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Potential of Small Modular Fast Reactors

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Author(s)	Sara Boarin (CIRTEN), Marco Ricotti (CIRTEN), Camille Auriault (LGI consulting), Pierre Joly (LGI consulting), Eva Boo (LGI consulting), Ferry Roelofs (NRG)
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Summary

A general overview of the past and the potential future of the SMR technologies is provided. The potential applications for the SMR technologies are explored, together with the study of the potential threats and opportunities of the European market. A top-down cost estimate of a NOAK lead-cooled SMFR is proposed, making use of the G4ECONS tool, as well as a comparative evaluation of economic scenarios in comparison with large reactors, is performed using the INCAS.

Approval

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List of Acronyms

Term	Definition
ADNA	Accelerator Driven Neutron Applications
AECL	Atomic energy of Canada Ltd
AHWR	Advanced Heavy Water Reactor
ALFRED	Advanced Lead Fast Reactor European Demonstrator
ANPP	Army Nuclear Power Program
B&W	Babcock & Wilcox
BNFL	British Nuclear Fuels Limited
BWR	Boiling Water Reactor
CEA	Commissariat à l'Energie Atomique et aux Energies Alternatives
CfD	Contract for Difference
CNNC	China National Nuclear Corporation
D	Debt capital amount
D&D	Decommissioning and Decontamination
DCF	Discounted Cash Flow
DHR	Decay Heat Removal
DOE	Department Of Energy
E	Equity capital amount
EBIT	Earnings Before Interest and Taxes
EDF	Electricité de France
ELFR	European Lead-cooled Fast Reactor
ENEA	Italian National agency for new technologies, Energy
ENHS	Encapsulated Nuclear Heat Source
ENSA	Equipos Nucleares, SA
EoS	Economy of Scale
EPC	Engineering, Procurement and Construction
EPR	European Pressurized Reactor or Evolutionary Power Reactor
ESNII	European Sustainable Nuclear Industrial Initiative
ETDR	European Technology Demonstrator Reactor
EU	European Union
FBNR	Fix Bed Nuclear Reactor
FBR	Fast Breeder Reactor
FCF	Free Cash Flows
FHR	Fluoride Salt Cooled High Temperature
FNR	Fast Neutron Reactor
FOAK	First Of A Kind
FR	Fast Reactor
GCFR	Gas Cooled Fast Reactor
GEN II	Generation two
GEN III+	Generation III, advanced
GEN IV	Generation IV
GIF	Generation IV International Forum

Term	Definition
HPC	Hinkley Point C nuclear power station
HTR	High-Temperature Reactor
IAEA	International Atomic Energy Agency
INCAS	INtegrated model for the Competitiveness Analysis of Small-medium sized reactors
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
iPWR	Integrated Pressurized Water Reactor
IRIS	International Reactor Innovative and Secure
IRR	Internal Rate of Return
IThEMS	International Thorium Energy & Molten Salt Technology Inc. Company
JAEA	Japan Atomic Energy Agency
KAERI	Korea Atomic Energy Research Institute
LCOE	Levelized Cost Of Electricity
LEI	Lithuanian Energy Institute
LFR	Lead Cooled Fast Reactor
LGR	Light Water Cooled, graphite moderated Reactor
LMR	Liquid Metal Cooled Reactor
LWR	Light Water Reactor
MH-1A	Mobile High Power Nuclear Power Plant
MHI	Mitsubishi Heavy Industries
MSR	Molten Salt Reactor
NNL	National Nuclear Laboratory
NOAK	N-th Of A Kind
NPCIL	Nuclear Power Corporation of India
NPP	Nuclear Power Plant
NPV	Net Present Value
NRC	Nuclear Regulatory Commission
O&M	Operation and Maintenance
ORNL	Oak Ridge National Laboratory
PBMR	Pebble Bed Modular Reactor
PESTEL	Political, Economic, Social, Technological, Environmental, and Legal
PFBR	Prototype Fast Breeder Reactor
PHWR	Pressurized Heavy Water Reactor
PWR	Pressurized Water Reactor
PWR-SMR	Small Modular Reactor with Pressurized Water technology
RES	Renewable Energy Sources
SCC	Siberia Chemical Combine
SFR	Sodium Cooled Fast Reactor
SM-1	Stationary Medium Power Prototype Number 1
SMART	System Integrated Modular Advanced Reactor
SMFR	Small Modular Fast Reactor
SMR	Small Modular Reactor
SNERDI	Shanghai Nuclear Engineering Research and Design
TPS	Triga Power System
TRLS	Technology Readiness Levels

Term	Definition
USS	United State Ship
VNIPIET	Eastern-European chief research and project institute of energy technologies
WACC	Weighted Average Cost of Capital

Executive Summary

The development of small nuclear reactors is dated back in the 1950s and was mainly driven by military purposes (naval propulsion). As soon as nuclear was considered for civil applications, the size of nuclear power plants increased thanks to the benefits deriving from the increased economic competitiveness ("economy of scale"). Exceptions are represented by installations in remote regions (e.g., more than 20 units deployed in Russia between 1950s and 1980s) or by specific technologies fitting in the power range nowadays considered as small to medium reactors (e.g., 16 PHWRs having an average power of 220 MWe operating in India, starting with Rajasthan 1 in 1970s).

Recently, SMRs are attracting increasing interest worldwide thanks to their potential advantages, when compared to large NPPs, in terms of a significantly decreased investment risk achieved on the one hand by lower initial capital investment per unit and on the other hand by generation of revenues of initial units while constructing follow-up units, shorter construction schedule, higher design simplifications and potential to use passive systems, increased resilience against external hazards and terroristic acts, potential to reduce emergency preparedness zones. Many different countries (Russia, USA, China, France, India,…) have governmental strategies supporting the development of small modular reactors (mainly integral PWRs, but also HTRs, LFRs, GFRs, MSRs) with projects lead by both research centers and industries.

Typical power applications for SMRs (supply for isolated/remote grids, cogeneration, stabilization of intermittent sources, access to nuclear power for non-nuclear countries, generation-demand matching, replacement of fossil fuelled plants, military applications) are analyzed in the European context. One main potential application is represented by installations of SMRs having power in the order of 100 MWe for the compensation of renewables, due to the policies supporting the increase of share and priority of dispatch of this intermittent energy source. However, the consequent reduced capacity factor would have a detrimental impact on the return of investment making SMRs even less attractive, unless the loss in competitiveness is compensated by national policies. On the other hand, multi-units sites with a total power in the range 350-700 MWe will represent an option for the replacement of fossil fuel power plants and the supply of process heat to industrial clusters. In this case, SMRs should be demonstrated to match the temperature needs of the industrial application and be safely co-sited close to the end-user.

Main opportunities in Europe would be represented by ageing of current nuclear fleet (average age of NPPs in Europe is approximately 30 years), continuous increase of oil price rise, population increase and introduction of carbon footprint taxes at national level. In general, threats are expected to have a bigger impact on the SMRs deployment; main ones are the lack of SMR consensus, the decrease of gas prices, the "nuclear fear" and lack of "nuclear vocation", the dense European electric grid and the lack of a licensing framework specifically applicable to advanced SMR technologies. Improved safety, sustainability, proliferation resistance and economics of Gen-IV FRs are considered key factors to mitigate the identified societal, economic and environmental threats.

Among the ESNII concepts, the LFR was considered for both a top-down cost assessment and an economic and financial simulation of a deployment scenario.

The cost estimate for a 600 MWe ELFR performed in FP7 project LEADER is taken as a basis for the current assessment for an nth-of-a-kind ALFRED-like SMFR, using the G4Econs tool developed by GIF EMWG and applying typical scaling and modularity factors. The nominal costs, including

contingencies, sum up to about 750 M€2014 (assuming no account for R&D costs and interest during construction, and excluding approximately 30% uncertainty). When compared to the ELFR cost estimate, the nominal energy generation costs are found comparable. Slightly larger construction and O&M costs are compensated by decreased fuel cycle costs. The sensitivity studies show a large dependency of the result on uncertainties related to operation and maintenance costs and expected operational life. Moreover, modularity and scaling factors have a larger impact than uncertainties on reactor and turbine equipment costs.

The economic viability of SMFR is assessed through the financial analysis of a deployment scenario, considering a fleet of 3 GWe made of 24 SMFRs (125 MWe each), built on 4 nuclear sites over a 20-years time-period through a staggered schedule, allowing to distribute the capital investment effort. A Discounted Cash Flow (DCF) analysis provides a synthetic view of the economic performance of the SMFR fleet through a set of economic indicators. The scenario simulation is run by means of the INCAS Matlab program, developed by Polimi to catch “the economy of small” and “the economy of multiples” in the NPP investment projects. The SMFR deployment case is compared with two scenarios with the same total power installed based on 5 ELFR (600 MWe each) on 2 sites, 3 GEN III+ AP1000-like LWRs (1000 MWe each) on 2 sites and 24 PWR-SMRs having similar power output as the SMFR.

Construction cost of SMFR is a key assumption that influences the whole analysis; for this reason it has been evaluated by means of a top-down estimate with appropriate scaling factors. “Economy of multiples” and “Economy of small” intervene to reduce the average overnight cost of an SMFR plant in a fleet of 24. Government support to the nuclear project (e.g. by means of public guarantees on the bank loans, export credit, etc.) is essential to reduce the investment risk. Any form of public support that might have an impact on the capital structure and on the cost of capital, would have a social benefit, limiting the LCOE. Liberalized capital and electricity market conditions are an emerging concern for nuclear investments. A favourable capital structure (i.e. 60% debt stake and 40% equity) and cost of debt (i.e. 4%), as well as an electricity cost fixed at the same value negotiated at the HPC in UK (equivalent to 110 €/MWh), are key factors to lead to a profitable investment in all scenarios.

Based on a sensitivity analysis, the technical areas of improvement to build a viable economic case are: the reduction of construction costs (by design simplifications and plant modularization), the increase of the availability factor and the construction time. Design and modularization factors around 0.8x and 0.85x, respectively (i.e. 20% and 15% saving factors compared to reference ELFR cost), are necessary for the SMFR to achieve a profitability in line with PWR technology. Profitability is sustained by the shorter deployment time of each SMFR compared to ELFR, anticipating the revenue stream and the pay-back time compared to a large plant scenario.

Some not-easily-measurable advantages of the smaller NPP could give the SMFR a competitive advantage that is not included in the performed quantitative analyses. Complexity linked to the large size might be a reason behind recent failures to deliver large-NPPs on-schedule and on-budget. SMRs are expected to be easier to manage from the EPC point of view, thus improving the “actual” performance of smaller units, as far as a size reduction might increase the number of equipment suppliers, as far as modularization should enable the parallelization of fabrication and installation activities, as far as higher factory fabrication options might reduce the chance of non-compliance with the quality standards, etc. Moreover, the enhanced sustainability in terms of natural resources and the minimization of spent nuclear fuel brought by LFRs, are not factorized in the present analysis, but could determine potential savings at system level and higher public acceptance, when a broader view is considered.

New standards need to be developed and integrated in the existing licensing and certification regimes, with more chances for knowledge sharing and implementation of lessons learned. Although initiatives are ongoing worldwide, licensing regimes in place for the last few decades represent a barrier to meet the ideal goal of internationally harmonized standards. The EU has the opportunity to develop a legal framework for SMRs, compatible with standardized designs and international certification. The long term advantage will be the possibility to deploy an internationally certified module in any country adhering to the certification program. EU's commercial prospects in deploying a certified technology will improve the competitiveness of the local nuclear supply chain. Modular construction of factory built Systems Structures and Components (SSCs) for a standardized SMR/SMFR design will centralize the return of experience, with a progressive improvement in quality. Moreover, the associated costs and time schedules will be constantly optimized, for an on-budget and faster delivery.

1 General overview on worldwide SMR market

When referring to nuclear reactors, the International Atomic Energy Agency (IAEA) defines small those reactors with a capacity under 300 MWe and medium those between 300 and 700 MWe. In this study, the acronym SMRs is used to designate Small Modular Reactors. This clarification is made as the same acronym is used by the IAEA to refer small and medium sized reactors. Small modular reactors (SMRs) specifically refer to small reactors that are designed for serial construction, maximising manufactures on plants.

The scope of this study is limited to small modular reactors, considering small, reactors with an electrical capacity under 300 MWe.

First interests in SMRs were expressed at the end of the 1950s. However, during the following decades, the size of reactors units grew from 60 MWe to more than 1600 MWe. Nowadays, there is a revival interest in SMRs, which is driven by the desire to reduce the impact of capital costs (due to economies of scale provided by the numbers produced) and to provide power away from large grid systems.

The forecast scenarios estimate a worldwide SMR capacity between 4.6 GWe and 18.2 GWe (base and conservative scenarios respectively) in 2030 (Navigant Research, 2013). In 2009, in the frame of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), an assessment conducted by the IAEA revealed that there could be 96 small modular reactors in operation around the world by 2030 in the optimistic scenario and 43 units in the pessimistic one (Navigant Research, 2013). A recent study carried out in UK (NNL, 2014) has estimated a plausible market of 65-85 GW for SMRs in the 2035 timeframe, for a cost-competitive technology in comparison to large nuclear plants. Since large potential markets are identified in the USA, China and Russia, competition and partnering strategies will likely reduce the size of the accessible market to 30-35 GW. On the other hand, in case SMRs are not cost-competitive with large NNPs, then the total global market potential is significantly reduced to a niche market of approximately 5 GW in the 2035 timeframe.

Another more recent OECD/NEA study on the economics and market of SMRs (OECD/NEA, 2016) showed that the share of SMRs in nuclear new build could depend on the proportion of Renewable Energy Sources (RES) in different countries; 15% for countries with low RES, and 20% for countries with high RES. This study indicated the SMR contribution in 2035 could be 9% of nuclear new build as a 'high scenario' equivalent to 21 GWe or 3% of overall installed capacity. The study also showed that depending on the power rating of the SMRs, if between 100 (200 MWe) and 400 (50 MWe) SMRs were built and there were a limited number of models, then this would probably be enough for viability of the supply chain.

1.1 History of SMR

The development of small nuclear reactors was initiated in the 1950s for naval propulsion purposes. The first nuclear-powered submarine, the USS Nautilus, was launched in 1955. Based on estimations from Lloyd's Register, around 700 nuclear reactors would have been taken to the water to power submarines, aircraft carriers and ice-breakers since then, with around 200 currently at sea (Ingenia, 2012).

In 1957, the US Army Nuclear Power Program (ANPP) started the development of a small, pressurised water reactor (PWR) called the Stationary Medium Power Prototype Number 1 (SM-1). The SM-1 was a stationary reactor, operated for 16 years and which provided training for the ANPP operators. Building on SM-1, the Army Program developed a PWR that could be moved in remote areas, called the Mobile High Power Nuclear Power Plant (MH-1A). MH-1A was built and operated on a converted ship where the engine room was removed to make the ship into a barge. This converted ship provided power to the Panama Canal Zone from 1968 to 1976. The major drawback of this installation was its high cost. Indeed, due to the small number of units that were produced, the reactor's fuel and components were very expensive. The operation and maintenance costs were also very high due to the mandatory presence of skilled personnel every time in remote areas. Due to these too expensive costs, the Army decided to stop the program. However, the MH-1A showed that small reactors could be sited, constructed or assembled in remote areas and safely operated by properly trained persons (US Department of Energy, Office of Nuclear Energy, Science and Technology, 2001).

In the meantime, from the 1950s to the 1980s, USSR developed about 20 autonomous small power reactors (i.e. not requiring continual fuel delivery) in remote areas.

India has a strong history with modular reactors as well. There are today 16 Pressurised Heavy Water Reactor (PHWR) on line, each with an average capacity of 800MWth, 220MWe. The first one, Rajasthan 1, was built in 1972 as a collaborative venture between Atomic energy of Canada Ltd (AECL) and the Nuclear Power Corporation of India (NPCIL). Over time, several evolutions have been developed on the following modular reactors to add a double containment, a suppression pool, and a calandria filled with heavy water (US Department of Energy, Office of Nuclear Energy, Science and Technology, 2001).

The UK had a major programme of reactor developments (thermal & fast reactors) from the 1950s to the early 1980s followed by successful reactor operations. A total of 28 gas-cooled, graphite moderated 'Magnox' reactors were constructed, mostly in the UK; these had electrical output in the range 50-500 MWe per unit, with up to 4 units constructed on a single site (World Nuclear, 2016). These were followed by the second generation Advanced Gas Reactors (AGRs). Many of the prototype reactors were at SMR scale, including the Steam Generating Heavy Water Reactor (SGHWR) – 100 MWe) at Winfrith and the Dounreay Fast Reactor (DFR – 14 MWe) and Prototype Fast Reactor (PFR – 300 MWe).

1.2 Government strategies

The progress of the different SMR projects and research programmes varies all over the world. In this section, the different government strategies have been mapped to analyse the current status of SMR projects internationally. The countries with most advanced programmes are Russia, China and the USA.

1.2.1 Russia

Russia has a strong history with SMRs. Today the country is developing a new range of innovative SMR designs. In 2012, Russia announced the construction of an experimental lead-cooled nuclear reactor at the Siberia Chemical Combine (SCC). This BREST 300 unit to be demonstrated is a 300 MWe reactor that would be built at the site with the manufacturing facility for the dense nitride uranium-plutonium fuel. This project was estimated at $805 million for the 300 MWe reactor with additional $54 million for the fuel plant. The design is expected to be completed in 2014 for a construction between 2016 and 2020. In January 2017, Rosatom announced that it is deferring the planned Brest-OD-300 lead-cooled fast reactor (NEI, 2017). Even if it is a small reactor, the objective of the BREST-300 unit is not the development of SMRs but to become the first step to commercialise widely Lead-cooled Fast Reactors (LFRs). The BREST-300 could be a forerunner to a 1200 MWe version (Nuclear Energy Insider [1], 2013).

Besides, Russia is showing high interest in the development of SMRs for barges or vessels. Currently, a 35 MWe barge-mounted PWR, the KLT-40S, is under construction. Based on a modified naval propulsion reactor design, this one could be used for applications ranging from powering coastal towns to desalinating water (Nuclear Energy Insider [2], 2013).

1.2.2 USA

The US government is heavily promoting the use of SMRs. This interest was publicly declared by US Energy Authorities (e.g. speech addressed by Steve Chu in 2012, former US Secretary of Energy (US Energy Government, 2012)):

"The Obama Administration continues to believe that low-carbon nuclear energy has an important role to play in America's energy future. Restarting the nation's nuclear industry and advancing small modular reactor technologies will help create new jobs and export opportunities for American workers and businesses, and ensure we continue to take an all-of-the-above approach to American energy production."

In January 2012, the Department of Energy (DOE) called for applications from industry to support the development of one or two US light-water reactor design. The budget allocated for this project came to $452 million over 5 years. Westinghouse, Babcock & Wilcox (B&W), Holtec and Nuscale Power all applied with units ranging from 225 down to 45 MWe. In November 2012, the DOE decided to support the B&W 180MWe mPower design to be developed with Bechtel and TVA (Tennessee Valley Authority, 2010), (Kimmel, 2012).

In December 2013, the DOE announced that its final funding award aiming at supporting a small nuclear reactor programme would be allocated to NuScale Power of Portland. Based on a 50-50 cost-share basis, the DOE decided to endorse the design development and the Nuclear Regulatory Commission (NRC) certification and licensing of the 45 MWe NuScale Power small reactor design (Barker, 2013). As a consequence, in February 2014, Westinghouse decided to back off research and development of their Small Modular Reactor design (scaled down version of their AP1000 reactor, designed to produce 225 MWe) there were not enough customers for the firm to return its investment in the development project (Litvak, 2014). However, in June 2014, Babcock & Wilcox's (B&W) Generation mPower division which was developing its 180-MW mPower SMR, has cut 200 from its workforce, slashed spending from $60 to $80 million per year to less than $15 million, restructured its management, and trying to sell up to 70 percent of the business (Dotson, 2014).

1.2.3 China

China is involved in the development of SMRs mainly in the domain of High-Temperature Reactors (HTRs). Indeed, China started the construction of HTR with HTR-10, a 10 MWt high-temperature gas-cooled experimental reactor in 2000, reaching reactor full power in 2003. Following the construction of HTR-10, China launched the construction of a larger version called HTR-PM in 2012. The HTR-PM installation is composed of two twin reactors, each of 250 MWt driving a single 200 MWe steam turbine. Each reactor has a single 566°C steam generator. The helium outlet temperature is 750°C (IAEA [1], 2011).

The plant is being built by a joint venture led by China Huaneng Group (the country's largest generator, but which has no nuclear capacity), China Nuclear Engineering & Construction Group, CNEC Corp, and Tsinghua University's Institute of Nuclear and New Energy Technology (Tsinghua University, 2010).

Concurrently to HTRs, China has operated the 298 MWe Qinshan Unit 1 since 1994. It is a pressurised water reactor owned by the Qinshan Nuclear Power Co.

1.2.4 Pakistan

Based on the IAEA database (IAEA, Power Rector Information System, 2014), as of September 2013, Pakistan has 750 MWe of capacity in its small nuclear power programme. The Chashma 1 power plant in Punjab province uses a 325 MWe two-loop pressurised water reactor supplied by China-based CNNC, called CHASNUPP-1. The plant started operation in 2000. CHASNUPP-2, a 300 MWe net reactor, began commercial operation in 2011. Two other PWR SMR are planned, CHASNUPP-3 and CHASNUPP-4 and their connexion to the grid is foreseen in September 2016 and July 2017, respectively.

In addition, the PHWR KANUPP, 90 MWe has been operated since 1971.

1.2.5 India

India operates SMRs for more than 40 years, using PHWR reactors. Indeed, the plants KAIGA, KAKRAPAR, MADRAS and RAJASHTAN are each composed of several PHWR units (whom capacity is between 187 and 205 MWe). The plant TARAPUR also includes two BWR SMRs (150 MWe) and two PHWR units (490 MWe).

The current development in India related to SMRs concerns the Advanced Heavy Water Reactor (AHWR) AHWR300-LEU, which is on final detailed design stage and prepared for construction (Subki, Hadid - IAEA [1], 2013).

1.2.6 France

In France, the development of SMR is mainly driven by the Flexblue concept developed by DCNS, a French naval defence company specialised in shipbuilding. Flexblue is an SMR subsea reactor of 50 to 250 MWe. The power plant will comprise a nuclear reactor, a steam turbine-alternator set and associated electrical equipment. Electricity will be carried using submarines cables from the Flexblue plant to the coast. Each hull and power plant would be transportable using a purpose-built vessel (plant housed in a cylindrical hull measuring around 100 metres in length by 12 to 15 metres in diameter for a total mass of around 12,000 tonnes) (DCNS, 2013).

1.2.7 UK

The UK Government has signalled its intent to support a mission to invest in developing SMR technology in the UK (NIRAB, 2017). There is an intention to put in place a programme of development for SMRs that would eventually lead to building an innovative SMR design in the UK. There are a number of SMR designs that are at differing levels of Technology Readiness Level (TRL) and under consideration for the UK. These will need to be prioritised as will R&D for potential deployment in the UK.

In the Spending Review and Autumn Statement 2015, the UK Government announced that £250M would be allocated to fund a new nuclear R&D programme to be delivered over the period 2016-2021. This programme is a first step in the investment to deliver the UK's long term energy strategy requirements out to 2050. The R&D programme includes:

- an R&D programme including development of nuclear expertise in innovative nuclear technologies, and
- a competition to identify the best value Small Modular Reactor (SMR) design for the UK.

A large number of SMR technologies are under consideration including Light Water Reactors (LWRs) of the present Gen III and III+ generations, also high temperature gas reactors (HTRs) and fast reactors (FRs), including the Gen IV fast spectrum systems. In addition to small and medium sized reactors the UK also maintains an interest in very-small or micro modular reactors (MMRs) or nuclear batteries.

1.2.8 Other countries

Other countries are also involved in the development of SMRs:

- In Argentina, ATUCHA-1 is a 335 MWe PHWR operational since 1974. Moreover, the construction of the SMR PWR CAREM-25 (25 MWe) started in 2014 (IAEA, Power Reactor Information System, 2014).
- In Japan, Toshiba develops the 4S design, a 10 MWe liquid metal cooled fast reactor. Licensing activities for the 4S design initiated with the U.S.NRC in 2007; now, Toshiba is conducting the detailed design and safety analysis for design approval (IAEA [3], 2013).
- In South-Korea, the Korea Atomic Energy Institute developed the 100 MWe System Integrated Modular Advanced Reactor (SMART). The reactor is an integrated Pressurised Water Reactor (iPWR). In 2012, the Korean Nuclear Safety and Security Commission approved the standard design of SMART, becoming the first iPWR receiving certification (Subki, Hadid - IAEA [2], 2013).
- In Italy, Politecnico di Milano and universities in Croatia & Japan are continuing the development of IRIS design - previously lead by the Westinghouse Consortium. IRIS is a 335MWe PWR (Subki, Hadid - IAEA [1], 2013).
- Various Pebble Bed Modular Reactor (PBMR) concepts have been under development in South-Africa since 1996. PBMR is a High Temperature Gas Cooled Rector with an electrical capacity of 165MWe (IAEA [2], 2011).

The different SMR installations and research programmes are represented on the Figure 1.1.

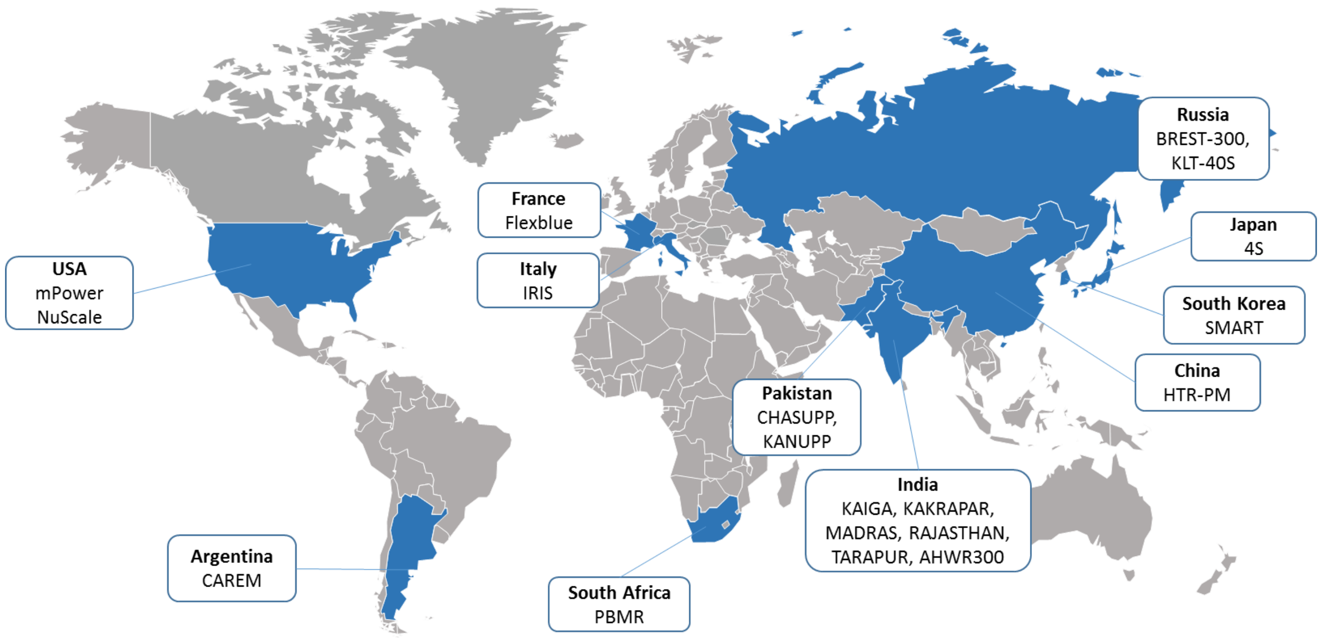

Figure 1.1: Worldwide representation of SMR initiatives, (LGI 2014)

1.3 A comparison with regular reactors

This section outlines the differences between (SMRs) and regular reactors (gen II or III type), in terms of power, construction, security, innovation, proliferation risks, waste reduction and economy.

1.3.1 In terms of power

SMRs are nuclear reactor whose electric power output doesn't exceed 300 MWe (IAEA [1], 2013), which is far less than regular reactors' power (minimum of 900 MWe for French nuclear GEN II reactors or 1600 for French GEN III reactors). Consequently, SMRs are not suitable for supplying places with high electricity needs. However, it is possible, as with any other regular nuclear reactor, to couple several SMR in order to match with the local needs. Thus, SMRs appear to be more flexible than classical high power reactors.

1.3.2 In terms of construction

Classical nuclear reactors are built on site, the SMR can be manufactured off site and brought to the site fully assembled. Some advantages derive from this fact:

The needs of on-site construction highly decrease. For example, in case SMR with encapsulated core are considered, the nuclear core is built on an assembly line, allowing economy of serial production, while increasing containment efficiency, and nuclear material security (Rosner & Goldberg, 2011).

1.3.3 In terms of security

Concerning security issues, SMRs are sometimes designed to be placed underground with their spent-fuel storage pools (Moniz, 2011). Thus, in case of terrorist attack, they would be more resistant than classical power plants. The SMR design allows that, in case of accident, the reactor to be cooled more easily, in some cases by natural mechanisms. Reducing the risk of escalade of chain reaction and core overheat and melt. (Vyjic, et al., 2012)

1.3.4 In terms of innovation

Further some SMRs are designed for the use of new fuel ideas, it allows a higher burn-up rate and longer lifecycles than classical nuclear reactors. The longer refuelling intervals have for immediate consequences, the decreasing of proliferation-risk and the decrease of the chances of escaping containment for radiation.

1.3.5 In terms of proliferation risk

Concerning the proliferation risk, which is mentioned in the latest paragraph, some of the SMRs share with other advanced technologies under development the following advantages:

- A very low-enriched uranium fuel (less than 20% ^{235}U),
- After being irradiated, the fission products mixed with the fissile materials are highly radioactive and then require special handling to be removed, preventing it from being stolen.

1.3.6 In terms of sustainability

Some SMRs are designed to use new fuel ideas, allowing higher burn-up rate, which increases the use of natural resources when compared to a classical reactors with lower burn-up rates. Moreover, some SMRs are also breeder reactors, which can convert ^{238}U into usable fuels.

1.3.7 In terms of economy

According to several SMR developers, because of the design of this kind of reactors, fewer staff members are required to run it (for the same installed capacity) mostly because of the passive safety systems. In addition, with the economies performed in the building of the plant, it is a real advantage for the SMRs on classical reactors, which need huge investments. All of these comparisons between SMRs and classical reactors are sum up in the chart below:

	SMR	**Classical Reactors**
Power	< 300 MWe	> 900 MWe
Flexibility	Yes	No
Construction	Serialization	Plant by plant
Proliferation Risk	lower	
Amount of waste	Function of the technology	Function of the technology
Possibility of alternative	Yes	Yes

fuel cycle		
Possibility of economy of scale	Yes	No
Operational staff member needed at same installed capacity	Fewer	Big

Table 1: Comparison between SMRs and Classical reactors (LGI, 2014)

1.3.8 In terms of licensing

Current licensing processes have evolved over many years, consistent with existing and established nuclear practices covering: design development, on-site construction, engagement with the plant designer, and the plant operator. The licensing for SMR will need to be revised to accommodate new practices including: factory manufacture and plant construction, multi-unit operations, novel operating monitoring and maintenance approaches etc. These issues are under current consideration by the World Nuclear Association-Cordel Group and a special task group committed to SMR licensing and economics has been convened.

1.4 Main stakeholders

The main stakeholders in the SMR market have been identified in this analysis by type of actor and by the technology of the reactor. There are four main kinds of actors involved in the SMR market:

1. Research centres, developing the technology in a theoretical level.
2. Manufacturers, using technologies developed by research centres or by themselves to create new products.
3. Power suppliers, the entities providing energy and using the technologies developed by research centres.
4. Consulting firms, providing design for new facilities.

As research centres, manufacturers and power suppliers are the most relevant actors in the market, they have been the core of the research analysis which is presented in this section.

1.4.1 Research centres

Research centres are the first step to any high technology development. In the nuclear field and in the SMRs technology development, they are highly involved. They are presented by type of reactor technology.

1.4.1.1 Pressurised Water Reactor (PWR)

In Russia, the Kurchatov Institute has developed and exploited a demonstrator of ELENA SMR (Andrew CMU, 2013) (0.1 MWe) for over 15 years, but today there is no politic will to pursue a commercialisation project. OKB Gidopress also developed a concept of SMR, the VVER-300 (Mokhov & Trunov, 2009), (300 MWe), in 2006 they were still designing it, but there isn't any update about it since. However, the main Russian actor in PWR technology is NIKIET, which has developed three kinds of SMR concepts. The first one was the UNITHERM (Andrew CMU, 2013)

(2.5 MWe), whose design was achieved in 2007 (IAEA, 2007), but remaining at that stage of development. The second one was the RUTA-70 (Andrew CMU, 2013) with the goal of heating districts. The design was fully achieved, but because of lack of funding there haven't been further developments. The last one was the NIKA 70 (Andrew CMU, 2013) (15 MWe), which has been supplanted by more advanced designs, like VBER or KLT-40S.

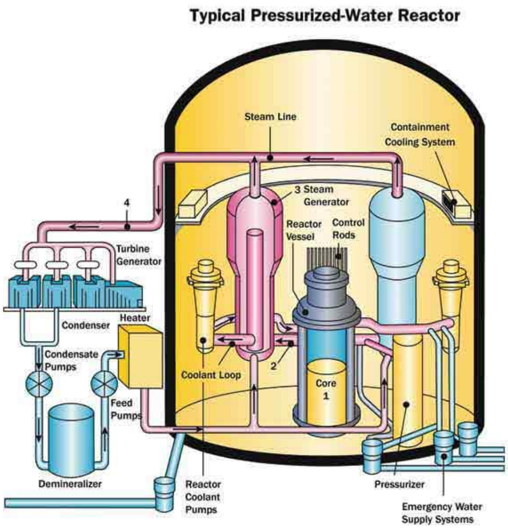

Figure 1.2: PWR design (NRC, 2014)[1]

In 2006 INVAP (Argentina) planned to build a prototype of the CAREM, SMR (World Nuclear Association, 2014). Its construction has started in February 2014 (Steiner-Dicks, 2014) and a second bigger version is planned for 2021 (200 MWe).

The Japanese JAEA and MHI designed the MRX (JAEA, 1995) (30 MWe), for both marine propulsion and small needs of energy. The Tsinghua University INET (Beijing, China) has also worked on their own design, the NHR-200 (JIA & ZHANG, 2008) (65 MWe). After they finished the design in 2000, they haven't made any further progress since. The Korean KAERI developed the SMART SMR (Park, 2011) (100 MWe), a licensed SMR that will be constructed in 2017 (World Nuclear Association, 2014).

In the USA, the Oregon State University has funded the NuScale Power Inc. company, which developed the Nuscale SMR (Nuscale Power, 2014) (45 MWe). The certification of this designed is expected for 2016 (United State Nuclear Regulatory Commission, 2014). Several American research centres and companies (Berkeley, ORNL, Georgia Tech, and Westinghouse) were involved in a large worldwide consortium which aimed to construct the IRIS SMR (335 MWe). But the project has been shelved because of the elevated output power to match the needs of potential consumers.

Several European research centres and companies have joint their forces in the IRIS consortium (LEI, ENEA, Polimi, University of Zagreb, University of Pisa, Polytechnic University of Turin, University of Rome, BNFL, Ansaldo, and ENSA). Despite, that project have been shelved some actors like Polimi, are still working on some research aspects of itlftr. In France a consortium of four actors (DCNS, CEA, AREVA, and EDF) has been working on an SMR design, the Flexblue (50-

[1] NRC website [Online] Available: http://www.nrc.gov/

250 MWe). Several sites have been evaluated for the construction of the first Flexblue, which will probably leave shipyard in 2017 (DCNS, 2013).

1.4.1.2 The Boiling Water Reactor (BWR)

Russia is the only country that has been working on this kind of SMR technology. Two research centres were involved in the development of two different reactor designs: OKB Gidropress that was working on the VKT-12 SMR (Andrew CMU, 2013) (12 MWe) and NIKIET, working on the VK-300 (Andrew CMU, 2013) (150-250 MWe). Nevertheless, since 2010 the Russian nuclear energy policy is focus on PWR technologies, so the two designs were shelved.

1.4.1.3 Heavy Water Reactor (PHWR)

Researchers from Babha Atomic Research Center (India) have developed their own kind of nuclear reactor. Since 1981 they have deployed sixteen PHWR (Bajaj, 2006) (202 MWe), a kind of reactor that is well known in the sector. Moreover they are currently working on the next step, the AHWR (BHABHA, 2014) (284 MWe). India has planned to take advantage of its huge thorium reserves by using it as a fuel for this kind of reactor. The building of the first unit is foreseen between 2014 and 2017 (Ghunawat, 2014).

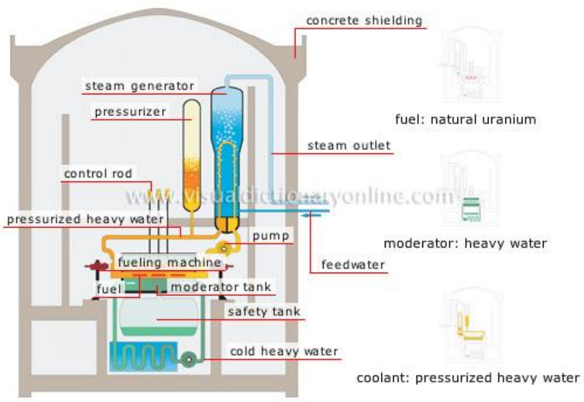

Figure 1.3: PHWR design (Bhabha, 2014)

1.4.1.4 Liquid Metal Cooled Reactor (LMR)

Russia is the world leader on this technology. This type of reactor has been used in Russian submarines for decades. The main stakeholder working on this area is OKB Gidropress, which has designed) the ANGSTREM (OKB Gidropress, 2013) (6 MWe) SMR in 2013. This concept is fully ready to be industrialised. They also worked with the Institute of Physic and Power Engineering, JSC Irkutskernego, the Russian industrial VNIPIET (Eastern-European chief research and project institute of energy technologies) and the electricity supplier Atomenergoproekt to design the SVBR-100 (101.5 MWe) SMR (AKME, 2014). The Kurchatov Institut is another Russian stakeholder, which has designed a SMR prototype, called MARS (Andrew CMU, 2013) (6 MWe), but without the allocation of new investment, a soon deployment cannot be expected. Another Russian actor is N.A. Dollezhal Research and Development Institute of Power Engineering (NIKIET), which worked on the BREST-OD-300 (300 MWe), whose design have been approved by Russian government and is currently under development (Rosatom, 2014).

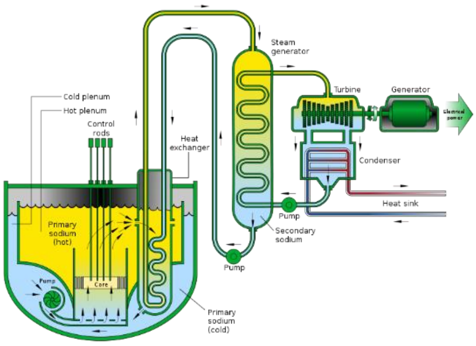

Figure 1.4: LMR design

USA also worked on this technology: the University of Berkeley has designed a concept of SMR called ENHS (Pescovitz, 2002) (50 MWe), whose first deployment will take place after 2025. Virginia Tech and Accelerator Driven Neutron Application (ADNA) have designed the GEMSTAR (ADNA Corporation, 2010) SMR (220 MWe), and they are currently looking for private investors to develop a demonstrator. The Argonne National Laboratory, has designed the STAR (10-100/178 MWe). They will build a demonstrator in 2015 (Lawrence Livermore National Laboratory , 2006).

In Asia, the Tokyo Institute of Technology (Japan) has designed the LSPR (53 MWe) in 2001, but there is no near term deployment project (Minour Takahashi, 2012). The CRIEPI developed their own kind of SMR, the RAPID (Kambe, 2014), (1 MWe), but in 2005 the conceptual development wasn't ended and there were no plans for near term deployment. But they also worked with the industrial Toshiba on the 4S SMR (10 MWe) (IAEA, 2012).The concept is fully achieved, but the licensing process is scheduled beyond 2020. The Korean research institute NUTRECK is currently developing a concept of SMR, the PEACER (NUTRECK, 2013), (300/550 MWe).

The English National Nuclear Laboratory (NNL) has been working in cooperation with General Electric Hitachi, on the S-PRISM (General Electric Hitachi, 2014), (311 MWe). In 2011 they planned to build one unit in UK.

1.4.1.5 Gas Cooled Fast Reactor (GCFR)

The European project ALLEGRO (Richard Stainsby & Horváth, 2011) is meant to design a Gen IV reactor demonstrator in the SMR category (75 MWth). The project is led by the V4G4 European consortium (MTA EK Hungary, VUJE Slovakia, UJV Czech Republic and NCBJ Poland), with CEA as associated member. The European Commission is currently supporting the development of this reactor.

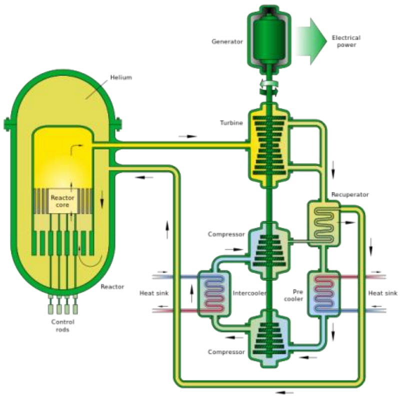

Figure 1.5: GCFR design (ALLEGRO, 2011)

1.4.1.6 Very High Temperature Reactor (HTR)

The Russian NIKIET have designed a concept of SMR air-cooled, le MTSPNR (Andrew CMU, 2013) (2 MWe). In 2009 they were looking for partner to build a demonstrator. In China, Tsinghua University INET, China Huaneng Group, China Nuclear Engineering & Construction Group, Shangai Electric Co. and Harbin Power Equipement Co. are collaborating in building a demonstrator of HTR-PM (Sun, 2013) (200 MWe) since 2012. The Japanese JAEA had been developing a concept of HTR, the GTHTR (Kazuhiko, et al., 2001) (275 MWe), but since the Fukushima disaster, the reactor's future is uncertain.

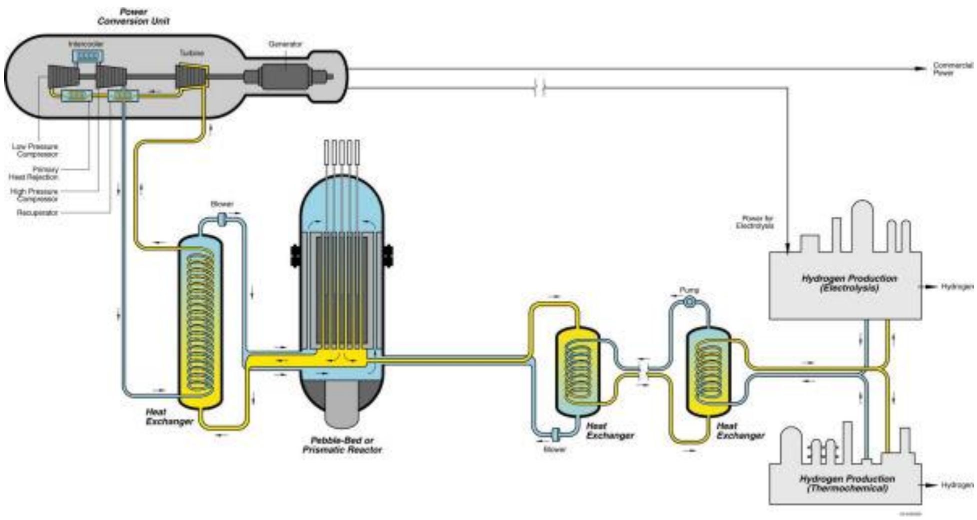

Figure 1.6: HTR (INL, 2014)[2]

1.4.1.7 Fluoride Salt Cooled High Temperature (FHR)

When researchers from the Oak Ridge National Laboratory (USA) were studying fluoride salt cooled reactor, they designed the SmAHTR (Barton, 2011) (Greene, 2013), conceived to produce both electricity and heat. Despite this, in 2012, the concept wasn't optimised and there were no imminent plans for deployment.

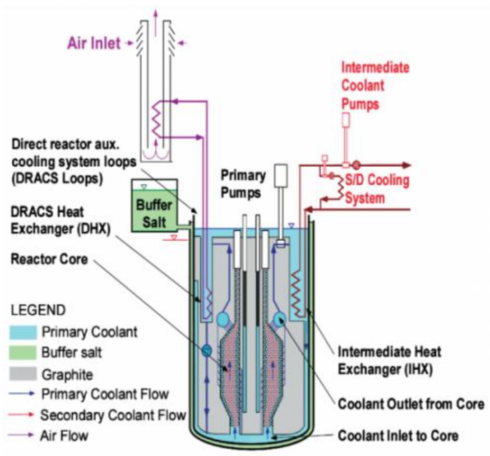

Figure 1.7: FHR design (MIT, 2011)

1.4.1.8 Fix Bed Nuclear Reactor (FBNR)

The Federal University of Rio Grande do Sul in Brazil has designed a unique kind of SMR, the Fixed Bed Nuclear Reactor (70 MWe) (Farhang Sefidvash, s.d.), which is a variation of pressurised water reactors (PWR). However the last available information about this design, dates 2011 and it refers to the conceptual design. No project of demonstrator has been identified.

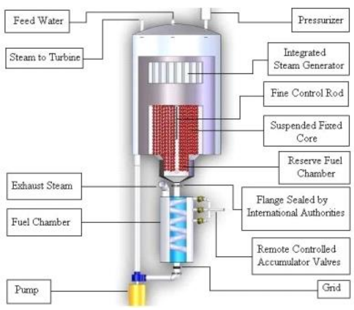

Figure 1.8: Fix Bed Nuclear Reactor design (Sefidvash, 2011)

[2] INL website: https://inlportal.inl.gov/

1.4.2 Industrials (Manufacturers & Power suppliers)

Industrials have been classified in two kinds: manufacturers and power suppliers. They have been identified and classified by type of reactor technology:

1.4.2.1 Pressurised Water Reactor (PWR)

One of the main actors currently developing a new concept of SMR in Russia is OKBM Afrikantov (OKBM Afrikantov, 2014). In 2000, the company began to work on floating nuclear power plants. The results of this work are the KLT-40S (Andrew CMU, 2013) (35 MWe) and the ABV SMR (Andrew CMU, 2013) (3-10 MWe). For the first one, the first deployment will take place in 2016, and for the second one, none is actually planned. The strategic choices of OKBM Afrikantov have also for consequences the development of the RITM-200 (Andrew CMU, 2013) (55 MWe) for artic applications and the development of the VBER-300 (Andrew CMU, 2013) (295 MWe), which is currently under licensing stage and will be soon deployed in Kazakhstan, but it also have for consequences the shelving of SAKHA-92 design (1 MWe) (Andrew CMU, 2013).

In China, two main actors are developing SMR concepts: China National Nuclear Corporation (CNNC) and Shanghai Nuclear Engineering Research and Design Institute (SNERDI). The first one developed the ACP100 design, which will be deployed this year (2014) (21cbh, 2014).

Apart from the previously introduced Nuscale and IRIS, in the USA there are other important stakeholders. One of the smallest SMRs developed by industrial companies in USA is the TPS (16.4 MWe). The Triga Power System (TPS) has been designed by General Atomics in the mid-1980s (Ux Consulting Company, 2014). Subsequently, they decided to focus their efforts on their gas-cooled SMR. The Radix Power and Energy Corporation also are developing what we can call a Mini Modular Reactor, The RADIX (Powell & Farrell, 2010) (10 MWe), which is designed to target the market of off-grid application like the islands, contrary to the classic SMR, which are targeting on-grid applications (Wesoff, 2012). In 2009, B&W Company and Bechtel Powel Corporation announced a new design of SMR, the mPOWER (Generation mPower, 2014) (180 MWe), but because of lack of investment, the project is today slowing down (Nuclear Engineering International, 2014). The company Holtec has also developed a concept of SMR, the SMR-160 (160 MWe) and they plan to have their first unit operating in 2018, but today they are still waiting for construction permit and preliminary safety analysis (World Nuclear News [4], 2013). Finally, the company Westinghouse is also developing a SMR, called Westinghouse SMR (225 MWe), but it seems that they're backing off due to lack of customers (Litvak, 2014)

In France, there is the Flexblue concept, presented in the previous section, but AREVA also worked on another concept of SMR, the NP-300 (100-300 MWe). In 2005, they were waiting for certification by nuclear regulatory authorities. But since, no further development has been identified.

1.4.2.2 Light Water Cooled, graphite moderated Reactor (LGR)

In Russia, four units of EGP-6 (11 MWe) have been built and operated since 1974 by Teploelectroproeckt, it's a kind of SMR really adapted to extreme cold conditions (Andrew CMU, 2013).

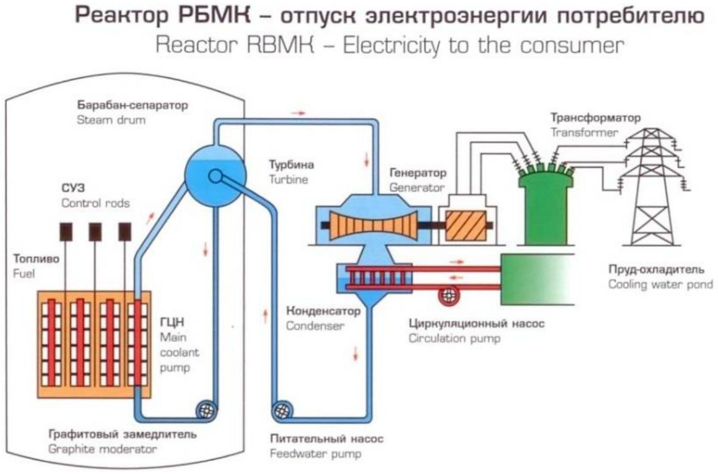

Figure 1.9: LGR design

1.4.2.3 Liquid Metal cooled Reactor (SFR &LFR)

The US Company Gen 4 Energy (formerly Hyperion Power Generation) is currently developing a SMR, the Hyperion Power Module (HPM, 25 MWe). They are currently licencing their concept and they will soon build demonstrator (GEN4 Energy, 2012).

Also in Russia, as previously presented, the SVBR-100 was developed by VNIPIET, Atomenergoproekt Moscow and JSC Irkutskenergo. Other examples of this technology are the Toshiba 4s in Japan and the GE S-PRISM in USA. Since 2010, the company Advanced Reactor Concepts, LLC is currently developing an SMR concept, the ARC-100 (100 MWe) (ARC, 2013).

Examples of fast neutron reactors cooled by molten lead having SMR-oriented features are:

- BREST-OD-300, NIKIET/ROSATOM, Russian Federation,
- SVBR-100, JSC AKME Engineering, Russian Federation,
- LFR-AS-200, Hydormine, US,
- SEALER, LeadCold, Sweden-Canada,
- SMR derived from the ALFRED concept, FALCON consortium, Europe.

1.4.2.4 Gas Cooled Fast Reactor (GCFR)

As presented in the previous section, a large European consortium is working on ALLEGRO project, with the collaboration of both research centres and industrial partners.

1.4.2.5 Very High Temperature Reactor (HTR)

Introduced in the first paragraph of the SMR stakeholders, China is building a demonstrator since 2012.

In South Africa, there was a project of building a reactor by PBMR (Pty), the PBMR (165 MWe), but for political reasons, the project was cancelled in 2013 (United States Nuclear Reguatory Commission, 2013), (PBMR, 2013).

A partnership between the American General Atomics and the Russian OKBM Afrikantov worked on the GT-MHR (286 MWe) (Andrew CMU, 2013), but since 2003, there isn't any progress in development of it. General Atomics also designed the EM2 SMR (240 MWe), and launched in 2010 a 12-year programme to develop it, in July 2013, they applied for subvention from DOE (World Nuclear News [2], 2013), but they have not been chosen (World Nuclear News [3], 2013). Another important American stakeholder was Adams Atomic Engine which worked on the Adams Engine (1-100 MWe) in the 1990s. The company disappeared in 2010.

In France, AREVA's SMR design, ANTARES (285 MWe) have been chosen by NGNP Industry Alliance in February 2012 as the optimum design, but there is no more recent information about it (World Nuclear News [1], 2013).

1.4.2.6 Molten Salt Reactor (MSR)

Despite the Fukushima events, the Japanese International Thorium Energy & Molten Salt Technology Inc. Company (IThEMS) is still working on the development of the FUJI MSR (10 MWe first and subsequently 200 MWe) (Halper, 2013).

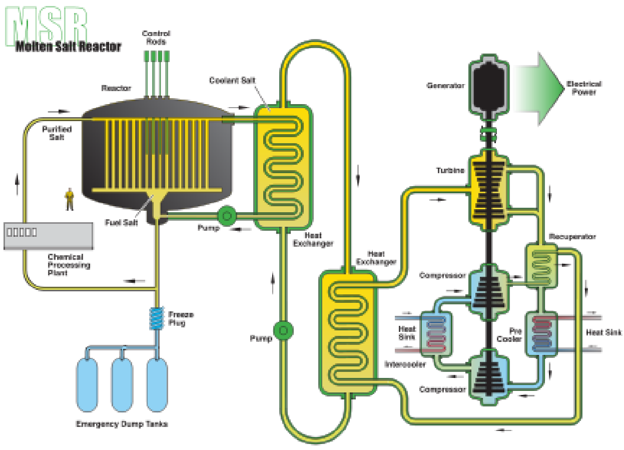

Figure 1.10: MSR design (Halper, 2013)

Also in the USA, there are other stakeholders, such as Flibe Energy which is currently working on this technology that has previously been shelved (Thorium MSR, 2013). Their design is called the LFTR.

2 The opportunities for SMR in Europe

This section presents the opportunities in Europe for Small Modular Reactors. Firstly, some existing or potential applications are presented, followed by the main opportunities and threats for market penetration.

2.1 SMR's potential applications

The main advantages of fast reactors compared to Generation II and III reactors are superior fuel utilization and a capability for the reduction of wastes. As a consequence, there are no application specific to fast reactors. The following table present the potential applications for SMRs in general. The feasibility of each application for SMFR in Europe has been assessed assuming that fast reactors and reactors from Generation II and III are at the same Technology Readiness Levels (TRLS). Indeed, if the potential of SMFRs is assessed at the present time, for each application, investors might be discouraged by the fewer TRL of fast reactors technologies.

Application	Description	Feasibility in Europe for SMFR
Power supply for isolated or remote electricity grids	SMRs could be used to power isolated installation, which does not have a high-quality energy service. SMRs would be installed close to the installation and would not be connected to the Grid. Such cases gather rural areas, military bases or isolated industries (Kurth, 2013).	Fast Reactors are adapted to this application. However, remote areas affect more large countries or countries with difficult living conditions (Alaska in the USA, Siberia in Russia, Australia, etc.). In Europe, this application could target only a few areas in Eastern Europe (Estonia, Lithuania) or in Northern Europe (Extreme North of Norway, Sweden and Finland) (Raw & Refined Company, 2010).
Non-electrical applications	These applications involve the simultaneous production of electricity and useful heat (cogeneration). Nuclear cogeneration can be used for district heating, water desalination or to power different industries.	Nuclear cogeneration is already a reality in Europe for district heating (examples in Sweden, Switzerland and Hungary). Moreover, within Europe's industry, around ¼ of the heat is supplied in CHP mode especially for the refineries, chemical, ceramics and paper industries in which cogeneration penetration is over 35% (COGEN Europe, 2013). The advantage of SMRs compared to large conventional NPPs is that their output size corresponds more to the thermal power capacity of cogeneration applications. The outlet temperatures of fast reactors vary from 450°C to 850°C. As a

Application	Description	Feasibility in Europe for SMFR
		result, in addition to low-temperature applications, SMFR can provide heat to other industries[3] using steam at these higher temperatures (NEI, 2012).
Stabilising role as complement to intermittent Energy Sources	Future energy systems will have increasing share of Renewable Energy Sources (RES). Some of these sources can be intermittent (wind, solar, etc.) and so affect the electrical grid operation. More flexible back-up concepts are then required. Compared to a one GW-size NPP, in an installation using SMRs, each unit represents a smaller base-load power addition to the system, allowing more flexibility. In a longer-term view, new concepts will have enhanced load follow capability. (Subki, 2013).	Europe is a potential market for this application since raising the share of EU energy consumption produced from renewable resources to 20% towards 2020 is one of the objectives targeted by the European Commission (Commission, 2014). Moreover, fast reactors can have a strong advantage compared to other type of reactor for this application. Indeed, recycling nuclear waste should be well perceived in an environmental-friendly context.
Access to nuclear power for the first time (new nuclear countries)	To reduce the risk of a considerable investment and construction of a large reactor, investors and government might be reassured by a smaller installation and a smaller investment offered by SMRs. Moreover, at this stage, the construction of SMR is maximised on plants and might thus appear simpler to governments with no experience in nuclear energy production.	Some countries in Europe are actively considering embarking upon nuclear power programs (IAEA, 2010) (Poland, Belarus, Turkey, Estonia, etc.). In these cases, SMRs compete with more traditional large reactors which benefit from experiences. Moreover, within the SMR offer, fast reactors might suffer from their innovative status with less past feedback experiences. PWR SMRs might be more reassuring for countries just entering into nuclear energy.
Generation and demand matching	SMRs can be built individually or deployed in multiple units on the same site. They can represent an interesting	Europe has not a rapid population growth. This growth can be easily managed by European government to forecast the energy demand and plan appropriate infrastructure

[3] These industries are detailed in the deliverable 4.3 of the ESNII+ project.

Application	Description	Feasibility in Europe for SMFR
	solution in markets where anticipated electricity demand is projected to increase gradually ; for such markets, SMRs constitute an interesting solution since additional units can be built accordingly to the demand growth, avoiding overcapacity installed (Young, 2012).	in their policy. This application does more affect countries such as India or China.
Replacement of fossil fuel Power Plants	Due to carbon emission regulation or aging power plants, governments will have to replace existing fossil fuel power plants.	Fossil fuel power plants produce the majority of electricity in the EU, mainly through pulverised coal combustion. Most pulverised coal plants are over 15 years old (European Commission - SETIS, 2014). The power capacity of SMRs is adapted to replace the fleet of fossil fuel burning power plants (the power of a coal and gas-fired power plants are typically between 330MW and 700W (ECOFYS, 2012)).
Power source for military applications	This is the original application of SMRs. Today, several nations use nuclear reactors to power submarines such as Russia, the USA, the UK, France, India or China (Ma, 2001).	Several European countries use nuclear energy to power submarines

Table 2: Potential applications for SMRs (LGI, 2014)

The previous applications are represented on Figure 2.1 according to two discriminant criteria:

- The Market potential for SMFR in Europe: does the application represent a market in Europe?
- The power required for each application: what range of power does the application represent?

The applications were placed in the axes using a relative scale to allow the comparison between the applications.

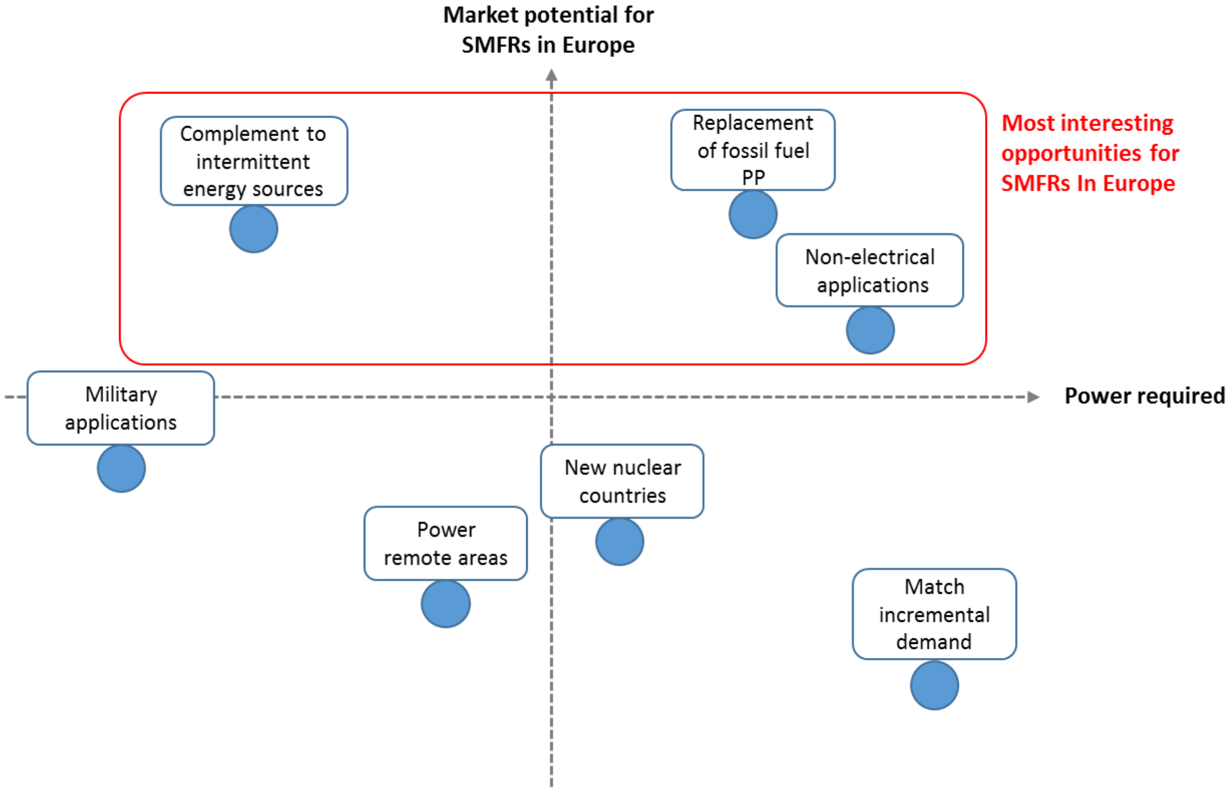

Figure 2.1: Overview of the potential applications for SMFRs using a relative scale (LGI 2014)

The most interesting applications for SMFR in Europe are:

- Complement to intermittent energy sources
- Replacement of fossil fuel power plants
- Non-electrical applications

These applications are the most likely applications to find customers in Europe in the following years. The applications "Replacement of fossil fuel power plants" and "Non-electrical applications" will require larger SMRs, with a capacity between 350 and 700 MWe whereas, the "Complement to intermittent energy sources" will require SMRs with a capacity below 100 MWe.

Additional opportunities could arise outside of Europe in the form of potential export markets, for example:

- **Remote applications.** In particular, Canada has very large areas which are sparsely populated and is actively pursuing Generation IV small modular reactor technology as a potential solution for remote areas (CNL, 2017). Multiple European small modular Generation IV reactor concepts including LFR (Leadcold, 2017), MSFR (Moltex, 2017) and the Urenco U-Battery HTR (World Nuclear News, 2017a), are actively engaging with Canada as a potential export market.
- **Access to nuclear power for the first time.** Countries with ambitions to commence nuclear energy programmes have in several cases engaged with vendors of SMR concepts, notably Saudi Arabia's interest in HTR (World Nuclear News, 2017b)

In both the above examples, a long refuelling interval and single batch core can be advantageous by reducing on-site maintenance requirements. It is possible to design small modular fast reactors which exhibit these particular features, potentially making them particularly suitable for these applications. A good example of this is the Russian SVBR-100 concept, a liquid metal fast reactor with a long refuelling interval and single batch refuelling intended for remote applications (Pioro et al., 2016).

2.2 SMR main opportunities and threats

In this section, the PESTEL analysis is used to identify the main threats and opportunities for SMR in the European Market. PESTEL stands for Political, Economic, Social, Technological, Environmental, and Legal. It describes a framework of macro-environmental factors used in the environmental scanning component of strategic management. It is a useful strategic tool for understanding market growth or decline, business position, potential and direction for operations.

- **Political factors** are basically to what degree the government intervenes in the economy.
- **Economic factors** include economic growth, interest rates, exchange rates and the inflation rate.
- **Social factors** include the cultural aspects and include health consciousness, population growth rate, age distribution, career attitudes and emphasis on safety.
- **Technological factors** include technological aspects such as R&D activity, automation, technology incentives and the rate of technological change. They can determine barriers to entry, minimum efficient production level and influence outsourcing decisions. Furthermore, technological shifts can affect costs, quality, and lead to innovation.
- **Environmental factors** include ecological and environmental aspects such as weather, climate, and climate change.
- **Legal factors** include discrimination law, consumer law, antitrust law, employment law, and health, safety law, and licencing policy.

A focus group was created, with representatives from different sectors and expertise (a total of 8 representatives with expertise in nuclear, renewables, chemistry, energy policy, environment and energy supply) aiming at bringing out the most relevant macro-environmental factors. In the following paragraphs, all of these macro-environmental factors have been studied. The representatives of the focus group quantified the weight of the different factors as follows:

- Intensity of the consequences for the market for each factor, if they occur (rated from one to four; one representing a weak intensity and four a strong one).
- Probability to occur (rated from one to four; one representing a weak probability and four a strong one).
- Time horizon (rated from one to four; one means long term and four, short term).

An average of the weights of each expert resulted in the final weight of each factor. The three factors, intensity, probability and time horizon, were multiplied to obtain the potential impact of the macro-environmental factor.

To represent the results, the different factors have been plotted into diagrams intensity-probability. The size of the bubbles represents the value of the potential impact (intensity-probability-time horizon). The positive or negative impact in the SMR market of each factor is represented by different colours in the diagrams. Red is used for a negative impact on the SMR market, green for positive impact, and grey for a neutral impact, depending of the future evolution of the factor.

Political factors

- **Phase-out**: Some countries in the European Union are willing to phase out from nuclear. In August 2011, Germany decided to shut down immediately its nuclear reactors, after Fukushima. And France, former president François Hollande has proposed cutting nuclear power's electricity contribution by more than a third by 2025, among other EU strategies.
- **Ukrainian crisis**: The Ukrainian crisis, and the tensions with Russia resulting of it, might have good consequences for the SMR European market. The EU will of energy independency and the consequences of the gas market crisis, some EU countries may revise their positioning on nuclear (Jaffe, 2014).
- **SMR consensus**: There don't seem to be a consensus of the main stakeholders on the SMR's products, and it might handicap the development of a defined offer able to answer to the European market.
- **Proliferation risk**: In Europe and globally, there is an increase of concerns about the risk of nuclear proliferation, and with SMR's features decreasing that risk, the SMR may have a role to play (IAEA, 2003).
- **CO2 reduction**: The European Commission has set goals of decreasing greenhouse gas emissions that might push nuclear technologies and the SMR market (European Commission [1], 2014).
- **Pro nuclear projects**: The European Commission has launched pro-nuclear research programmes, within EURATOM, which can only help to the deployment of SMR.
- **Asian Competitors**: the potential competition with Asian countries, which are currently developing SMR products, and might penetrate the European market before Europeans (World Nuclear Association, 2014).

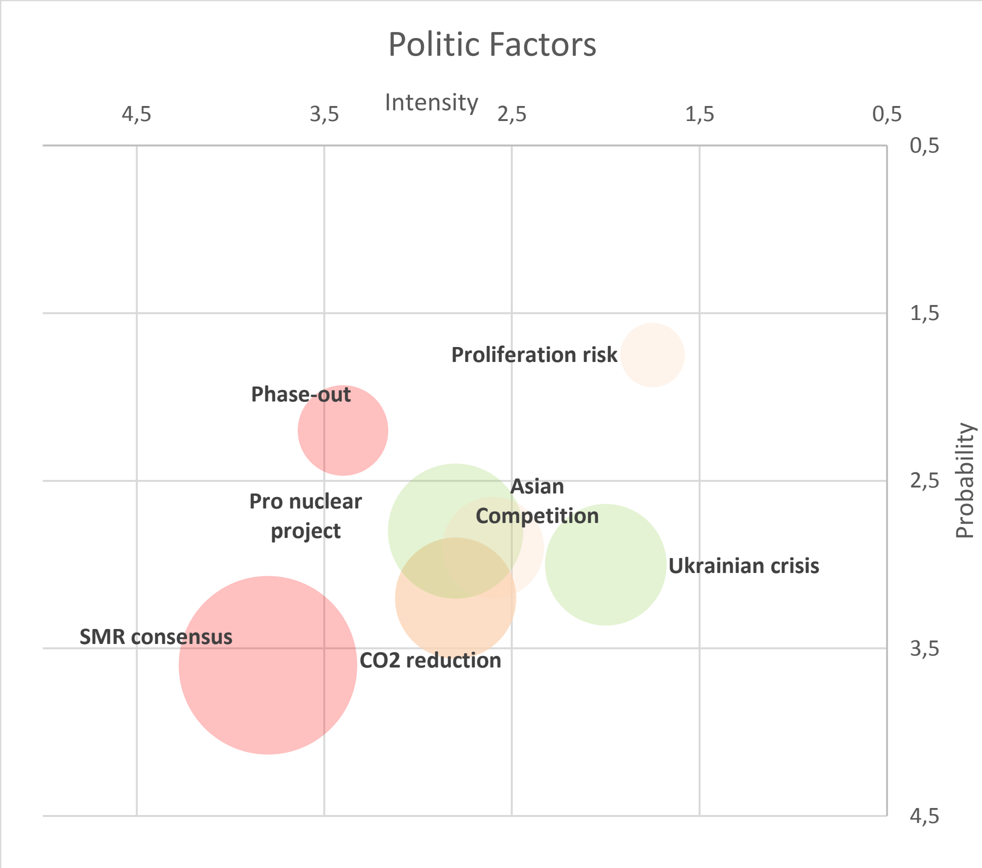

Figure 2.2: Politic factors (LGI, 2014)

The political factors having negative impact on the SMR market are the current lack of consensus among the different stakeholders and the phase-out of different EU countries. The lack of consensus is the one with higher impact and probability as if a coordinated strategy is agreed among the actors the SMR deployment will be boosted. The positive factors are the pro-nuclear projects, Asian competition, CO2 reduction, proliferation risks and the Ukrainian crisis, related to EU energy independency. European projects will be essential to maintain EU competitiveness in the fight with international competition. CO2 free strategies in EU may have a positive impact on nuclear to reduce the fossil fuel consumption, and thus a potential positive factor for the SMR deployment.

Economic Factors

- **Cuts in funding**: In some countries of the EU, there have been cuts in public funding in nuclear research, which might endanger the development of SMR. (Réseau sortir du nucléaire, 2013)
- **Bank investment**: The contextual crisis situation has generated bank unwillingness to finance projects with high upfront investments. The SMR technology offers solutions with lower capital needed in the first phases of the project, thus a positive factor for SMR development.
- **CCE (Country of Central Europe) development**: The development of the industry in Central Europe is followed by new energy needs, and that can be a great opportunity for the SMR products (Timu, 2014).

- **Natural Resources**: The presence, or absence of natural resources, in the different European countries, will also impact the potential development of the SMR market in each country.
- **Oil price rising**: The continuing rise of oil price, make it a less competitive energy producing way (Natural Ressource Canada, 2010). Thus the SMR will turn into a more and more competitive way to do it.
- **Gas price decrease**: As a substitute of nuclear, the gas price has an impact on the SMR market, it could make the SMR an expensive solution to produce energy (YCHARTS, 2014).
- **Energy consumption rise**: This is a fact, that Europeans use more and more energy for their individual needs, which imply an enlargement of the energy market, and then of the potential SMR market.

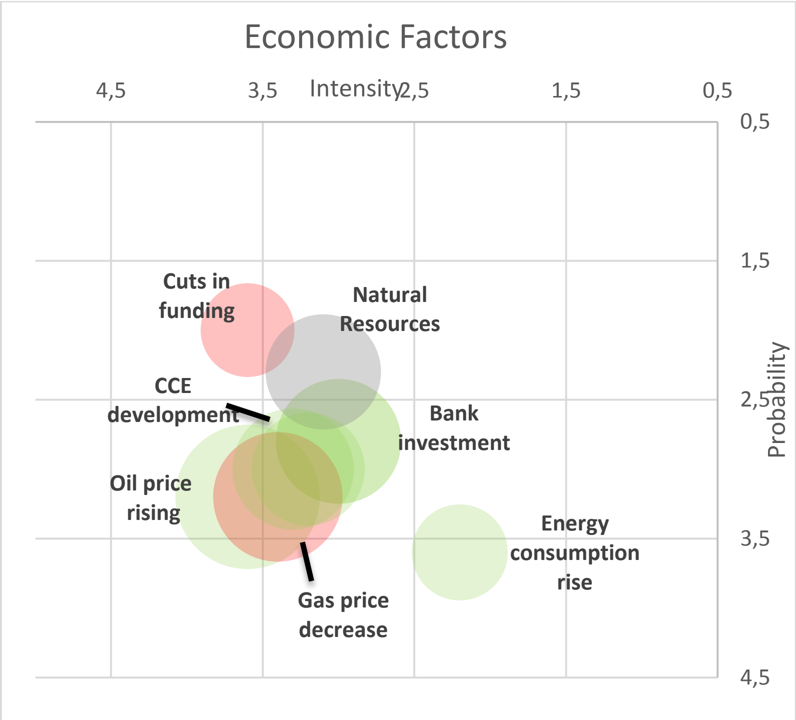

Figure 2.3: Economic factors (LGI, 2014)

The negative economic factors are the gas price decrease and the cuts in funding, as they represent a threat for SMR development. Factors having a positive impact are CCE development, oil price rising, energy consumption rise and bank investment. Natural resources might have a positive or negative influence in the future deployment of SMR. The development of the industry in Central Europe and the rise on energy consumption may be a real opportunity to develop the SMR market. However the competition with other solutions and its prices of producing energy might be a real threat to monitor.

Societal Factors

- **Nuclear fear**: Since the first nuclear incident, there is a real fear about nuclear power plants. The proximity to them is frightened the general public (Le Monde, 2011) mainly because they don't understand nuclear technology. It might be a real drag to the deployment of SMR technologies.

- **Population rise**: In 2030, there will be more than 519,000,000 people in European Union, and the rise of population will be followed by a rise of energy demand, which might be an opportunity for SMR to enter the market. (United Nation, 2004)
- **Fukushima trauma**: More than the previous nuclear incidents, the Fukushima disaster has created a worldwide trauma about the nuclear technology (Institut BVA, 2011) leading to the phase-out of some countries. That worldwide feeling might be a huge threat for all of nuclear technology developments, including SMR.
- **Nuclear vocation**: The last societal factor we have to pay attention, is the number of vocations in nuclear field, indeed, in case there was a decreasing of it, it could put in jeopardy the entire future of nuclear field, including the SMR one.

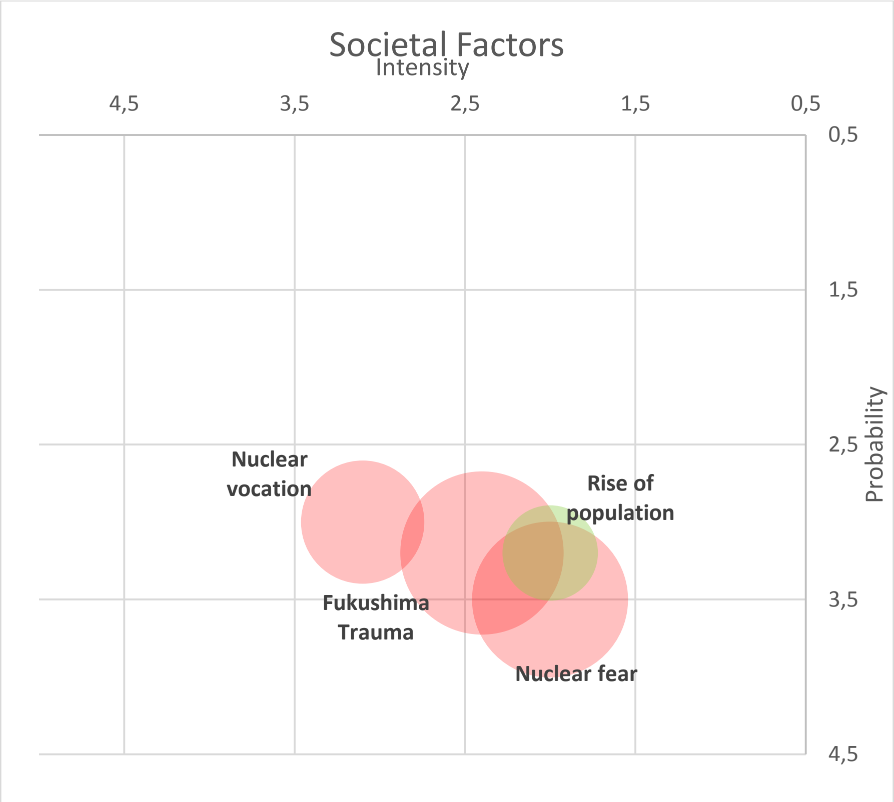

Figure 2.4: Societal factors (LGI, 2014)

The only positive factor in this case is the rise of population that could entail higher energy needs and a potential SMR development. The nuclear fear and especially the Fukushima trauma is a high barrier for nuclear power, and consequently to new nuclear projects deployment as SMR. The nuclear vocation is also a negative factor, as less young engineers are interested in nuclear power and new staff is needed to develop new nuclear concepts.

Technological Factors

- **Lack of knowledge**: One major issue of the SMR field is that, despite the lot of theoretical knowledge on the technologies, only a few have been built in Europe (and most of them for research reactors or for propulsion purposes). The lack of experience in SMR building may slow down the development of SMR market. (IAEA [2], 2013)

- **Dense electric grid**: The existence of a dense electric grid in Europe decreases the interest of SMR, which are most useful in remote locations with no access to the electric grid (Raw & Refined Company, 2010).
- **Alternative technologies**: The development of new alternatives technologies would be another threat on the SMR market.
- **Nuclear fleet ageing**: The ageing of nuclear fleet is a real opportunity for the SMR to take the place of the old nuclear power plants, when they are decommissioned.

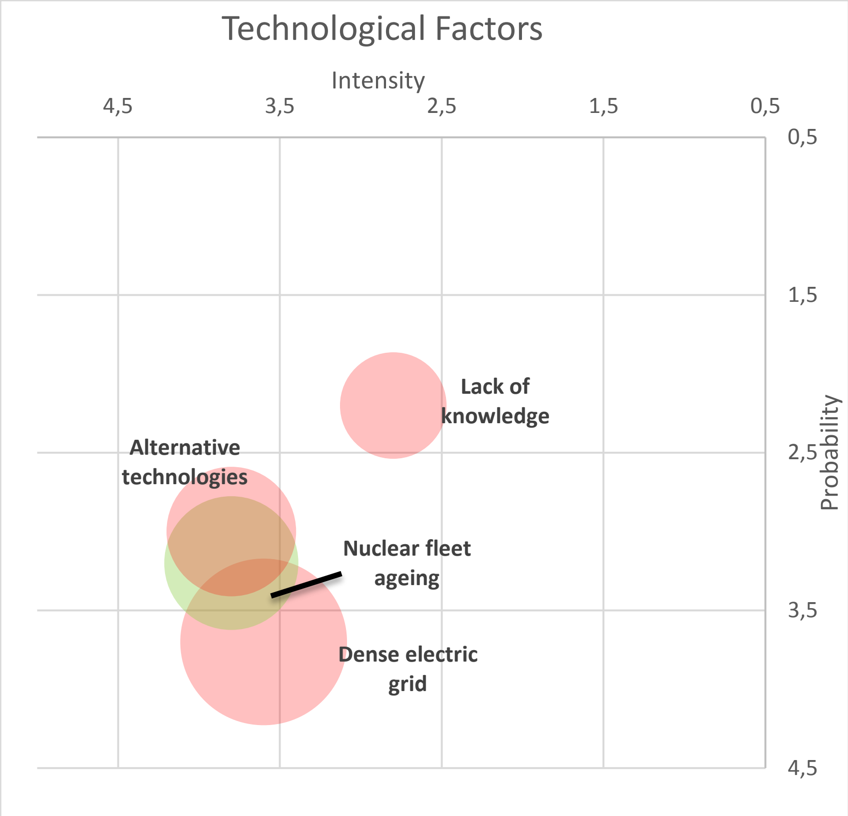

Figure 2.5: Technological factors (LGI, 2014)

The only positive factor for SMR is the aging of the nuclear fleet. The need of construction of new sites, may take into consideration SMR. The EU dense electric grid, the presence of competitive alternative technologies and the lack of experience of SMR makes important technical barriers for the SMR deployment. SMR stakeholders may face a huge competition with other new emerging solutions to produce electricity, which will benefit of a better reputation than nuclear ones.

Environmental factors

- **CO_2 reduction**: The EU has set goals of reducing CO_2 emissions (European Commission [2], 2014). And that's a positive factor for the SMR technologies, as they release few CO_2 comparing to other alternative ones.
- **Waste management**: One of the main environmental threats for the SMR technology, or more generally for all nuclear technologies, is the waste management

(Europa, 2011). If researchers can't solve this issue, the SMR technology will be threatened by other cleaner technologies.

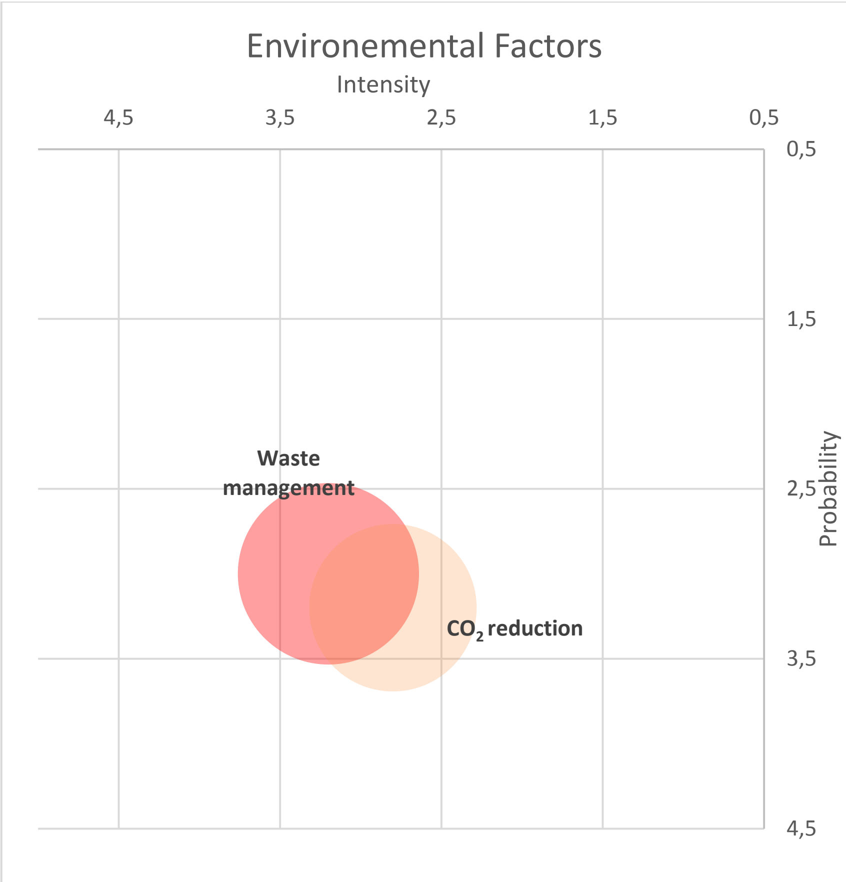

Figure 2.6: Environmental factors (LGI, 2014)

Waste management is a negative factor with high impact and probability as the nuclear waste problem has not been solved yet. Considering fast reactors the impact is fewer, but it is not completely solved. The solution may come with the results of European research programmes on recycling nuclear used fuel (e.g. SACSESS), which will enhance the waste management process. The CO2 reduction strategy of the EC could be a positive factor in the SMR deployment with high probability to happen.

Legal Factors

- **Transport laws**: The European legislation on nuclear material transport is really strict (European Commission [3], 2014). The SMR reactors are supposed to be built in manufacturing plants and then transported. The transport of SMR would have to be adjusted to the EU laws and adjustments and modifications in the transport mechanisms might have to be considered.
- **Nuclear licensing**: Like all the nuclear facilities, the future SMRs will have to be authorised by nuclear authorities (ENSREG, 2007). So the SMR developer will have to be careful to respect all the requirements of these authorities.
- **Shale gas exploitation**: The rise of the energy price will make the SMR technologies competitive, that's why the shale gas exploitation will threaten the potential SMR market.

For now some European countries are drilling it (Denmark, Sweden, UK, etc.) and some don't (France, Bulgaria, etc.).

- **Safety requirement**: Due to the recent events in Fukushima, in Japan, the safety requirements of all nuclear facilities, past, present and future have been enhanced. It will be a real challenge for the SMR developers to answer these new requirements.
- **Carbon footprint taxes**: One of the most advantageous legal factors for the SMR technologies is the development of carbon footprint taxes. Indeed, it advantages the SMR technologies, because of their low carbon footprints.
- **EU different legislations:** Moreover, the difficulty of the European market is the throng of legislations, the differences between each country and its markets is a threat for a complete EU deployment. Indeed, the SMR developers will have to adapt their products to fit to the legislation of each country, and so we will lose the interest of mass production.

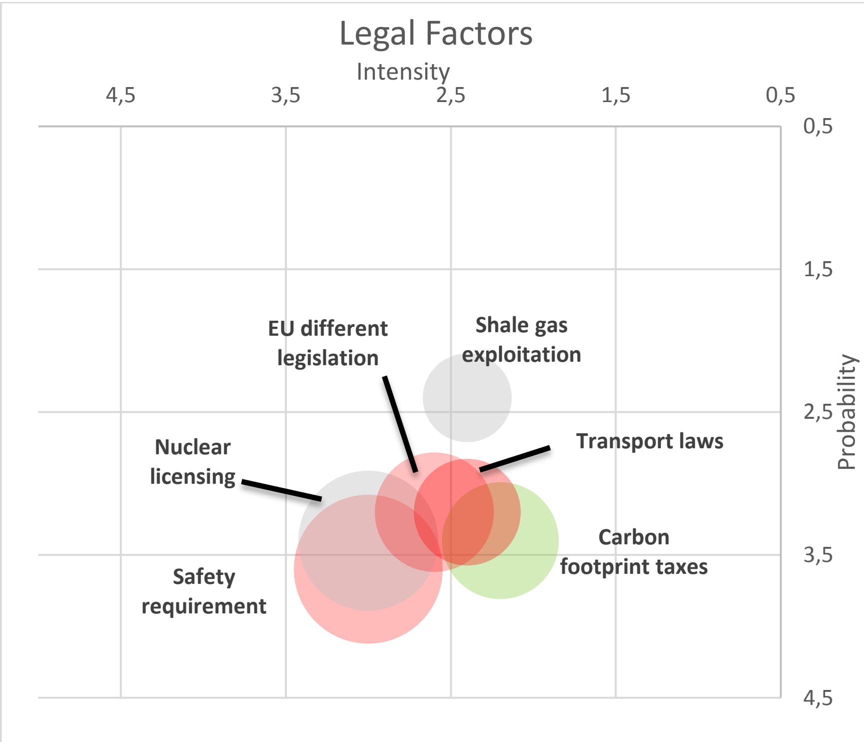

Figure 2.7: Legal factors (LGI, 2014)

Safety requirements, EU different legislations and transport laws could be considered as a threat for the SMR deployment. A positive factor is the carbon footprint taxes related to SMRs. Two factors have been considered as neutral, the shale gas exploitation and the nuclear licensing as their situation is diverse in the EU.

2.3 The advantages of fast reactors in the SMR market

Among all the SMR technologies studied in this report, some are more promising than others, the fast reactor technologies are part of them. In order to understand what the specificities of these technologies are, the general features are described first, their main advantages and drawbacks are presented followed by their main opportunities and threats are presented.

A fast neutron reactor (FNR) is a category of nuclear reactor, in which the fission reaction is sustained by fast neutrons (neutrons whose energy is greater than 1 MeV). In the classical thermal nuclear reactors, the chain reaction is sustained by thermal neutrons (neutrons whose energy is about 0.025 eV). Such reactors have no neutron moderator (allowing faster neutrons) but need richer in fissile material fuels.

Advantages

The fast neutron reactors have some advantages compared to thermal reactors:

- The partitioning and transmutation is possible within reactor
- They can be fed by almost all actinides
  Some of them (the fast breeder reactor) even produce more fuels than they consume (their conversion factor is > 1 and the fuel utilization is much higher than in thermal reactors)

All of these advantages lead to the following consequences:

- Former wastes are now valuables
- The use of these reactors decrease the total radiotoxicity of nuclear waste
- The use of these reactors decrease the waste's lifetime from tens of millennia (from transuranic isotopes) to a few centuries.

Drawbacks

The fast neutron reactors have some drawbacks compared to thermal reactors:

- The need of richer in fissile material fuels increase the nuclear proliferation issues
- Fuel reprocessing (required to exploit some of the above listed advantages) isn't currently economically competitive
- Lack of operating experience.

Opportunities and Threats in the European market

The lack of SMR consensus hampers the development of a general strategy and overall agreement to develop SMR in the EU. The SMR market would be developed only if there is a consensus of direction, and a real will from all the stakeholders.

One example of international consensus in the development of fast reactors is a major agreement between Japan's Atomic Energy Agency (JAEA), France's CEA and the US Department of Energy was signed in October 2010. This expanded previous FNR collaboration toward the joint design and development of reliable world-class FNRs and getting private manufacturers involved. JAEA is working on the design of a demonstration reactor to succeed the prototype FBR Monju, France is leading the development of the Advanced Sodium Technical Reactor for Industrial Demonstration (ASTRID), and the USA is standing back from new plants and is focused on systems, materials and safety analysis but has an extensive base of information and experiences as a result of past efforts to develop FNRs, notably FFTF and EBR-2.

The main market opportunity for the SMR technologies is closely linked to the increasing of energy prices. The **rise of oil price** and the **decrease of gas prices** have a strong influence in nuclear development.

The main barrier for the development of an SMR market is the social acceptance of new nuclear power plants, the generalised **fear to nuclear** and the **lack of nuclear vocation** are the main factors blocking the SMR market deployment.

Considering technical aspects, the **EU dense electric grid** impedes a rapid growing of SMR, one of the main applications of SMR. A **nuclear ageing fleet** might have a positive impact on SMR as new solutions have to be proposed to replace existing ones.

The **CO2 reduction** could trigger the SMR market development as there is a strong will from the EU to reduce CO2 in the upcoming years.

3 SMFR Top Down Cost Estimate

Using a top-down cost estimate approach, a cost estimate for an nth-of-a-kind ALFRED based SMFR is provided. Confidence in the obtained results is derived from comparison with the bottom-up cost estimate for a 1st-of-a-kind ALFRED demonstrator which was performed during the 7th framework program LEADER project.

The results show that the nominal costs including contingencies for an nth-of-a-kind ALFRED based SMFR, under the assumptions provided in the report, sum up to about 750 M€. This value excludes approximately 30% uncertainty.

When compared to the cost estimate for the larger scale ELFR as performed within the LEADER project, it is shown that the nominal energy generation costs are comparable. Although the construction and O&M costs are slightly larger as can be expected for a smaller scale reactor, this is compensated by decreased fuel cycle costs. This is probably due to the fact that the ELFR design was not as mature as the ALFRED design.

Compared to contemporary LWRs, the O&M costs are larger. However, it is shown that the fuel cycle costs are expected to be comparable to contemporary LWRs.

The sensitivity study shows a large sensitivity towards operation and maintenance costs and the expected operational life.

3.1 Approach

Cost estimates of future complex technological systems (like a nuclear reactor system) which are only available in a (pre-)conceptual stage are complicated and show large uncertainties. On the other hand, such cost estimates are essential to challenge the justification of the ongoing developments and investments as the economic performance will determine the market potential and penetration of a new nuclear plant design to a large extent, considering the fully competitive deregulated market in which they will have to be built and operated. Most often, such cost estimates are made in a bottom-up approach. The reactor system under consideration is broken down into components and realistic cost estimates are made for each component. However, as the fourth generation nuclear reactor concepts are often in a preliminary stage, a thorough bottom-up cost estimate from component level cannot be made accurately.

In this report, a top-down cost estimate of a future small modular fast reactor is described. This cost estimating approach has been developed to provide as realistic as possible cost estimates for future nuclear reactor systems and their associated fuel cycles. The approach is based on a comparative analysis using a structured accounting system as applied in the G4Econs model which is developed by Economics Modeling Working Group of the Generation IV International Forum (GIF EMWG). The approach has been described in the article of Roelofs & Van Heek (2011).

The presented top-down cost estimate approach, uses, like most bottom-up approaches, a cost accounting system. This system breaks the reactor system down into small(er) accounts (components) for which cost estimates are to be determined. The International Atomic Energy Agency (IAEA) has developed a comprehensive account system capable of addressing a spectrum of capital, fuel cycle, and operations and maintenance costs, from a complete nuclear energy plant down to individual systems and components (IAEA, 2000). Because this accounting system has a high degree of flexibility, it can be used for all types of reactor systems, single or dual-purpose energy plants, and various contract or deployment approaches. To meet the needs of the EMWG and the system designers/estimators, some revisions were made to the IAEA account system to create the GIF code of accounts (COA). The GIF COA has multiple levels of detail, the first level being the most generic and later levels containing increasing details.

Following the COA provided by GIF/EMWG (2007) the construction costs for the different reactor types are estimated relative to the construction costs of a reference plant which are put to 100%. In this case, a Generation III nuclear power plant is used as a reference plant. Even if no data is available for the separate accounts or ultimately for the overall capital costs of the reference plant, the approach still provides a qualitative inter comparison of different reactor systems.

For the second level of accounts, several references provide the relative distribution of the costs for different reactor types. This indicates to what extent a specific account contributes to the overnight construction costs for a given reactor type. For example, the reactor vessel and other reactor plant equipment may be expected to pay a larger contribution to the overnight construction costs for Generation IV plants than for Generation III plants because of the application of more expensive materials which can withstand elevated temperatures and more demanding coolants.

As a second step in the assessment, using these relative cost distributions based on the second level of accounts, the costs for different accounts are determined relative to the reference plant which is put to 100% using certain assumptions. The third step is to make the comparative analysis. Figure 3.1 provides an overview of the developed comparative COA based approach. On top, the cost distribution for a (Generation III) reference plant is displayed as segments in a circle. Below this, two different Generation IV plants are considered each having different cost distributions and presented as two further circles for comparison. The bullets below the two lower circles represent the individual accounts, showing that the evaluation of these individual accounts may lead to different conclusions for the designs under consideration.

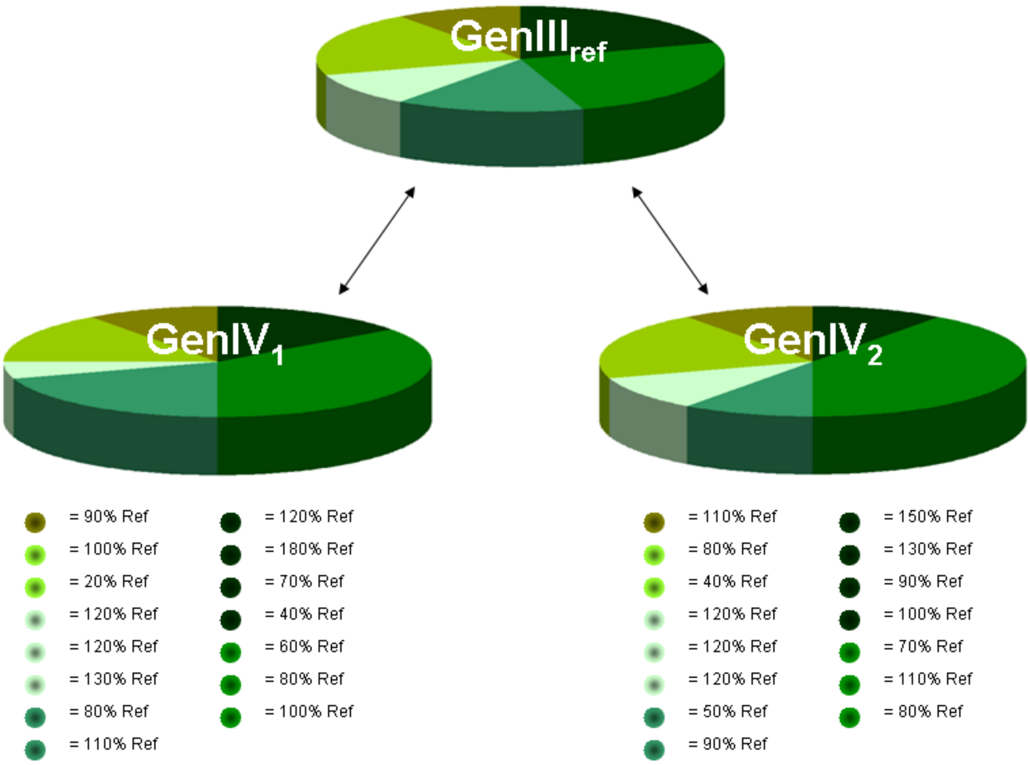

Figure 3.1: Visualization of the comparative COA based cost estimate approach

The purpose of the current assessment is to estimate construction costs, operation and maintenance costs, the fuel cycle costs, and ultimately the energy generation costs. The information on construction costs is used as input for the general energy generation cost assessment using the G4Econs tool developed by GIF EMWG. This tool uses a similar accounting system for the derivation of costs. Ultimately, a similar approach was followed here for many of the accounts, i.e. their values were derived mainly by comparing against existing data for a reference system.

Within the European 7th framework project LEADER, a top down cost estimate was produced for a large scale nth-of-a-kind lead fast reactor reported by Vazquez & Roelofs (2013). This cost estimate for a 600 MWe European Lead Fast Reactor (ELFR) is taken as a basis for the current cost assessment for the lead based SMFR.

3.2 General Assumptions

3.2.1 Inflation

Many of the data are available for a certain date. As currencies change over time and inflation rates are different from country to country, assumptions have to be made with respect to historical inflation rates. All data selected originates from European sources. Therefore, the historical inflation rates of the euro have been considered. These data were derived from Eurostat. The historical data retrieved are interpolated and a fit is made using a constant inflation rate (see Figure 3.2). The following constant values of the fits are used:

Euro (1998-2013): 2.1%

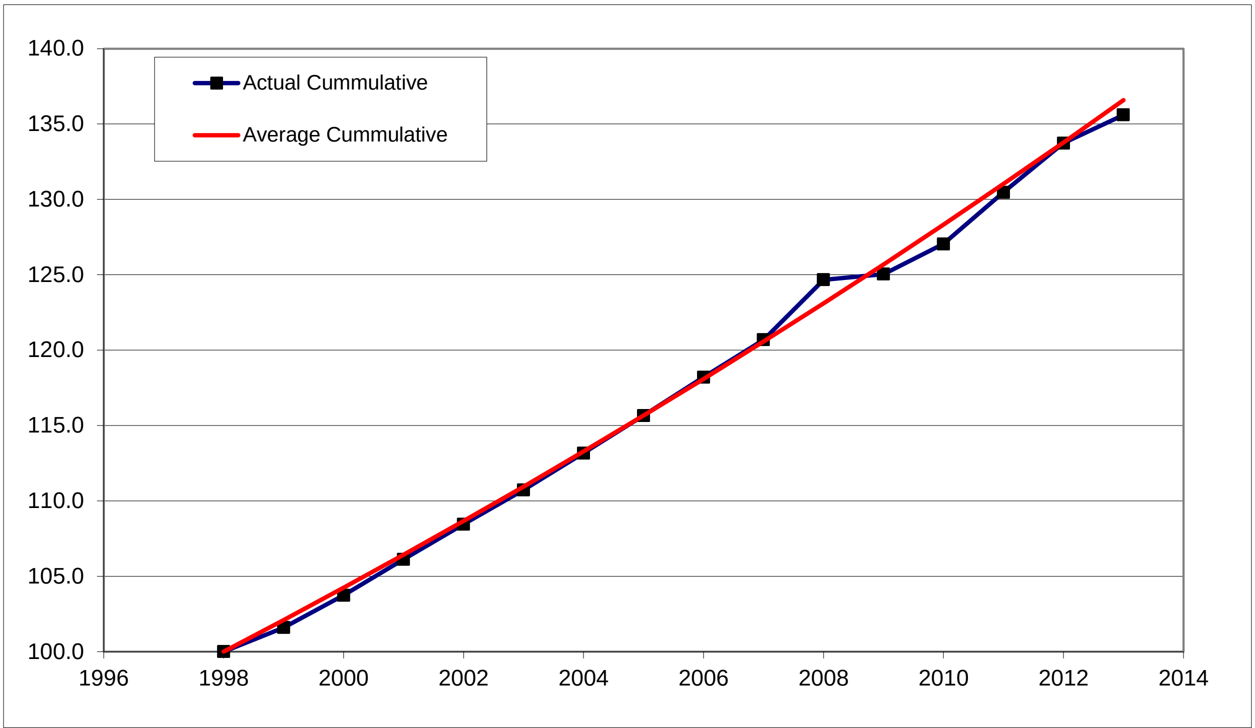

Figure 3.2: Historical inflation rate of the Euro compared to a fit with 2.1%

3.3 Cost Accounting

A comprehensive account system capable of addressing a spectrum of capital, fuel cycle, and operations and maintenance costs, from a complete nuclear energy plant down to individual systems and components has been developed by the IAEA (2000). Because this accounting system has a high degree of flexibility, it can be used with all types of reactor systems, single or dual-purpose energy plants, and various contract or deployment approaches. The GIF EMWG has adopted this accounting system. However, to meet the needs of the GIF system designers and cost estimators, some revisions were made to the IAEA account system to create the GIF code of accounts (GIF COA). The GIF COA has multiple levels of detail, the first level being the most generic and later levels containing increasing details.

3.3.1 Cost Distribution

At the second level of accounts, a cost distribution between the different main components forms the starting point. This indicates to what extent a specific account contributes to the overnight construction costs for a given reactor type. For example, the reactor vessel and other reactor plant equipment may be expected to pay a larger contribution to the overnight construction costs for Generation IV plants than for Generation III plants because of the application of more expensive materials which can withstand elevated temperatures and more demanding coolants. The cost distribution for an LFR is derived from the assessment made by Perezagua & Orden (2010) for the cost estimate in the frame of the ELSY project. The same cost distribution is assumed for ALFRED. Table 3 presents the cost distribution applied for ALFRED.

The special costs for having lead as a coolant instead of demineralized water are taken into account under 'specials'. The estimate of 1% is based on the statement by Gromov et al. (1997) that the bismuth costs for a lead-bismuth cooled reactor are at least ten times that of lead and still only make up about 1% of the total investment costs.

Table 3: Assumed cost distribution for ALFRED based on LEADER and ELSY documentation

Account	Cost Distribution
Buildings & Structures	19%
Reactor	37%
Turbine	14%
Electric	1%
Miscellaneous	12%
Heat Rejection Systems	1%
Specials	1%
Simulator	1%
Construction	7%

Services	
Other (Owner costs)	7%

3.3.2 Comparison to a Reference Plant

In order to enable a comparative analysis, a reference plant has to be selected. To this purpose, the cost estimate for the ELFR (Vazquez & Roelofs, 2013) has been selected as a reference.

One of the main considerations for each code of account is to scale plant data to the reference plant data with the net electric (or thermal) power. For this, scaling relationships like presented below can be employed based on the data provided in the Nuclear Energy Cost Data Base provided from Delene et al. (1988).

$$Cost_{new} = Cost_{ref}\left(\frac{Power_{new}}{Power_{ref}}\right)^{a}$$

In which '$Cost_{new}$' and '$Cost_{ref}$' are the costs of the considered plant and the reference plant respectively, '$Power_{new}$' and '$Power_{ref}$' are the power levels of the considered plant and the reference plant respectively, and 'a' is the scaling factor.

Existing values for the scaling factor are usually only valid for reactor systems which employ comparable net power. Using those as a basis, MacDonald & Buongiorno (2002) derived scaling factors for systems with large differences in net power. As ALFRED and the reference plant ELFR employ net powers which differ a factor of 5, these values, presented in Table 5, for the scaling factor are applied.

Table 4: Scaling factors (MacDonald & Buongiorno, 2002)

Account	Small Power Difference	Large Power Difference
Buildings & Structures	0.5	0.59
Reactor	0.6	0.80
Turbine	0.8	0.83
Electric	0.4	0.39
Miscellaneous	0.8	1.06
Heat Rejection Systems	0.3	0.59
Construction Services	0.42	0.66

A proper cost assessment should not only be based on scaling relationships like presented above, but should also take into account the benefits of modular construction (increased standardisation and faster learning curves) which are especially true for smaller sized reactors. This approach follows the analysis of Boarin & Ricotti (2011). In their analysis, they separate four effects of modular construction:

1. Learning factor
   The number of similar plants constructed world-wide will lead to increased experience in construction and therefore in decreased costs
2. Modularity factor
   Modularization factor assumes capital cost reduction for modular plants, based on the reasonable assumption that the lower the plant size, the higher is the degree of design modularization
3. Multiple Units factor
   Multiple units saving factor shows progressive cost reduction due to fixed cost sharing among multiple units on the same site
4. Design factor
   The design factor takes into account a cost reduction by assumed possible design simplifications for smaller reactors

Figure 3.3 shows the curve constructed when all these separate effects are combined. A simplified curve was fitted through this graph requiring only input with respect to the reference plant net power '$Power_{ref}$' and the net power of the plant under consideration '$Power_{new}$'. As shown in the graph, this simplified curve is only valid for reference plants in the range of 600-1800 MWe. The simplified equation for the modular construction factor (*mcf*) reads:

$$\mathrm{mcf} = \min\left(0.195 \ln\left(\frac{Power_{new}}{100}\right) + 0.63 \cdot 10^{-4} Power_{ref}\ ; 100\%\right) \qquad (1)$$

Application of this equation to the 125 MWe ALFRED in comparison with the 600 MWe ELFR leads to a modular construction factor of 62%.

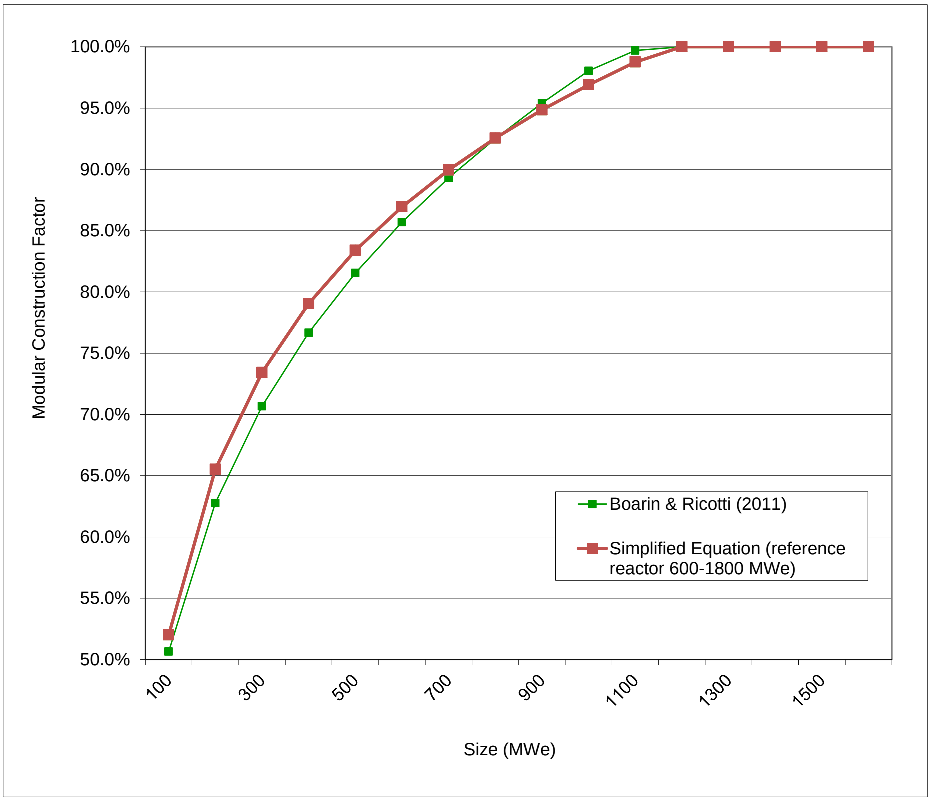

Figure 3.3: Modular construction factor

3.4 G4Econs

3.4.1 G4Econs Tool

G4Econs (**G**eneration **4 E**xcel **C**alculation of **N**uclear **S**ystems) is an Excel based nuclear fuel cycle simulation tool (GIF/EMWG, 2008) developed by the Economic Modelling Working Group (EMWG) of the Generation IV International Forum (GIF). Apart from the elaborate description by GIF/EMWG (2008) and the cost estimating guidelines provided by GIF/EMWG (2007), a short description of the tool can be found in Williams (2007). The tool allows to calculate levelised unit electricity costs by taking into account design characteristics, fuel characteristics, the associated fuel cycle and it's costs, the O&M costs broken down in a code of accounts, the capital costs broken down in a code of accounts, financing costs, and contingencies.

In the application of G4Econs, a range of values for every account can be specified by providing an optimistic, nominal, and pessimistic value. This feature has been used to calculate a range for the electricity generation cost. Optimistic, nominal, and pessimistic values were specified for most reactor characteristics, O&M accounts, and fuel cycle costs. The range was determined by selecting for all accounts either the optimistic values or the pessimistic values.

3.4.2 Assumptions Construction Costs

The construction costs are adopted from the COA based approach as described earlier. As both tools are based on the same set of accounts, the transition can be made fairly easy. It should be noted that an important assumption is made concerning the research and development (R&D) costs and decommissioning and decontamination (D&D) costs. Like it was decided within the framework of the LEADER project, the R&D costs were not to take into account. Furthermore, again like in the LEADER project, the D&D costs are included in the construction costs. Following the recommendation of GIF/EMWG (2007), these costs are considered 1/3 of the construction costs.

3.4.3 Assumptions Operation and Maintenance Costs

The operation and maintenance (O&M) costs within G4Econs are separated in a number of accounts. The values used for ALFRED are based on the ELFR assessment and scaled with net reactor power. For an estimate of the permanent staff, the equation derived in Roelofs et al. (2011) is followed. This shows that the number of permanent staff for ALFRED would be 32% compared to the ELFR.

3.4.4 Assumptions Fuel Cycle Costs

The fuel cycle costs including a lower and an upper bound are based on the costs provided in the Advanced Fuel Cycle Costs Database published by Shropshire et al. (2009).

3.4.5 Assumptions Contingencies

Assuming that contingencies are not taken into account in the literature values which are used e.g. for the determination of the construction costs of the reference power plant, the contingencies presented in Table 5 have been taken into account. These values are largely based on the contingencies employed by Gokcek et al. (1995) for a sodium cooled reactor. However, based on expert evaluation within the LEADER project, these contingencies were considered too low for the current status of ELFR development. Because these figures originate from a study on a relatively proven reactor system design compared to the ELFR, the values employed by Gokcek et al. (1995) are scaled on a case-to-case basis using approximately a factor of 1.5. The same assumption is employed in the current top down cost estimate for an ALFRED based SMFR.

Table 5: Contingencies applied to ALFRED based on Gokcek et al. (1995)

Account	Contingency
Structures	10%
Reactor	30%
Turbine	5%
Electric	10%
Miscellaneous	30%
Heat Rejection	10%
Construction Services	25%
Owners Costs	30%
Fuel Cycle	30%

3.4.6 Other Main Assumptions

Apart from the assumptions mentioned before, within the G4Econs exercise the following assumptions have been taken into account:

- No interest during construction;
- ALFRED aims at 300 MWth and ~125 MWe (Cuadrado & Alonso, 2015);
- ALFRED will have a net efficiency of 41.5% as presented by Cuadrado & Alonso (2015);
- It is assumed that the ALFRED based SMFR will employ the same level of availability as ELFR. LEADER DEL003 (Frogheri et al., 2012) mention that ELFR will aim at an availability of 80 to 90%. The mean value of 85% is selected for the G4Econs assessment;
- Relevant core and fuel data is obtained from LEADER DEL007 (Petrovich & Sciora, 2012);
- Insurances and taxes have been taken into account as 0.45% of the (pre-)construction costs as recommended by GIF/EMWG (2007);

3.5 Cost Estimate

3.5.1 From ELFR 2010 to ALFRED based SMFR 2014 cost estimate

The current cost estimate for an ALFRED based SMFR assumes an n^{th}-of-a-kind reactor. The starting point of the current estimate is the top-down cost estimate for the larger scale ELFR as presented by Vazquez & Roelofs (2012) in the frame of the LEADER project. In this analysis the year 2010 was considered as the reference year for the value of money. However, in the current analysis, it was agreed to take the year 2014 as reference year for the value of money. Therefore, the cost estimate for an ALFRED based SMFR is first made with the year 2010 as reference year for the value of money and in a next step the year 2014 is taken as reference year for the value of money. At the same time, this allows for a comparison between an n^{th}-of-a-kind ELFR and an n^{th}-of-a-kind ALFRED based SMFR.

The results of the cost estimates are presented in Table 6. The table clearly shows that the energy generation costs for an ALFRED based SMFR are comparable to the larger ELFR. The analysis shows that this results mainly from the fact that although the construction and O&M costs are larger, the fuel cycle costs for ALFRED are smaller. Probably this is due to the fact that the core design for ALFRED is in a more advanced and therefore optimized state than the preliminary core design which was made for ELFR.

The nominal construction costs including contingencies for an ALFRED based SMFR are in the order of 750 M€.

Table 6: Cost estimate ALFRED based SMFR in comparison with cost estimate ELFR

	Nominal Costs ELFR €2010	Nominal Costs ALFRED €2010	Nominal Costs ALFRED €2014
Engineering, licensing & construction (€/kWe)	4100	4400	**4800**
Engineering, licensing & construction (€/kWe) (incl. first core, D&D, and contingencies)	5200 (3100 M€)	5500 (690 M€)	**6000 (750 M€)**
O&M (€/kWe/a)	110	125	**135**
Fuel Cycle (€/MWh)	8.1	5.4	**5.8**
Energy Generation (€/MWh)	37.5	37.5	**41.3**

3.5.2 Sensitivity Analysis

The influence of the main assumptions is analysed in a separate limited sensitivity study. For this purpose, reasonable bandwidths were assumed for the main assumptions and the influence of their variations on the ALFRED construction and energy generation costs is determined.

Table 7 summarizes the results of the limited sensitivity analysis towards the engineering, licensing and construction costs resulting from the COA based analysis. The analysis clearly shows a large sensitivity towards the scaling and modularity factors. The overall uncertainty is determined to be in the order of 25%, leading to a range in construction costs from 3800 €/kWe as the lower bound to 6100 €/kWe as the upper bound, with 4800 €/kWe as the reference value.

Table 7: Sensitivity with respect to the engineering, licensing and construction costs

Assumptions (lower-reference-upper)	Lower Bound	Upper Bound
Reactor Plant Equipment (90%-100%-110%)	97%	103%
Turbine Plant Equipment (90%-100%-110%)	99%	101%
Modularity Factor (0.58-0.614-0.65)	94%	106%
Scaling Factors (85%-100%-115%)	88%	114%

Within the G4Econs assessment, the uncertainty range was determined by setting optimistic and pessimistic values for each account. The outcomes of this analysis are shown in Figure 3.4 through Figure 3.7. Figure 3.4 shows the engineering, licensing & construction costs ranges with and without inclusion of first core, D&D and contingency costs. The nominal value of 6000 €/kWe corresponds to the cost estimate of 750 M€ for an ALFRED based SMFR.

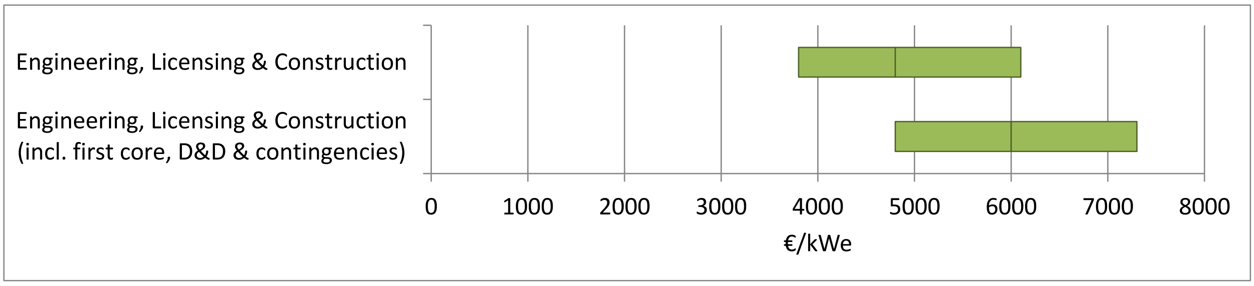

Figure 3.4: Engineering, licensing & construction costs (€2014)

Figure 3.5 shows the O&M costs for an ALFRED based SMFR in comparison with ELFR and a typical contemporary light water reactor (LWR). The nominal value is 135 €/kWe/a which is slightly higher than the O&M costs for a large scale ELFR. Typical operation and maintenance costs for a generic light water reactor plant are considered in the range of 41 to 93 €/kWe/a. This shows that for

ALFRED based SMFR the expected operation and maintenance costs are considerably higher than for a light water reactor plant.

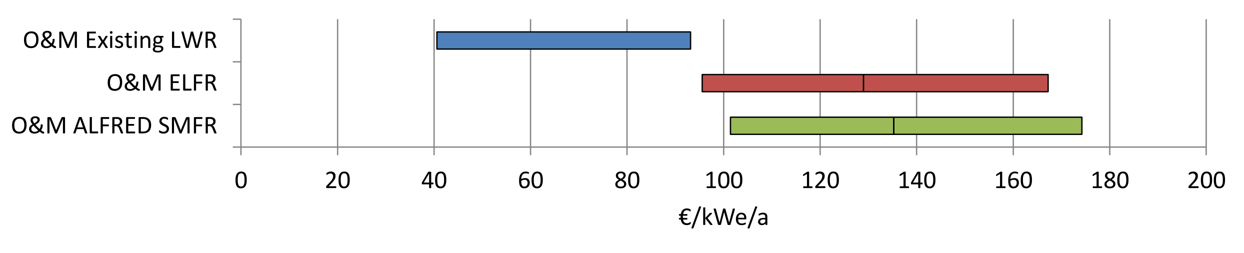

Figure 3.5: O&M costs (€2014)

The fuel cycle costs are depicted in Figure 3.6. The nominal value is 5.8 €/MWh which is lower than the value derived for ELFR. However, as mentioned before, this is probably due to the fact that the core design of ALFRED is more mature and optimized than the ELFR core design. Typical values for a light water reactor are in the range of 6 to 17% of the energy generation costs (OECD, 2005). Assuming energy generation costs of about 60 €/MWh (MIT, 2009) for a typical third generation light water reactor, this would correspond to a range of about 4.2 to 11.9 €/MWh. It is clear that the fuel cycle costs expected for the ALFRED based SMFR are in the same range.

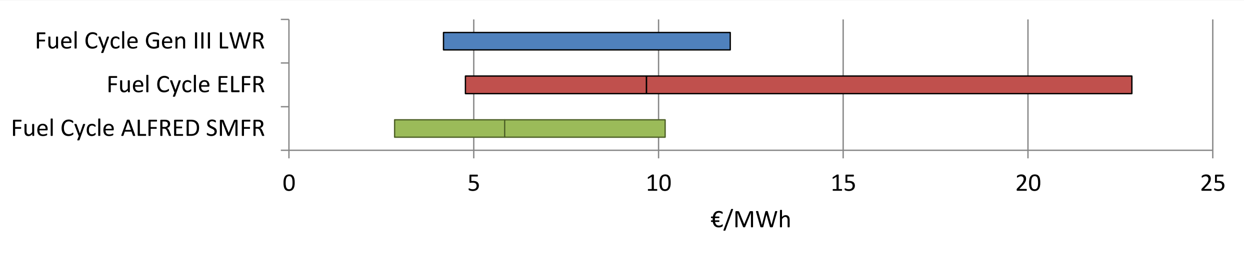

Figure 3.6: Fuel cycle costs (€2014)

The G4Econs tool eventually allows to calculate the energy generation costs for a reactor system and its associated fuel cycle. For the ALFRED based SMFR, this sums up to energy generation costs with a nominal value of about 41.3 €/MWh. This is low compared to the value given for contemporary light water reactors in MIT (2009) which is about 60 €/MWh. However, it should be noted that the latter value includes interest during construction (typically 10%) which is not taken into account in the ALFRED based SMFR cost estimate and which plays an important role.

A sensitivity analysis was performed with respect to the different aspects contributing to the total energy generation costs. Figure 3.7 shows the influence of variations in the different aspects. It can clearly be seen that largest sensitivity rises from uncertainties in O&M costs and in the uncertainty in operational life. Although for the operational life of new generations of nuclear plants typically 60 years is assumed, it can be noticed that taking into account a lower bound of 40 years and an upper bound of 80 years has a significant influence. Most of the other aspects have smaller contributions to the total uncertainty of the energy generation costs.

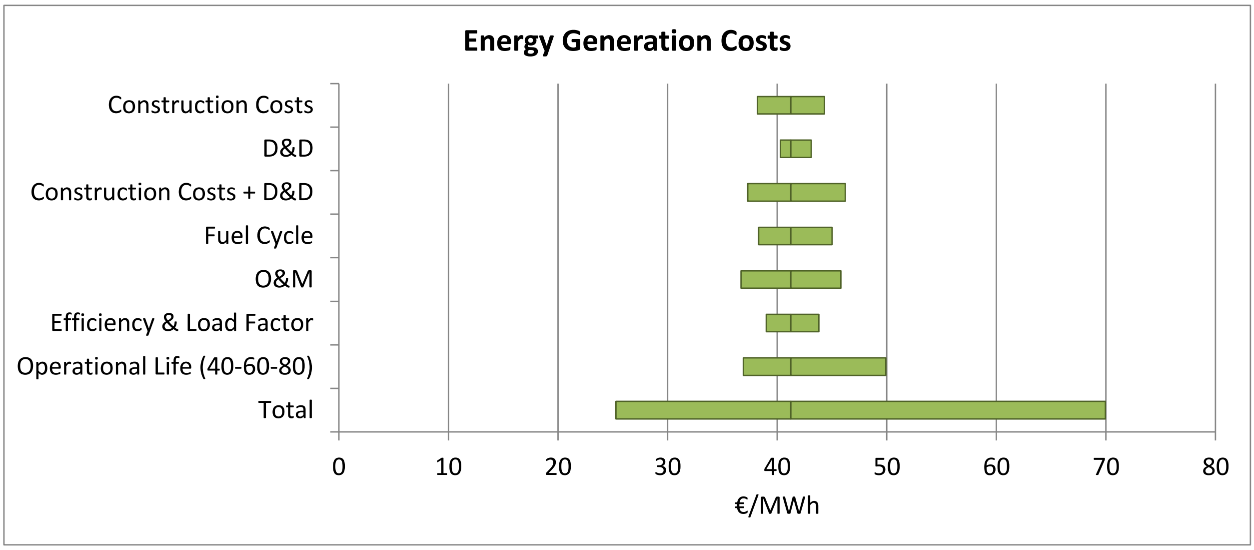

Figure 3.7: Energy generation costs (€2014)

3.5.3 Comparison to ALFRED FOAK bottom-up cost estimate

A comparison can now be made between the current cost estimate and the bottom-up cost estimate made for the first-of-a-kind ALFRED demonstrator reported by Vazquez & Roelofs (2013). In order to have a fair comparison, the assumptions of both cost estimates have to be checked carefully. The bottom-up assessment was performed using 2010 as the reference year for money. Therefore, also this comparison is based on that same reference year.

3.5.3.1 Top-down cost estimate ALFRED FOAK

Table 6 shows that the nominal costs including contingencies for an n^{th}-of-a-kind ALFRED based SMFR were about 690 M€. As the contingencies in this assessment are approximately 20% based on the data provided in Table 5, the nominal costs without contingencies can be determined at about 570 M€.

Subsequently, the cost estimate for the n^{th}-of-a-kind ALFRED based SMFR can be translated to first-of-a-kind costs. OECD/NEA (2000) provides suggestions for the difference between first and n^{th} of-a-kind reactors. Typically this difference is in the order of 84%. On top of that, the only benefit included in the modular construction factor that remains if only a first-of-a-kind is considered, is the so-called 'design factor'. Taking this into account, the nominal costs without contingencies can be determined at about 990 M€. Taking into account contingencies at a level of 20% (Table 5) to 43% (as assumed in the bottom-up cost estimate presented by Vazquez & Roelofs (2013)) this leads to nominal costs in the range of 1200 to 1400 M€.

3.5.3.2 Bottom-up cost estimate ALFRED FOAK

A bottom-up cost estimate for a first-of-a-kind ALFRED demonstrator is reported by Vazquez & Roelofs (2013). They arrive at nominal costs without contingencies of 915 M€. Taking into account 43% of contingencies this lead to a cost estimate of 1305 M€, which is well in the range of the top-down cost estimate including contingencies for a first-of-a-kind ALFRED based SMFR.

3.5.3.3 Summary

Table 8 clearly shows that the first-of-a-kind top-down and bottom-up cost estimates are in the same range of costs which increases the confidence in the methodology of the top-down cost estimate as it is applied for the ALFRED based SMFR.

Table 8: Comparison of top-down and bottom-up ALFRED FOAK cost estimates

ALFRED based SMFR cost estimate	Nominal costs incl. contingencies (M€2010)
Top down n^{th}-of-a-kind	690
Top down 1^{st}-of-a-kind	1200-1400
Bottom-up 1^{st}-of-a-kind	1305

3.6 Conclusions

Using a top-down cost estimate approach, a cost estimate for an n^{th}-of-a-kind ALFRED based SMFR is provided. Confidence in the obtained results is derived from comparison with the bottom-up cost estimate for a 1^{st}-of-a-kind ALFRED demonstrator which was performed during the 7^{th} framework program LEADER project. Both cost estimates are in the same range.

The results show that the nominal costs including contingencies for an n^{th}-of-a-kind ALFRED based SMFR, under the assumptions provided in the report, sum up to about 750 M€. This value excludes approximately 30% uncertainty.

When compared to the cost estimate for the larger scale ELFR as performed within the LEADER project, it is shown that the nominal energy generation costs are comparable. Although the construction and O&M costs are slightly larger as can be expected for a smaller scale reactor, this is compensated by decreased fuel cycle costs. This is probably due to the fact that the ELFR design was not as mature as the ALFRED design.

Compared to contemporary LWRs, the O&M costs are larger. However, it is shown that the fuel cycle costs are expected to be comparable to contemporary LWRs. Finally, the sensitivity study shows a large sensitivity towards operation and maintenance costs and the expected operational life.

4 Economic and financial simulation of SMFRs deployment scenarios in comparison with Large Reactors

4.1 Summary

4.1.1 Approach

The economic viability of SMFR is assessed through the financial analysis of a deployment scenario.

The scenario considers a fleet of 3 GWe corresponding to 24 SMFR (125 MWe each), built on 4 nuclear sites. The deployment occurs over a 20 years time period through a staggered schedule, to distribute the capital investment effort.

A Discounted Cash Flow (DCF) analysis is performed to calculate a set of economic indicators of the project: Internal Rate of Return (IRR), Net Present Value (NPV), average overnight construction cost, Levelized Cost Of Electricity (LCOE), etc.

These indicators provide a synthetic view of the economic performance of the SMFR fleet deployment.

The scenario simulation is run by means of the INCAS Matlab program, developed by Polimi (Boarin, Ricotti et Al. 2012) and specifically intended to catch “the economy of small” and “the economy of multiples” in the NPP investment projects.

This deployment case is compared with two alternative scenarios with the same total power installed:

- 5 ELFR (600 MWe each) on 2 sites;
- 3 GEN III+ AP1000-like LWR (1000 MWe each) on 2 sites.

A comparison is also provided with a fleet of 24 PWR-SMR SMRs having similar power output as the SMFR.

Electricity generation costs of an ALFRED-like, n-th of a kind SMFR have been estimated in Section 3, including construction, O&M and fuel cycle costs. In particular, SMFR construction costs are derived from ELFR by means of a top-down estimation and the application of suitable scaling factors, following the approach recommended by GIF/EMWG for innovative projects in early development stage (GIF/EMWG, 2007).

ELFR construction cost estimation was in turn performed by (Roelofs & Vasquez, 2013).

In this section, the assumptions and key input parameters of Section 3 on construction costs are reviewed and discussed, for the purpose of the economic and financial simulation of deployment scenarios.

New assumptions are formulated concerning the sources of financing, the cost of capital and the deployment schedule.

Finally, the impact of the change in some key input parameters on scenario results is evaluated, in order to provide the sensitivity to the relevant assumptions.

4.2 INCAS Simulation tool

The INCAS (INtegrated model for the Competitiveness Analysis of Small-medium sized reactors) is intended to account for the economic paradigms specific to small sized NPPs, that affect construction costs: learning curve, modularization, co-siting economies, design simplification, etc., together with the loss of economy of scale on the construction costs.

- Learning curve is related to the improvements in the use of equipment, material and labour, with the increase in the number of units deployed on the same site and in the world. The former effect has more weight than the latter in the total learning, since good practices are better retained and replicated at local level.
- Modularization accounts for the process enhancements allowed by modular construction approach, like the parallelization of some fabrication and procurement activities, the standardization and the shop-built efficiencies instead of the stick-built concept.
- Co-siting economies are related to the fixed cost sharing among multiple plant units deployed on the same site. They are not specific to small NPPs, but have greater impact on smaller plants, since, given the same power at site level, a higher number of smaller NPPs can be deployed on the same site.
- Design saving factor is related to layout improvements and innovative solutions that are allowed by the small plant size as compared to the Gigawatt scale with the same technology (e.g. in the PWR domain are: passive safety and reduced active components, integral primary circuit, etc.).

Construction costs are, by far, the main component of nuclear electricity generation costs. Nuclear investment is highly capital-intensive; therefore INCAS devotes special attention to the estimation of construction and financing costs.

INCAS is an investment simulation tool that develops a time-series Discounted Cash Flow analysis. This means that it calculates the time-series development of key accounting prospects, such as the Profit and Loss statement, a simplified Balance Sheet and a Cash Flow statement, with the aim of calculating the Free Cash Flows (FCF) generated by the project.

The key items of the above-mentioned prospects are: revenues, operating costs, asset depreciation, interest expenses, taxes, and net profit. During the plant operation lifetime, an annual provision to a D&D fund is considered, to face the final estimated expense. Revenues are calculated based on the expected capacity factor of the plants and on the long-term forecast of the electricity price. Free Cash Flows are calculated each year from the revenues, net of the investment costs and all the cash-costs (including D&D annual provisions). During the construction period, FCF will be negative, turning to positive values during operations, if revenues are high enough to cover all the costs. FCF represent the net value generated each year by the project for the investors. INCAS calculates the FCF from the perspective of shareholders, which means that cash flows are ‘Free’ of debt obligations: residual cash flow after debt capital repayment and interest expenses is left to the shareholders (i.e. the owners of the NPPs).

The stream of FCF over the project lifetime is discounted to the present in order to calculate the Net Present Value (NPV) of the investment project. ‘Discounting’ or ‘actualization’ of a cash flow relates the time-value of money: today, a given amount of money has more value than the same amount earned in some year in the future (e.g. today, 1000 € has higher value than 1000 € in 10 years). The underlying assumption is that investors can make a positive profit margin r on the 1000 € by investing it in a ‘good’ activity or asset. If an amount X of money is expected to earn r (%) profitability, than its value in one year will be X*(1+r). Conversely, the present value (the value as of today) of next year earning Y, will be Y/(1+r).

This recalls the concept of ‘cost-opportunity’ of the money: the ‘opportunity’ is evident and intuitive and is represented by the chance of making profit; the ‘cost’ of money is less intuitive and is represented by the fact that, by investing money in the SMFR fleet, investors give up the opportunity of making profit from alternative industrial ventures; this is what the nuclear venture will cost to the investors. Therefore, the condition for the investors to undertake the nuclear venture and give up alternative industrial projects is to earn at least the profit margin of a ‘standard’ industrial activity. Actually, they will ask more than this: since the nuclear industry is particularly ‘risky’ as compared to a conventional industrial activity, they will ask to earn a ‘risk premium’ on top of the above-mentioned ‘standard’ profit margin. The result will be considered as the ‘cost’ of the capital of the SMFR investors, i.e. the minimum capital remuneration required for engaging in the SMFR deployment.

This profit margin (r) is embedded in the NPV calculation formula, in the discounting factor at the denominator of each annual FCF:

$$NPV = \sum_i \frac{(FCF)_i}{(1+r)^i}$$

In the case of the plant owners, r will be the cost of equity.

The discounting process brings to the present the current values of money earned by the project each year: each cash flow is evaluated at the same reference (initial) year and summed to give a total value generated by the project (NPV).

The capital remuneration r required by investors represents a sort of ‘bet’ on the project capability to generate value. If such profitability target is not met, then the NPV value will be negative. This does not necessarily means that investors lose their money, but it simply might be that the Free Cash Flows generated by the project provide a profitability r’ which is still positive, but lower than r. In this case, the investment will be profitable, but less than expected/required.

On the contrary, if the NPV is positive, it means that the project will overcome the profit expectations. The positive NPV is the value generated in excess of the remuneration required. In this case, the actual profitability will be r’’ > r.

On the other side, it is possible to calculate the exact value of the profit margin that arises from an investment project, given all the set of boundary conditions and variables (e.g. electricity price, construction cost, cost of debt, etc.). Considering r as a variable rate in the discount factor, that value of r that brings the NPV value to zero will be the exact remuneration rate of the investment project, known as ‘Internal Rate of Return’ (IRR).

NPV is a key extensive indicator of the economic performance of an investment, while IRR is a dimensionless ratio that provides a measure of the profitability, independent of the investment scale.

The calculation of ‘Levelized Cost Of Electricity’ (LCOE) is also based on the Net Cash Flows actualization method. LCOE represents the generating cost of electricity in €/MWh and depends on the cost structure of the plants. LCOE must be set in order to cover the capital costs, operating and fuel costs and D&D annual provisions. It has to be viewed as the minimum electricity sale price, constant over all the period, that allows recovering the above-mentioned costs. It is calculated as follows: electricity price is varied and cash flows are calculated from revenues, net of all the relevant costs. That electricity price able to bring the NPV of cash flows to zero, is defined as the LCOE. Indeed, NPV of cash flows equal to zero means that electricity price is able to cover exactly all the cost items included in the cash flows calculations and to grant the profitability rate required by investors. In the case of the LCOE calculation, the discount rate is the Weighted

Average Cost of Capital (WACC), including the cost of debt and equity, since the financing structure and expenses are not considered in the LCOE calculation. WACC is defined as follows:

$$WACC = K_e \, Eq_{share} + K_d \, D_{share} \, (1 - tax\ rate)$$

Where: Ke is the cost of equity; Kd is the debt interest rate; Eq_share is the equity share in the capital investment: D_share is the Debt share in the capital investment; (1-tax rate) represents the deducibility of interest expenses.

The DCF analysis provides the detail useful to evaluate the self-financing capability of the investment project. This is the use of Free Cash Flows from early-deployed NPPs units to pay the construction of later units of the fleet. Self-financing relieves the negative financial position and reduces the need of new up-front capital investment and, consequently, the investment risk.

Finally, cumulated Free Cash Flows over the investment period provide another useful piece of information: the time needed by the investment project to recover capital costs and start to record positive profit. This turning point is defined as the Pay Back Time (PBT) and is the point in time where the cumulated FCF profile crosses the x-axis.

Table 8 summarizes the calculation of Cash Flows depending on the indicator, with the relevant discount rate.

Table 8: Calculation of the Cash Flow (Free or Unlevered).

	Free Cash Flows	Unlevered Cash Flows
Accounting items considered	- Equity share of Construction cost	- Construction cost
	+ Self-financing	
	+ EBIT	+ EBIT
	+ Asset Depreciation	+ Asset Depreciation
	- Tax	- Tax
	- Debt repayment	
	- interest expenses	
Discount rate applied	Cost of Equity	Weighted Average Cost of Capital
Application	Calculation of investment profitability (IRR) and value generated (NPV)	Calculation of electricity generating cost (LCOE)

INCAS can be used to assess the economic performance of a deployment scenario, given a set of input and assumptions, or it can be used as an optimization tool, to understand which are the assumptions and boundary conditions that make a deployment scenario profitable (i.e. how to comply with suitable profitability targets or financial constraints). INCAS is suitable for the assessment of an investment project based on a single reactor type or a NPP fleet, either on a stand-alone analysis, or in comparison with a different NPP plant type or size.

INCAS has been fruitfully used in the evaluation of several deployment case studies (Boarin, Ricotti et Al. 2011a, 2011b).

4.3 Assumptions

4.3.1 Overnight construction costs

A key input parameter to the INCAS simulation model is represented by the construction cost of a reference plant, which is the basis for the top-down cost estimation and the application of scaling factors. The ELFR (600 MWe) is assumed as the reference plant for the SMFR cost estimation.

The INCAS code calculates the construction cost of each SMFR of the fleet, based on the reference ELFR cost and on the application of scaling factors that are specific to the progressive unit number in the deployment program and to the siting strategy. The construction cost figure for every SMFR in the fleet is not unique, but it is different for each progressive NPP unit, with a decreasing value on account of the learning effect and on the co-siting economies.

In Section 3, the ELFR reference cost is 4100 €/kWe (expressed in 2010 currency value), excluding D&D, contingencies and 1st core. This figure is the outcome of a previous work of (Roelofs & Vasquez, 2013), where a cost scaling process was applied to a reference AP1000 LWR and whose construction cost was assumed equal to 3200 €/kWe (NOAK, in 2010 currency value).

That reference value was first adjusted to account the loss of economies of scale from 1100 MWe to 600 MWe in the same LWR technology domain, then further adjusted to account for the cost differences due to the lead technology. These two steps correspond to an overall factor of 1.47x on the construction costs, moving from a single AP1000 to a stand alone ELFR unit.

Finally, an overall 87% "modular scaling factor" was applied to account for learning, modularization, co-siting and design economies from the reference plant size of 1100 MWe down to 600 MWe. The total scaling factor between the AP1000 and the ELFR unit construction cost was 1.28 (Table 9). Alternatively, a value of 5200 €/kWe (in 2010 currency value) is provided as overnight construction cost of ELFR, including contingencies, 1st core and D&D fund at 30% of actual construction value.

Table 9: Estimation of construction cost of ELFR (values at 2010) – see Section 3

AP1000 Reference cost €/kWe	Scaling factor for EoS & lead technology	ELFR Intermediate result €/kWe	Modular scaling factor (Learning Modularization Multiple-units Desing)	Overall Scaling factor	ELFR Final result €/kWe
3200	1.47	≈ 4700 (3200x1.47)	87%	1.28 (1.47x87%)	4100 (i) (3200x1.28) 5200 (ii)

(i) NOAK, excluding contingencies, 1st core and D&D fund

(ii) NOAK, including contingencies, 1st core and D&D fund

Table 10: Estimation of construction cost of ELFR, considering NOAK and including contingencies and 1st core, but excluding D&D funds (values at 2015)

AP1000 Reference cost, FOAK €/kWe	AP1000 Reference cost, NOAK €/kWe	Overall Scaling factor ELFR/AP1000	ELFR Final result €/kWe
4700 *(i)*	3950 (84% of NOAK)	1.28	5040(ii) (3950x1.28)

(i) *Assumed to include contingencies and 1st core, but excluding D&D funds, financing and transmission.*

(ii) *NOAK, including contingencies, 1st core and excluding D&D fund*

Table 10 summarizes the ELFR cost estimation starting from an updated reference value of an AP1000 reference plant. The cost information about the Vogtle and Summer plants under construction in the US, give an average value of 4700 €/kWe, in 2016 currency value (The State, 2015, 2016; WNO 2016), excluding financing and transmission, which is in accordance with the average overnight unit construction costs calculated by OECD/NEA (OECD-NEA, 2015) in Western Countries. It is assumed that the Vogtle and Summer cost data include contingencies. It is also reasonable to assume that the 4700 €/kWe figure includes 1st core and excludes D&D cost. This is in accordance with the INCAS algorithm that treats D&D separately from construction costs.

Nevertheless, this value represents a FOAK cost estimate (at least in Western Countries, excluding new build in China) and therefore it is reduced to 84% to get the NOAK figure, using the same corrective factor suggested by (GIF/EMWG, 2007). Then, the same overall scaling factor used in (Roelofs & Vasquez, 2013) is assumed, i.e. 1.28x, to scale from a 1100 MWe LWR to a 600 ELFR.

This gives a unit overnight construction cost of 5040 €/kWe for a 600 MWe ELFR, which becomes the reference cost used by INCAS to calculate the SMFR fleet construction cost. It is assumed that the incidence of the inflation on the different time-values of currency is negligible compared to the order of magnitude of the capital cost amount for the construction of an NPP.

4.3.2 Scaling factors

Within the same lead reactor technology, the construction cost scaling from 600MWe to 125MWe NPP produces a unit cost increase of about 81%, due to the loss of Economy of Scale. According to the so-called Economy of Multiples, SMFR should recover from other benefits linked to their smaller size and number of units.

Modularization factor is set equal to 90%, meaning that very limited modularization enhancement can be achieved by pool-type lead plant, scaling from the 600 MWe ELFR to the 125 MWe SMFR concept, based on the current design status

As far as design savings are considered, SMFR is not expected to present relevant technical improvements in layout or systems simplifications versus the pool-type ELFR. No design saving factor will therefore be considered (design factor=1x).

These two assumptions are very conservative compared to the PWR domain and are based on the current design status. Further modularization and design savings thanks to simplified design choices, reduced safety margins, higher performances could be engineered with the progress in the knowledge of the LFR technology and with the development of a regulatory framework more specific to the small sized plants, encompassing advanced reactors and innovative technologies. The weight of these two factors on the project economics is very sensitive and will be highlighted in section 4.4.2

As said in 4.3.1, according to the INCAS approach, construction learning and co-siting economies reduce the construction cost of each SMFR plant in the fleet at a different extent, depending on the number of plants already built (i.e. the “learning” cumulated until the construction of the next SMFR) and on the number of plants deployed on a single site (co-siting economies).

Figure 4.1 (right) shows the cost reduction from learning effect, with increase in the number of NPP built on the same site and on other sites in the world. When NPP are built on a new site, construction cost will benefit from the experience gained on previous sites, but some learning is lost and then gradually built-up again at site level; this explains the saw tooth shape of the curve.

Figure 4.1 (left) shows the cost reduction arising from the construction of multiple units on the same site, with a maximum of 6 NPPs on a site, like in the SMFR scenario.

As a result, each SMFR will have a specific learning and co-siting economy factor different from the other plants in the fleet. As a consequence, each plant will also have a different overnight construction cost. An average figure will be provided as representative value. The INCAS approach to the scaling factor is plant-specific and substitutes the application of a 62% overall “modularization scaling factor” to the whole fleet. Table 11 summarizes the scaling factors applied on the reference ELFR to calculate the construction cost of a specific SMFR. The overall scaling factor from a single ELFR to each of the 24 SMFR in the fleet is shown in Fig.4.2 (left).

In the case of PWR technology, the size reduction allows significant design simplifications and the enhanced application of passive safety, with reduced active components and streamlined system layout. This is already visible in the design developed by PWR-SMR vendors worldwide: PWR-SMRs present integrated primary system and significant construction modularity by-design. This is expected to provide cost benefits in the construction phase. As far as the licencing regulations will accommodate the SMR distinctive features in terms of design improvement, these cost savings would be enabled. Quantification of factors in SMRs/large plant comparison provided in (M. D. Carelli, 2007), points at 0.83 design specific factor. This saving factor has been evaluated on the basis of the IRIS concept, but the analysis and conclusions are applicable to the whole spectrum of small nuclear plants in the iPWR domain.

Table 12 summarizes PWR-SMR specific scaling factors applicable to the top-down construction cost estimate from an AP1000 reference plant, to a multiple PWR-SMR fleet.

Table 11: Scaling factors applicable to the top-down construction estimate from a single ELFR to multiple SMFR

Economy of Scale	Modularization	Design	Learning	Co-siting
1.81x	0.9x	1x (no change)	Plant-specific (Fig 4.1, left)	Plant-specific (Fig.4.1, right)

Table 12: Scaling factors applicable to the top-down construction estimate from a single AP1000 to multiple PWR-SMR

Economy of Scale	Modularization	Design	Learning	Co-siting
2.2x	0.71x	0.85x	Plant-specific (Fig 4.1, left)	Plant-specific (Fig.4.1, right)

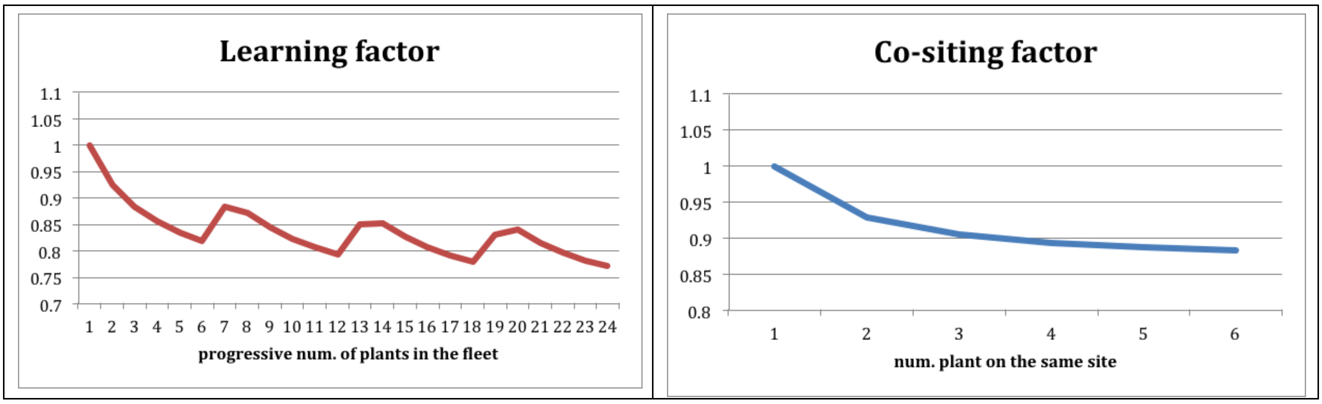

Figure 4.1: Learning and co-siting factor values with multiple NPPs

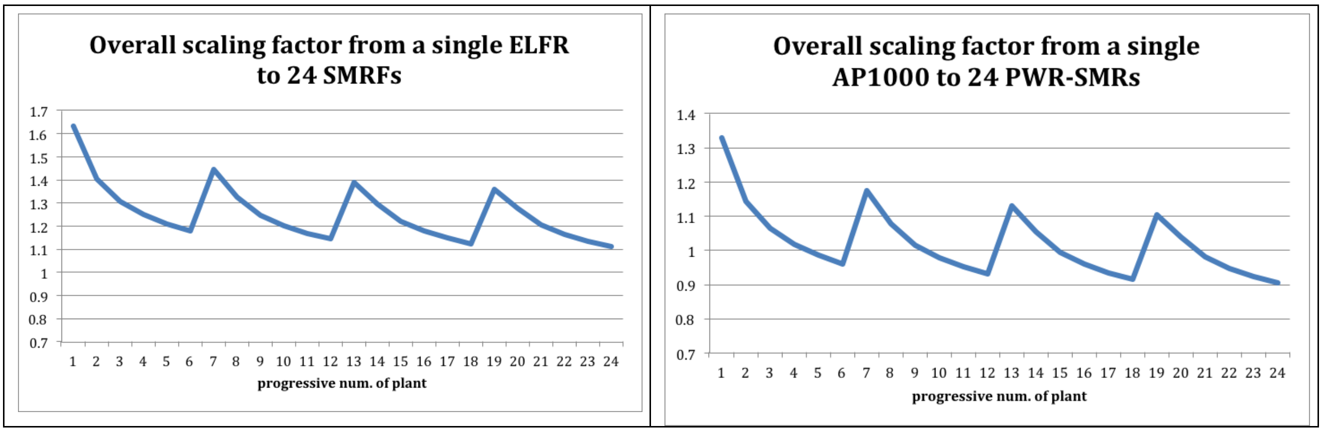

Figure 4.2: Overall scaling factor values from a single ELFR to each of the 24 SMFR (left) and from a single AP1000-like to each of the 24 PWR-SMR (right)

4.3.3 Other assumptions

Plant availability is a sensitive parameter for the project economics, since it affects the revenue stream; section 3 provides the assumptions for plant availability, O&M and fuel costs for lead technology (ELFR and SMFR). Higher O&M cost of smaller NPPs compared to larger plants are coherent with an expected loss of economy of scale that affects the operating costs as well (Mario D. Carelli, 2008). A plant availability of 90% is here assumed for the SMFR in the reference case (in line with the ESNII key performance indicators for LFR and with the upper bound of the range considered for the ELFR – see Section 3.4.6); plant availability is one of the parameters whose effect is analysed through sensitivities in Section 4.4.2.

O&M costs of a smaller plant are affected by a loss of economy of scale on a single plant basis. When multiple SMR are deployed on the same site, some of this loss of economy of scale could, in principle, be recovered through the sharing of some fixed structures and personnel.

Available studies on nuclear O&M cost for SMR (Trianni A., 2007) highlighted that, in the US framework, there were no significant savings from multiple SMR deployment since regulatory safety requirements prevent the sharing of structures/personnel. This is a potential cost saving area that would be enabled by a licensing approach specific to the SMR.

O&M and fuel costs for AP1000 are taken from (EIA, 2016), with reference to the advanced nuclear technology entering service in 2022. They include back-end costs, such as used fuel storage or disposal in a waste repository. Due to the lack of specific data, fuel cost of a PWR-SMR is assumed equal to the AP1000.

Plant availability of AP1000 is in line with advanced passive PWR, including forced and planned outages; PWR-SMRs are expected to offer the highest available factor (95%).

Plant lifetime of advanced PWRs is 60 years, without the reactor vessel replacement. The same values are assumed for PWR-SMR.

Conversion efficiency is not considered by INCAS, since all the cost values are related to the electric output of the plant.

Decommissioning cost is represented by annual contributions to a sinking fund during all the plant operating life, to face D&D expense of 15% of construction cost. This is in accordance with (OECD-NEA, 2015) and (EIA, 2016). The discount rate for the D&D fund 3% (as appropriate for trust fund management) and that the fund earns a rate of return over the plant's lifetime (in line with a risk free rate, e.g. 2%). Because of the long lifetime and the return on the fund, the annual contribution is thus a small part of a nuclear power plant's LCOE.

The shorter plant lifetime of AP1000 makes the unit contribution to the D&D slightly higher than the lead technology. Nevertheless, the impact of the operating, fuel and D&D costs on the project economics are not paramount, as shown in section 4.4.2.

Table 13: Other assumptions, plant-specific

	SMFR	ELFR	AP1000-like	PWR-SMR
Plant availability	90%	85%	93%	95%
Operating life (y)	80	80	60	60
O&M (€/MWh)	16.8	14.8	11.5	13.8
Fuel cycle (€/MWh)	5.8	8.1	10.5	10.5
D&D (€/MWh)	2.4	1.9	2.0	2
Construction period	5y	6y	6y	4y

4.3.4 Financial assumptions

Information about the mix of financing sources and on the cost of the different sources of capital of nuclear investment projects is generally undisclosed. Usually, the percentage of debt is inversely proportional to the investment risk. Debt holders (i.e. banks) want to avoid risks and engage only if some risk mitigation mechanism is in place. Political decisions have a relevant impact on the investment scenario and conditions; if an investment project is backed by public institutions (e.g. through export credit, state guarantees on the debt, or even a direct participation in the investment), the investment risk decreases. As an example, in the Olkiluoto-3 EPR investment case, long-term electricity price sale contracts have been set up to off-set the market risk (possible decrease in the electricity price over time). French and Swedish governments provided export credit guarantee; finally, the EPC contract was 'turn-key', with the construction risk placed upon the vendor. On paper, the "Finnish" model offered such a low financial risk that lenders engaged for a majority stake of the total capital investment, with a very low cost of capital (2.6% interest rate on 60% of debt issued) (Grant Harris, August 2012).

On the other side, if an investment is more exposed to the rules of free markets, shareholders have to engage the majority stake of the capital investment: the higher the financial risk, the higher the engagement of equity investors in the business.

It can be assumed that lead-cooled Gen-IV technology would meet the support of public institutions for being considered strategic in the energy generation portfolio of the host country: in this case, the investment risk profile would decrease, increasing the share of debt and decreasing its cost. On the contrary, without any specific information about the political and financial framework, the assumption can be made of a 50% equity/debt contribution to the capital investment and a capital cost at the higher bound of the assumption range.

Concerning the cost of the sources of capital, the interest rate on bank loans is always lower than the cost of equity, due to the fact that equity investors (the "owners of the plant") bear higher risk in the venture: lenders have a priority in the capital and interest recovery over shareholders. If the cash flows generated by the investment project are high enough to pay the debt obligation, a residual is left for shareholders; otherwise, banks must be paid anyway (e.g. making new debt or providing new equity capital) and shareholders might record a net loss of capital. Lower financial risk corresponds to lower cost of capital (which, as said in section 4.2 is the capital remuneration required to engage in the project). For the purpose of this analysis, 5% cost of debt and 15% cost of equity are assumed (in real terms), that correspond to an average cost of capital of 9.3% (WACC, Weighted Average Cost of Capital). Lower cost of debt (4%) could be assumed if risk mitigation condition would be in place. This result is in line with the (OECD-NEA, 2015) recommendation for the use of a 10% discount rate (corresponding approximately to an investment in a high-risk environment).

Inflation rate is set to 1% over the investment horizon. Inflation rate represents the rate of increase of all the costs and of the electricity price as well. The value has been assumed averaging the high volatility and the decreasing trend evident in the last 5 years (Figure 4.3).

Table 14: Financial assumptions for the deployment scenario simulations

	Input values
Capital sources: D/(D+E)	60-50%
Cost of debt	4-5%
Cost of equity	15%
Inflation rate	1%
Debt amortization period (y)	10
Depreciation for fixed assets (y)	20
Tax rate	30%

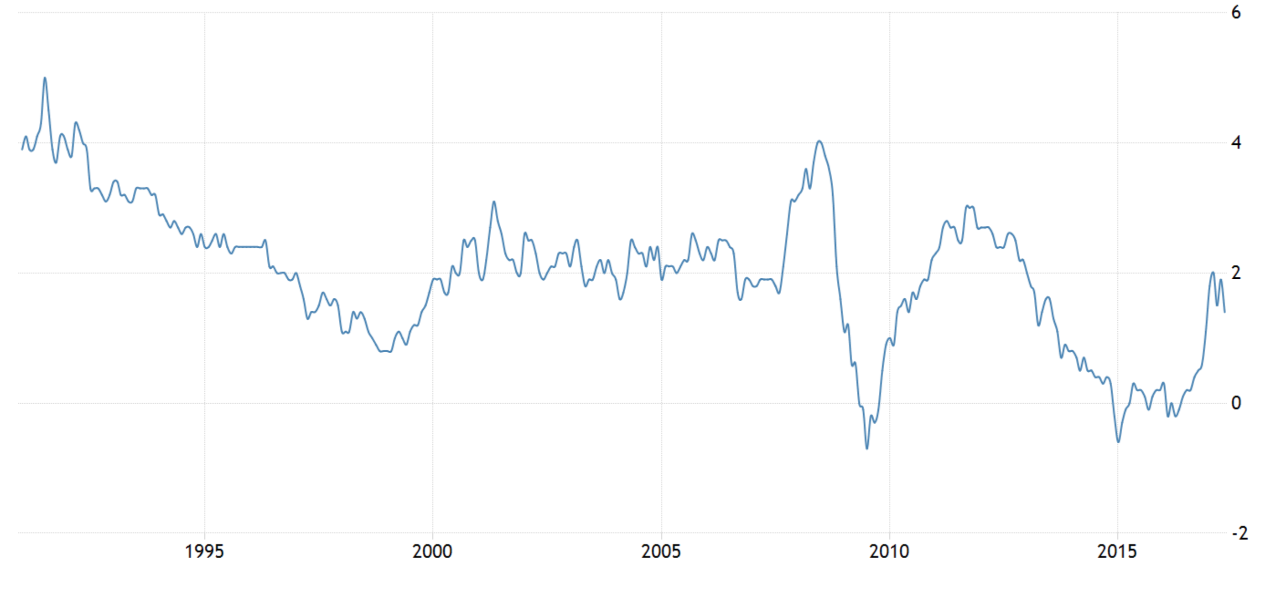

Figure 4.3: Euro zone, inflation rate (Tradingeconomics)

4.3.5 Construction schedule

The 3 GWe deployment scenarios are set up as in Table 15 and construction schedules are presented in Figures 4.4 to 4.6.

- 24 SMFRs or PWR-SMR (12 twin plants) distributed on 4 sites
- 3 AP1000-like plants on 2 sites (1000 MWe)
- 5 ELFRs on 2 sites

Construction schedule of PWR-SMRs follows the same pattern illustrated in Fig. 4.4 for SMFRs.

Table 15: Deployment scenarios strategy

	MWe per NPP	num sites	site 1: num NPP	site 2: num NPP	site 3: num NPP	site 4: num NPP	num tot NPP	MWe tot installed
SMFR	125	4	6	6	6	6	24	3000
power per site			750	750	750	750		3000
AP1000-like	1000	2	1	2			3	3000
power per site			1000	2000				3000
ELFR	600	2	2	3			5	3000
power per site			1200	1800				3000

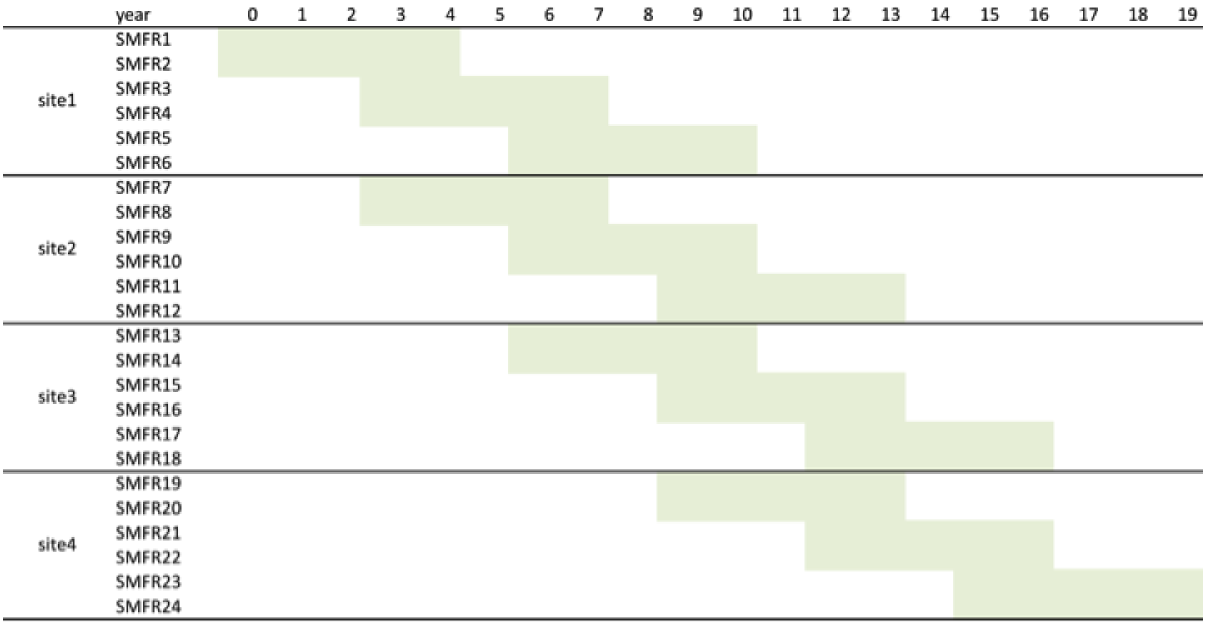

Figure 4.4: Deployment schedule of SMFR and PWR-SMR

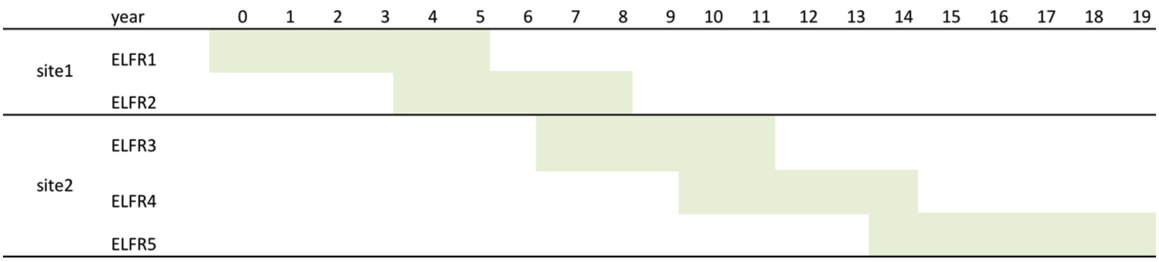

Figure 4.5: Deployment schedule of ELFR

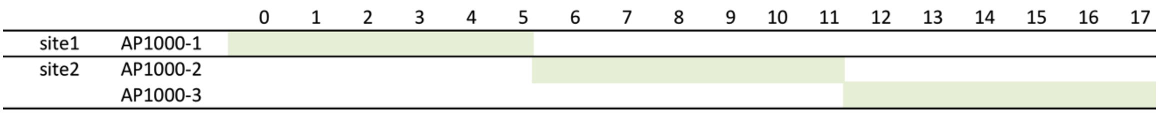

Figure 4.6: Deployment schedule of AP1000-like

4.3.6 Case studies

Table 16 summarizes two different case studies on SMFR deployment.

Base-Case considers the top-down estimate of SMFR construction costs that follow the assumption in sections 4.3.1 and 4.3.2: those assumptions produce the expected value of SMFR construction costs, given the current available information and concept development status. Base-Case also considers that NPP is 'price-taker' on the electricity market, as expected for a base-load power technology, and that the electricity price is free to decrease or increase according to changes in the offer/demand equilibrium over time. In absence of very-long term forecast of electricity market price value, the current average electricity price in the Euro zone is assumed. As a consequence of these volatile conditions on the revenue side, the capital remuneration would be set at a high value (i.e. 5% interest rate on bank loans and 15% equity remuneration).

Best-Case assumes a long-term contract for the electricity price, which is set to a fix higher value. The reference considered is the Contract for Difference (110€/MWh) agreed between Hinkley Point C nuclear power station and the UK government.

In this case, the effect of favourable political framework and public support decreases the investment risk and the cost of debt at 4%. The debt stake in the capital investment is raised at 60%. Also, a more extensive re-engineering of the SMFR concept is supposed to enable further capital cost savings:

- Design modularisation is enhanced, allowing 15% cost savings in procurement and construction (modularization saving factor=0.85x)
- Design and layout simplification, and new technical solutions to decrease plant complexity will enable 10% savings (design saving factor=0.9x)

Table 16: Summary of key assumptions in Base-Case and Best-Case investment scenarios

Key input values	Base-Case	Best-Case
Capital sources: D/(D+E)	50%	60%
Cost of debt	5%	4%
Electricity price (€/MWh)	40	110
Modularization factor for SMFR	0.9x	0.85x
Design saving factor for SMFR	1x (no savings)	0.9x

4.4 Results

4.4.1 POLIMI scenario for SMFR

In Base-Case, the SMFR deployment project is not economically viable: electricity price is not able to cover the debt service (interest and principal repayment) that grows tremendously during the 20-year construction period. Generally, the pattern of cumulated Free Cash Flows of an investment project, starts from negative values, due to the investment costs, and gradually turn to positive values, when the plant enters in operation and revenues from the electricity sale progressively repay the investment. In the Base-Case cumulated cash flows never become positive, but diverge to negative values. This means that electricity price of 40 €/MWh does not provide revenues high enough to cover capital costs, operating and financial expenses. Average unit construction cost of the first SMFR in fleet is in the order of 8230 €/kWe, that decreases to 6320 €/kWe considering the whole fleet, due to co-siting and learning economies. Cash outflow are systematically higher than cash inflows and debt grows disproportionately (Figure 4.7 and 4.9): the investment project goes into bankruptcy.

NPV is large and negative; no IRR can be calculated, since no positive cash flows will ever be earned. Therefore, by definition, the project cannot grant any profitability.

Electricity generating cost at 144 €/MWh is able to cover construction, capital remuneration and operating costs.

The economics improve in Best-Case. Raising the electricity price at 110 €/kWe makes the project profitable, but with a profit rate still too low to be acceptable by shareholders: 11.5% (< 15, which is the cost of equity). In Best-Case NPV of the investment is still negative (-1016 M€), but this time it does not mean that investors lose their money, as in Base-Case.

Since positive profitability is got, negative NPV simply means that profitability rate is lower that the discount rate applied to the net cash flow actualization (i.e. 11.5% is lower that 15%). Therefore, negative NPV means that investors get lower profitability than expected or required. Figure 4.10 shows that the bank loans are gradually repaid.

In Best-Case, LCOE is 102€/MWh, since construction costs are significantly lower and have a lower incidence on generating cost of electricity. In this case, construction cost savings are enabled by additional design simplifications and enhanced modularisation, bringing average unit construction cost of SMFR fleet at 5340 €/kWe (7000 €/kWe for the first SMFR).

Cumulated cash flows become positive in year 21, meaning that the investment costs are recovered and that the project starts to become profitable (Figure 4.8). The investment pay back period in Best-Case is in line with the investment time scale (20 years). The smaller the sized of NPPs, the more 'modular' the investment is, allowing shorter capital recovery. Short Pay Back Time means lower investment capital exposure and this decreases the investment risk, as compared to large sized plants.

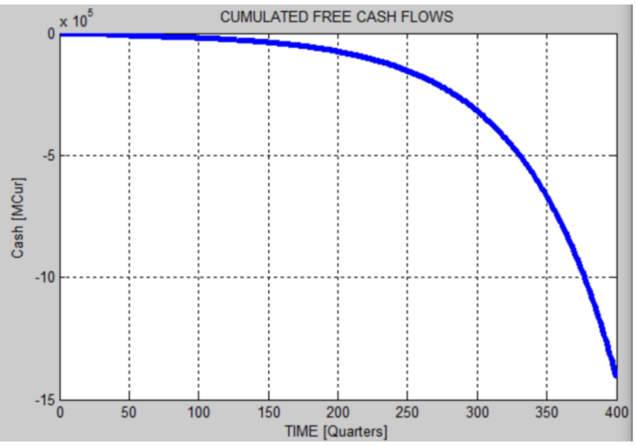

Figure 4.7: SMFR Base-Case; cumulated free cash flows

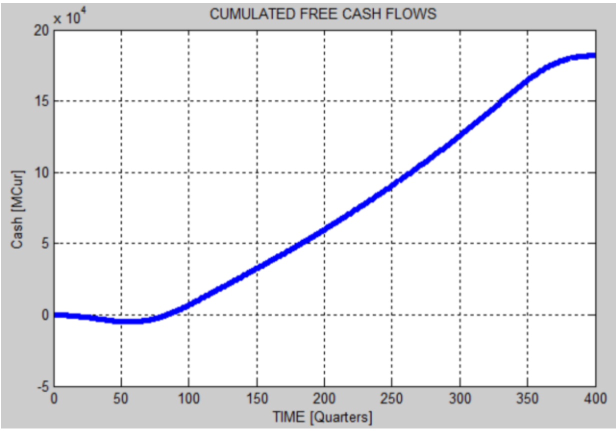

Figure 4.8: SMFR Best-Case, cumulated free cash flows

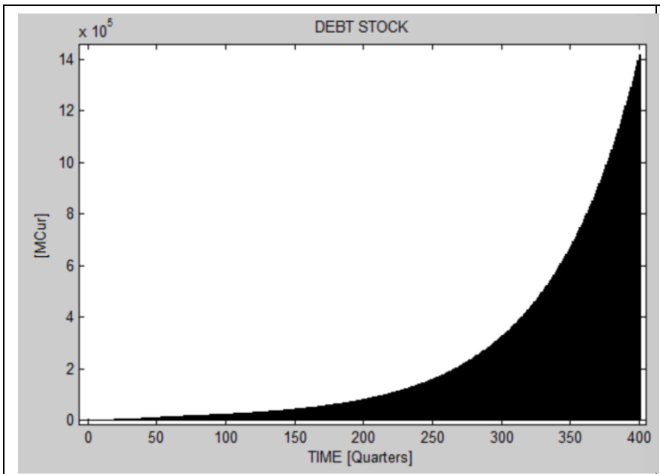

Figure 4.9: Debt stock exponential growth in SMFR Base-Case

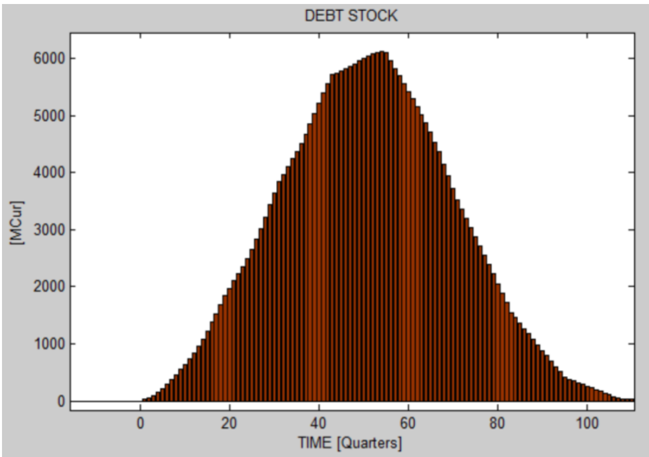

Figure 4.10: Debt stock repayment in SMFR Best-Case

Figure 4.11 shows that self-financing contribution is 16% of overnight construction costs; this means that 16% of construction cost is paid by re-investing in the residual cash flows from the electricity sale of early deployed units. The need of up-front equity or debt investment is reduced by the same extent. Self-financing contribution is more relevant in the financing of the last units on each site (6 NPP per each of the 4 sites) and at the end of the 20-years investment period, when Free Cash Flows become more significant (Fig.4.12).

Results comparison between Base-Case and Best-Case is summarized in Table 17.

Since Base-Case does not produce any positive profitability, Best-Case will be used to perform sensitivity analysis of key input assumptions on the economics. In Best Case all the economic indicators can be calculated and therefore the sensitivity analysis will provide information on the magnitude of their improvement or deterioration due to a different assumption on input values. Of course, those results will be applicable with SMFR average unit construction assumed for Best-Case, that are significantly lower than estimated in Base-Case (5340 €/kWe versus 6300 €/kWe).

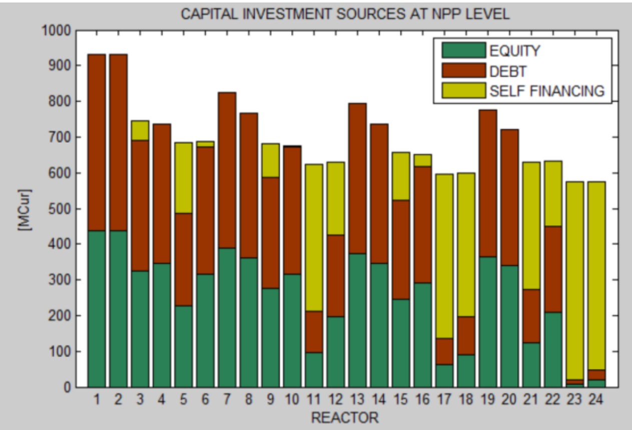

Figure 4.11: SMFR Best-Case: capital investment sources per each plant

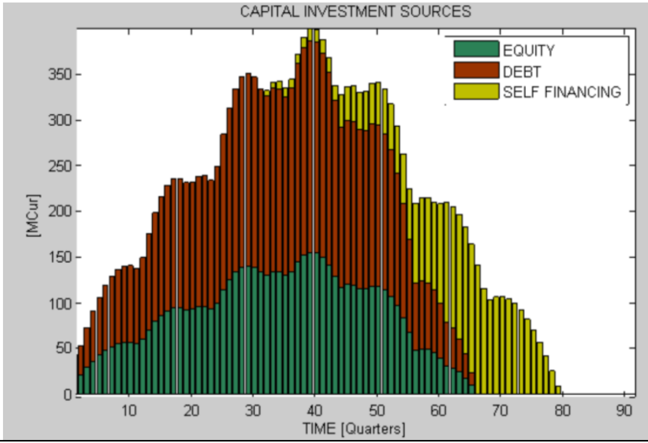

Figure 4.12: SMFR Best-Case: capital investment sources in time

Table17: Comparison between Base-Case and Best-Case

	Base-Case	Best-Case
LCOE (€/MWh)	144	102
IRR (%)	Bankruptcy	11.5%
PBT (y)	No investment recovery	21
NPV (M€)	-3562	-1016
Avg. cost of 1 SMFR (M€) (i)	785	668
Unit avg. construction cost (€/kWe)	6320	5340

(i) Including inflation over the construction period.

4.4.2 Sensitivity

Given the current SMFR concept development status, Best-Case construction costs are not supported by any plausible assumptions and therefore, sensitivity analysis is not to be assumed as information on possible economic performance of SMFR fleet deployment, but rather as information on the impact of different input values on the investment economics. Sensitivity analysis in this section indicates those input that have the main relevance in the improvement of the economics and that, for this reason, represent the key area of enhancement in the development of the design technology and in the set-up of an investment case.

Table18: Sensitivity of Best-Case: operating parameters

	Fuel cost +17% (=6.8 €/MWh)	Availability [75 ; 95%]	O&M cost +17% (=19.6€/MWh)	Avg. Constr. Costs = 6320€/kWe	D&D cost +100% (=4.8€/MWh)	Electricity price +17%= (=91.7 €/MWh)
LCOE (€/MWh)	103	123 ; 97	105	116	105	102
IRR (%)	10.4	9.0 ; 12.2	11.1	9.8	11.2	9.0
NPV (M€)	-1039	-1484 ; -851	-1089	-1590	-1079	-1484
PBT (years and months)	21y+3m	24y + 9m ; 20y	21y+6m	23+6m	21y+6m	24y+9m

Table 19: Sensitivity of Best-Case: financial parameters and plant lifetime

	Debt/(Debt+Equity) =50%	Inflation [0-3%]	Cost of debt [2%-6%]	Plant lifetime 60y	Constr. Duration 4y
LCOE (€/MWh)	121	104 ; 100	92 ; 113	103	99
IRR (%)	11.3	10.4 ; 13.4	12.2 ; 10.5	11.5	12.0
NPV (M€)	-1198	-982 ; -1073	-827 ; -1229	-1016	-958
PBT (years and months)	20y+6m	21y+3m ; 20y+6m	19y+9m ; 22y+6m	21	19y+9m

Tables 18 and 19 present a sensitivity analysis on some operating and financial assumptions separately.

Among the operating parameters, availability rate has a disruptive impact on the whole project economics: 17% deterioration of plant availability (from 90 to 75%) increases the LCOE from 102 to 123 €/MWh. This is due to the fact that all the costs must be charged on a reduced electric output, increasing the minimum price at which the costs can be recovered. The availability rate plays also a key role in the investment profitability (IRR) and on the economic value created (NPV), since it determines the revenues stream of the project. In particular, the project loses 2.5% profitability rate (=11.5%-9%). On the project investment scale translates in a loss of 468 M€ (=difference among -1484 and -1016 M€ NPV).

The opposite happens when availability rate of SMFR is increased to 95%: huge economic benefits are enabled. Generating cost may be decreased to 97 €/MWh, profitability reaches 12.2% and the whole investment is recovered in 20-year period, due to higher revenues generated by early deployed SMFR units. Construction of last SMFR units in the fleet may be completely self-financed.

The same 17% decrease applied to the electricity market price (91.7 rather than 110 €/MWh) produces the same effects than a 17% decrease in plant availability, since both have the same impact on the revenue stream. Nevertheless, a decrease in electricity price does not change the LCOE, since the latter depends on the cost structure of the project and not on the revenue stream.

On the other hand, the SMFR project can absorb a 17% increase in the O&M or in the fuel costs with much lower impact in terms of profitability decrease and LCOE increase. Sensitivity of generating costs to O&M and fuel costs is very low. D&D costs can be doubled (corresponding to a total expense of 30% of construction cost) without significant impact on the project economics.

Sensitivity to construction cost is very interesting: the value is set to the Base-Case, with all the other inputs set to the more favourable Best-Case. This means that, if no further saving were achieved on the SMFR construction cost, this sensitivity allows evaluating the economic benefit brought by the enhancement of the following boundary conditions altogether: better capital structure with higher stake of debt (60 rather than 50%), lower interest rate on debt capital (4 rather that 5%) and long-term sale contract for electricity with a 'supported' fixed price (110 rather than 40 €/MWh). Results show that the investment project could turn from Base-Case bankruptcy into a profitable venture (IRR=9.8%).

Sensitivity on financial parameters shows that generating cost is very dependent on capital structure and capital cost. Decreasing the debt share (i.e. increasing the equity share) of the total investment means increasing the average cost of capital, since the incidence of the cost of equity increases respect to the cheapest cost of debt. The same happens when the cost of debt increases. Since the cost of capital represents the capital remuneration rate required by investors, in these cases LCOE must also increase to cover the increased capital remuneration rate. It has to be highlighted that 2% decrease in the cost of debt has a huge positive impact on the project economics. These results lead to the conclusion that public support on a SMFR deployment project focused to mitigating the investment risk (thus enabling higher stake of debt capital investment and lower cost of debt), would have a significant social benefit, decreasing significantly the LCOE, which is the minimum sale price for the electricity produced by the plants.

Longer operating lifetime of SMFR does not cause a relevant improvement in the economics, since very far amount of money have negligible present value when evaluated at reference year '0'.

On the contrary shorter construction duration grant significant financial improvements: profitability rises by 0.5% and LCOE decreases from 102 to 99 €/MWh. On account of these results, it represents a very important goal for the engineering and supply chain management enhancement.

Finally, it has to be highlighted that inflation has some incidence on the project profitability, due to the very long time-horizon and the impact on the cost and revenues distributions in time: an inflation increase improves the project economics.

4.4.3 Deployment scenarios of ELFR, AP1000-like and PWR-SMR

The deployment simulation of alternative reactor fleets shows that, in the Base-Case, with electricity price equal to 40€/MWh, none of the scenarios is profitable. The best cost-structure is the AP1000-like, as demonstrated by the lowest LCOE. The LCOE calculated in the SMFR scenario is too high and out of the market. Due to learning and co-siting economies, the average unit construction cost of SMFR (6320 €/kWe) is 76% of the first stand-alone SMFR (8230 €/kWe), but despite this, construction costs are still too high to make the project economics comparable with the AP1000 and ELFR.

The four alternative investment technologies are also evaluated in Best-Case boundary conditions, with electricity price at 110 €/MWh, 4% cost of debt and 60% debt stake (see first 3 rows of Table 16). For the purpose of this comparison, SMFR are presented twice to account specifically for the impact of modularization factor and design saving (see last 2 rows of Table 16): with Base-Case construction costs (SMFR-1, with average 6320 €/kWe, according to assumption in sections 4.3.1 and 4.3.2) and with Best-Case construction costs (SMFR-2, with average 5340 €/kWe).

Results on total capital investment are also presented and analysed to highlight the contribution of self-financing and the weight of financial interest. Maximum outstanding capital is the lowest point in the cumulated FCF curve that represents the maximum capital invested, before getting any positive earning from the commercial deployment of the first NPP unit of the fleet. The higher this amount, the higher is the financial risk.

At first glance, Table 21 shows that SMFR are not competitive with the other technologies, in terms of generating cost. With Base-Case construction costs, SMFR-1 investment case is not attractive compared to ELFR, since the plant scale reduction is not accompanied by significant design change and related cost savings. In SMFR-2, construction costs are still higher than other technologies and LCOE increases to cover this cost component. Learning and co-siting effects have their higher impact on the very first units of a fleet and for this reason construction cost of ELFR reduce from 5040 €/kWe (single unit) to average 4420 €/kWe for the fleet of 5.

High construction costs undermine profitability in SMFR-1, while, if 5340 €/kWe unit average cost was achievable, profitability, NPV and PBT would be in line with ELFR.

Design and modularization factors around 0.8x and 0.85x respectively (i.e. 20% and 15% saving factors compared to reference ELFR cost) are necessary to SMFR to achieve 12.8% profitability, in line with PWR technology, and LCOE of 93.8 €/MWh. This would correspond to an average unit construction cost of 4747 €/kWe.

Lower availability rate of ELFR compared to PWR technology (85% versus 93% and 95% for AP1000-like and PWR-SMR respectively) explains lower profitability and higher LCOE. Also, due to higher availability rate and consequent higher revenue stream, PWR technology grants shorter Pay Back Time than lead fast reactors. This happens despite ELFR construction cost is almost in line with AP1000-like or even lower than PWR-SMR.

PWR-SMR show the highest profit margin (13.9%) despite construction cost higher than AP1000-like and ELFR fleets (14.3 versus 13 and 13.2 bn€). This is explained by the highest availability rate of PWR-SMR that translates into higher electricity sale and revenues and to a more favourable cash flow profile, with earlier revenues stream than the AP1000-like scenario.

Also, in the PWR-SMR case, more financial resources are generated and reinvested in the construction of later NPPs. Figure 4.14 compares the sources of financing per each NPP of the fleet in the SMFR-2 (left) and PWR-SMR (right) scenarios: the higher self-financing capability of the latter is evident, with 6 NPP units almost entirely covered by cash flow generated by the project itself.

PWR-SMR have shorter construction time and the economic performance depends a lot on the cash flow time distribution, since, due to the discounting process, earlier cash flows have higher weight and later ones have lowest relevance.

This is a 'time-effect' whose benefit has also been presented in the previous section (sensitivity on SMFR construction time). For the same reason, PBT of PWR-SMR scenario is the shortest and the maximum cash outlay is the minimum among the 4 technologies. In the case of AP1000-like, EoS plays an important role decreasing total construction costs and this explains their short PBT. These results are shown in Figure 4.15, where the Cumulated Free Cash Flows of the alternative investment scenarios are compared.

It has to be highlighted in Best-Case conditions (considering SMFR-2 construction costs) all of the four scenarios have LCOE under the threshold of the CfD negotiated for the HPC in UK.

Table 20: Scenario results for ELFR, AP1000-like and PWR-SMR: comparison with SMFR in Base Case boundary conditions

Base-Case	SMFR	ELFR	AP1000-like	PWR-SMR
Unit overnight construction cost, avg. (€/kWe)	**6320**	**4420**	**4330**	**4770**
LCOE (€/MWh)	144	117	106	107
IRR (%)	Bankruptcy	Bankruptcy	Bankruptcy	Bankruptcy
NPV (M€)	-3562	-2600	-2504	-2725

(i) including inflation over the construction periods

Table 21: Scenario results for ELFR, AP1000-like and PWR-SMR: comparison with SMFR in Best-Case boundary conditions

Best-Case	SMFR-1	SMFR-2	ELFR	AP1000-like	PWR-SMR
Unit overnight construction cost, avg. (€/kWe)	**6320**	**5340**	**4420**	**4330**	**4770**
LCOE (€/MWh)	116	102	95	87	89
IRR (%)	9.8	11.5	11.6	12.3	13.9
NPV (M€)	-1590	-1016	-1002	-882	-477
PBT	23y+6m	21y	20y+9m	19y+6m	17y+9m
Total overnight construction costs (M€)	*18849*	*16022*	*13262*	*12995*	*14312*
Interests During Construction (M€)	*1338*	*1074*	*1017*	*825*	*659*
Self-financing (M€)	*1720*	*2558*	*3252*	*4117*	*3631*
Maximum outstanding capital (M€)	-6891	-4958	-4064	-3773	-3446

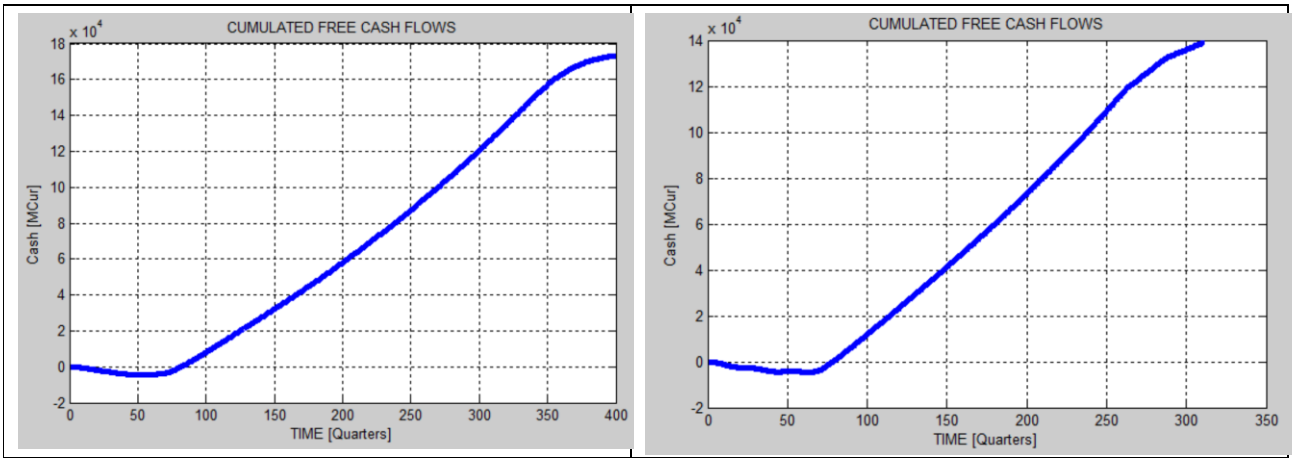

Figure 4.12: Cumulated free cash flows: ELFR (left) and AP1000-like (right) scenarios

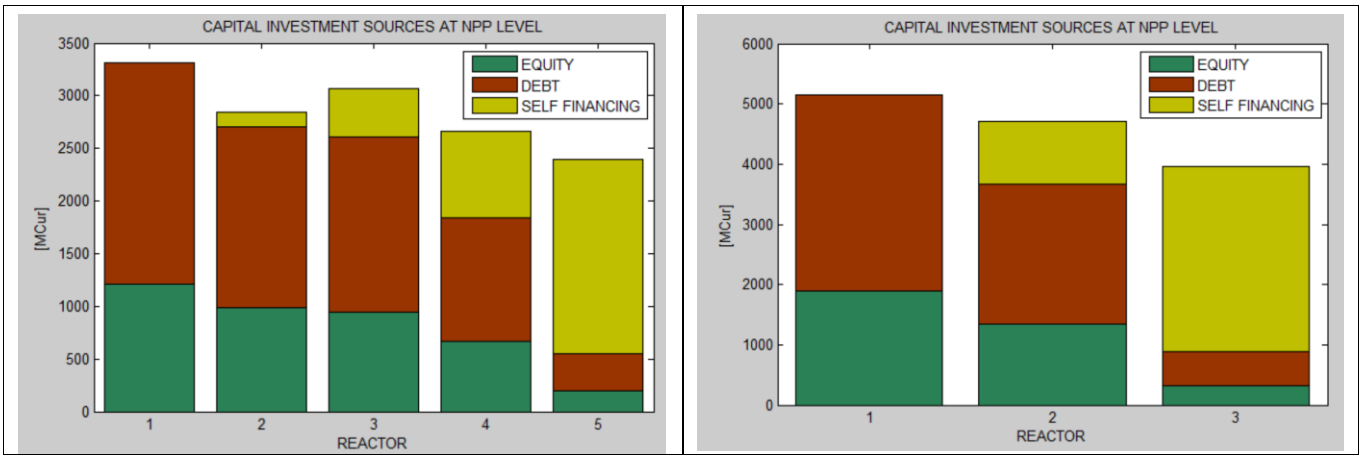

Figure 4.13: Construction costs of ELFR (left) and AP1000-like (right), per each NPP

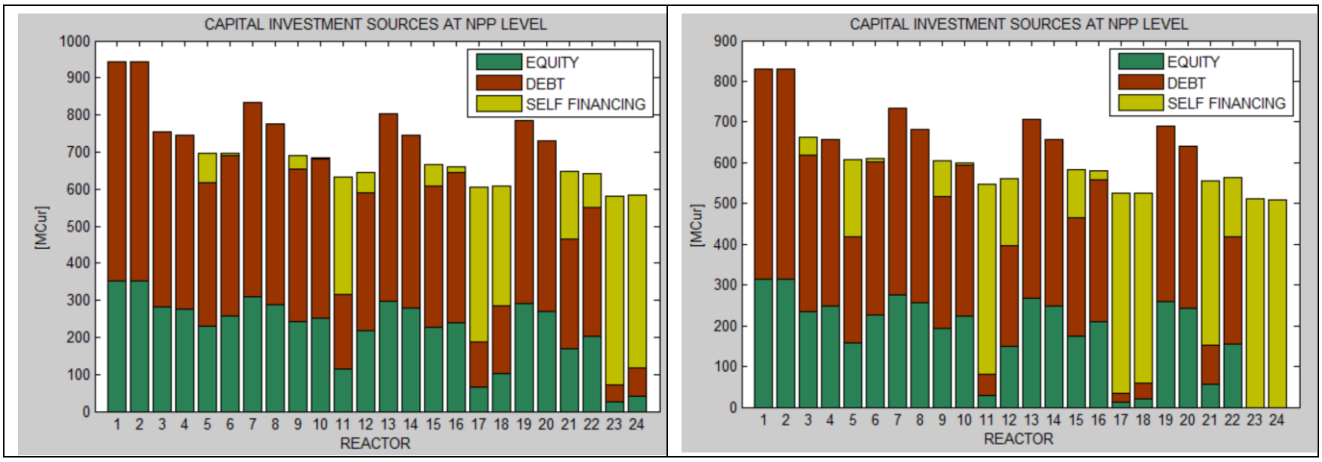

Figure 4.14: Construction costs of SMFR-2 (left) and PWR-SMR (right), per each NPP

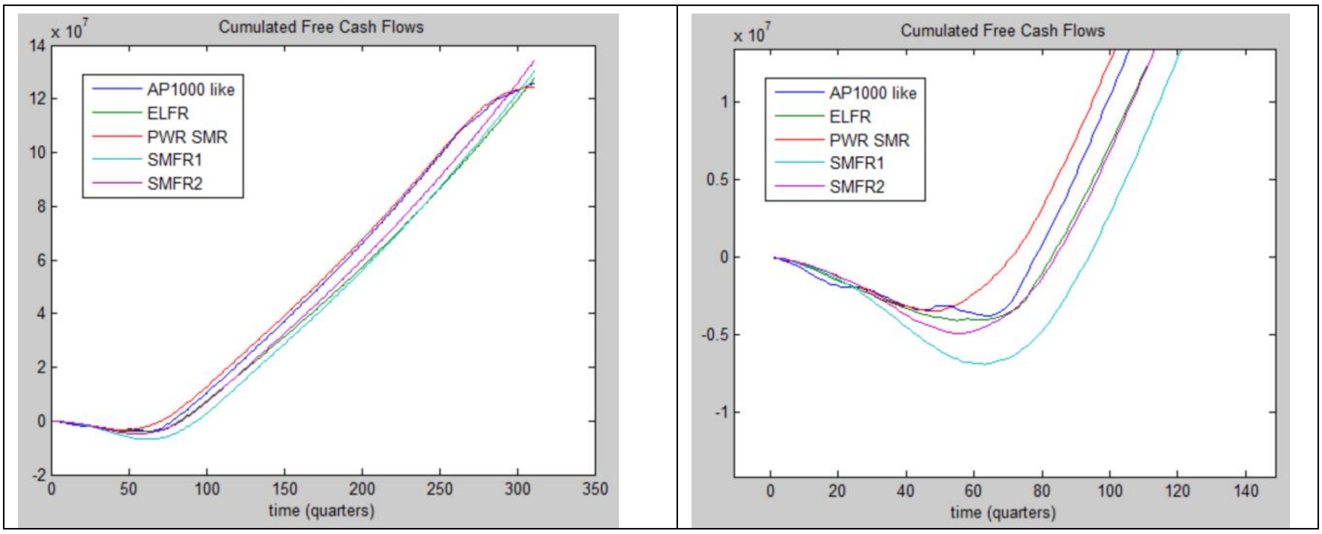

Figure 4.15: Cumulated free cash flows of the four reactor type fleets (left) and focus around the PBT (right)

4.5 Conclusions

Section 4 performs the simulation of a multiple SMFR deployment scenario and evaluates its economic performance. Sensitivity analysis highlights input assumptions with the highest impact on key economic indicators. Finally, SMFR deployment case is compared with alternative deployment scenarios based on different NPP technologies.

Construction cost of SMFR is a key assumption that influences the whole analysis; for this reason it has been evaluated by means of a top-down estimate with appropriate scaling factors. "Economy of multiples" and "Economy of small" intervene to reduce the average overnight cost of an SMFR plant in a fleet of 24. Nevertheless, conservative assumptions on the modularization effects and the design simplifications are over-killing, if compared to what foreseen for the same size scaling in PWR-LWR technology. In the Base-Case scenario, the scaling from ELFR to SMFR is conservatively assumed to bring limited layout enhancements for lead-cooled NPPs. As a consequence, SMFR has limited chance to compensate the loss of economy of scale in construction costs. These assumptions lead to an expected average unit construction cost of about 6320 €/kWe. The expected average cost of an SMFR plant is 785 M€, including contingencies, 1st core and excluding D&D cost. Due to the capital-intensive nature of the nuclear investment, this construction cost jeopardizes the economics of a SMFR fleet deployment, especially if current electricity price in the Euro zone is projected during the entire investment horizon.

A Best-Case is also considered with design and modularization enhancements and related cost savings to the extent of 5340 €/kWe unit average construction cost.

Best-Case is also characterized by better capital structure (i.e. higher debt stake) and cost of debt, and an electricity cost fixed at the same value negotiated at the HPC in UK (equivalent to 110 €/MWh). In this situation, SMFR profitability is in line with ELFR and LCOE is slightly higher, due to higher capital cost (average 5340 €/kWe for SMFR versus 4420 €/kWe for ELFR). Profitability is sustained by the shorter deployment time of each SMFR compared to ELFR; this timing effect has a positive impact on the economics, anticipating the revenue stream and the PBT compared to a large plant scenario.

Sensitivity analysis highlights the foremost areas of improvement to build a viable economic case. From a technical perspective, it is essential pursuing:

- construction cost reduction, by further design simplifications and by fostering the plant modularization. Sensitivity analysis shows that the SMFR fleet economics would get in line with PWR if breakthrough engineering solutions were able to bring design and modularization cost factors to 0.8x and 0.85x respectively, compared to the ELFR reference cost.
- Availability factor increase. Each percentage point has a significant impact on the economics.
- Construction duration.

From a scenario boundary conditions perspective, government support to the nuclear project (e.g. by means of public guarantees on the bank loans, export credit, etc.) is essential to reduce the investment risk; as a consequence, the capital structure might be improved by raising the stake of debt on total investment and by decreasing the interest rate. Those parameters have significant impact on the economics. LCOE decreases by decreasing the interest rate on the debt capital and increasing the share of debt on the total capital investment. Any form of public support that might have an impact on the capital structure and on the cost of capital, would have a social benefit, limiting the LCOE.

Finally, it is worthwhile noting that at current average electricity cost in Europe, none of the nuclear technologies considered (i.e., SMFR, ELFR, AP1000-like and PWR-SMR) is sustainable. In order to recover the capital investment and the operating costs, the electricity price must be raised to a value significantly higher than current average value in Europe. With a price of 110 €/MWh, equivalent to the CfD negotiated by the HPC project in UK, a profit margin of 9.8-11.5% is recorded (Base-Case and Best-Case respectively).

Lately, liberalized capital and electricity market conditions are an emerging concern for nuclear investments. In new nuclear investment projects in the western part of the world, e.g. Olkiluoto 3 and HPC, free-market rules have been overridden by long-term electricity sale contracts with fixed price. Also, institutional support to the financing has decreased the investment risk and cost of capital (Olkiluoto). The underlying assumption is that, on the long run, electricity market price is expected to include the cost of externalities that is currently not fully integrated in the cost of kWh from fossil fuel.

Comparison with ELFR, AP1000 and PWR-SMR scenarios highlights that, under the assumptions of the Base-Case scenario, ELFR are a better business case than SMFR; under the Best-Case, profitability of the two lead fast technology is in line (provided that 5430 €/kWe construction cost might be achieved), but LCOE of SMFR still reflects higher construction costs. It may be concluded that, if a small sized plant can achieve no significant design enhancement, then the power output should be maximized.

Nevertheless some key considerations are not included in those indicators. Some advantages of the smaller NPP, that are not easily measurable, could give the SMFR a competitive advantage that is not included in this quantitative analysis. It is evident from the observation of the new built projects in western countries, that construction delays and extra-costs are undermining the project economics of large plants. From Olkiluoto and Flamanville EPR projects, to the AP1000 projects at Summer and Vogtle US sites, it seems that large plants struggle to meet expectations in terms of project management, supply chain and execution. Complexity linked to the large size might be a reason behind those failures and, while on the paper (i.e. in terms of expected values) the project economics of large plants are better, then in practice, SMR are expected to be easier to manage from the EPC point of view. This would mean that “estimated” economics of large plant are better than SMR, but it might be the opposite in terms of “actual” performance. This is what is expected to happen in the PWR-LWR domain, but is not proved on the field yet. The same paradigm should apply to the LFR technology, as far as a size reduction might increase the number of equipment suppliers, as far as modularization should enable the parallelization of fabrication and installation activities, as far as higher factory fabrication options might reduce the chance of non-compliance with the quality standards, etc.

Clearly, as already said, the above-mentioned benefits should be accompanied and even enabled by breakthrough SMFR design simplifications, as compared to the large scale, like the integral primary circuit or the natural circulation represent in the PWR technology.

Nevertheless, small-modular plants might offer an opportunity for penetration in diverse markets and might represent the unique option for niche-applications (e.g., battery-type, sealed, no-refuelling, lower DHR requirements, co-generation applications). Also, SMR could be the suitable option for less-intensive power deployment scenarios, where grid constraints limit the size of new plants, bringing the advantages typical of the nuclear power: high availability rate and stable electricity generating cost. Finally, the smaller output size of SMFR could better fit with the need of balancing intermittent renewable share in the generation portfolio, although this would dramatically compromise financial aspects that should be compensated by other sources.

The analysis shows that PWR technology is still the most convenient choice to install 3 GWe, as far as assumptions are valid, but considering the degree of uncertainty that affects estimates and assumptions, the performance of the PWR and the ELFR technologies might be considered almost in line with each other. The enhanced sustainability in terms of natural resources and the minimization of spent nuclear fuel brought by LFRs, are not factorized in the present analysis, but could determine potential savings at system level and higher public acceptance, when a broader view is considered. As an example, public acceptance is a key, non-quantifiable variable that has a disruptive impact on a nuclear investment project; very often it may represent the binary-digit chance behind the success or the failure of a nuclear project. Public opposition is a feared event that might hinder the site individuation process, cause delays or extra-costs in the realization and influence the investment risk perception and environment.

New standards need to be developed and integrated in the existing licensing and certification regimes, with more chances for knowledge sharing and implementation of lessons learned.

Peculiarities of SMRs stimulating new openings on standardization are

- small size, meaning a reduced decay heat and radioactive inventory, but also added flexibility in terms of site capacity and electrical grid needs;
- higher sustainability to modular construction, typically based on factory fabrication, offering increased control of manufacturing and centralized implementation of lessons learned;
- enhanced passive safety, ensuring improved protection from accidents and threats also considering the presence of multiple modules on the same site;
- robustness against external events and threats, guaranteed by deep underground excavation expected to lower siting requirements.

The EU has the opportunity to develop a legal framework for SMRs, compatible with standardized designs and international certification. Design approval based on robust safety demonstration (including necessary tests and methodologies) and on safety performance dependent siting specifications (possibly reduced by design choices) are the most important steps towards the harmonization of an international licensing process.

The long term advantage of standardized regulatory frameworks will be the possibility to deploy an internationally certified module in any country adhering to the certification program. New prospects will be opened in countries interested in nuclear energy systems, either as importing or exporting entities. On the other hand, EU’s commercial prospects in deploying a certified technology will improve the competitiveness of the local nuclear supply chain. Modular construction of factory built Systems Structures and Components (SSCs) for a standardized SMR/SMFR design will centralize the return of experience, with a progressive improvement in quality. Moreover, the associated costs and time schedules will be constantly optimized, for an on-budget and faster delivery.

Although initiatives are ongoing worldwide, licensing regimes in place for the last few decades represent a barrier to meet the ideal goal of internationally harmonized standards. Incremental steps are the way to go to overcome the barrier. Allowing separate stages for approval of standard design and for construction license would be beneficial, but is not commonly available in all countries (unless a specific design phase is foreseen).

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