant miscellaneous items	$ 17.885.460,00	17.791.818,85 €	0%	57%	43%
22	**Reactor plant equipment**	**$ 727.315.634,00**	**723.507.698,74 €**	**79%**	**16%**	**5%**
231	Turbine generator	$ 321.562.255,00	319.878.682,98 €	93%	6%	1%
233	Condensing systems	$ 69.556.766,00	69.192.594,45 €	68%	28%	4%
234	Feedwater heating system	$ 56.613.122,00	56.316.718,22 €	67%	30%	3%
235	Other turbine plant equipment	$ 53.575.666,00	53.295.165,13 €	50%	45%	5%
236	Instrumentation and control *	$ 14.805.098,10	14.727.584,50 €	27%	67%	6%
237	Turbine plant miscellaneous items	$ 19.310.160,00	19.209.059,69 €	0%	57%	43%
23	**Turbine plant equipment**	**$ 535.423.067,10**	**532.619.804,97 €**	**78%**	**19%**	**4%**
241	Switchgear	$ 28.671.078,00	28.520.967,64 €	94%	5%	1%
242	Station service equipment *	$ 38.392.132,00	38.191.126,07 €	88%	10%	2%
243	Switchboard	$ 4.917.355,00	4.891.609,69 €	77%	17%	6%
244	Protective equipment	$ 10.227.327,00	10.173.780,79 €	0%	58%	42%
245	Electric structure and wiring	$ 53.524.039,00	53.243.808,43 €	0%	81%	19%
246	Power and control wiring *	$ 33.442.606,00	33.267.513,82 €	11%	56%	33%
24	**Electric plant equipment**	**$ 169.174.537,00**	**168.288.806,44 €**	**40%**	**44%**	**16%**
251	Transportation and lifting equipment	$ 14.385.191,00	14.309.875,86 €	84%	14%	1%
252	Air water and steam service systems	$ 68.941.570,00	68.580.619,37 €	30%	54%	15%
253	Communications equipment	$ 15.396.111,00	15.315.503,09 €	30%	60%	9%
254	Furnishings and fixture	$ 6.566.362,00	6.531.983,14 €	79%	18%	2%
255	Wastewater treatment equipment	$ 6.800.000,00	6.764.397,91 €	26%	66%	7%
25	**Miscellaneous plant equipment subtotal**	**$ 112.089.234,00**	**111.502.379,37 €**	**40%**	**49%**	**12%**
261	Structures	$ 10.398.528,00	10.344.085,45 €	4%	62%	34%
262	Mechanical equipment	$ 107.155.788,00	106.594.762,93 €	68%	28%	4%
26	**Main condenser heat rejection system**	**$ 117.554.316,00**	**116.938.848,38 €**	**63%**	**31%**	**6%**
	Total	**$2.143.342.623,10**	**2.132.120.933,97 €**			

* Cost adjusted following the assumption made in report [24]

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