The cost of new nuclear power plants in France

SFEN TECHNICAL NOTE - MARCH 2018

The French Nuclear Energy Society (SFEN) is the French knowledge hub for nuclear energy.

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Executive Summary & Recommendations

SFEN TECHNICAL NOTE - MARCH 2018

Guaranteeing the nuclear option for 2050

With its June 2017 Climate Change Plan (*Plan Climat*), France has set a greenhouse gas emissions neutrality target for 2050.

France currently relies on nuclear and renewable energy for generating low-carbon electricity, with one of the most competitive supplies in Europe.

France is committed to diversifying its energy mix at a pace that will depend on several factors which are not yet fully clear: the characteristics of demand, the technical and economic performance of the different technologies (renewable energy, storage, smart grids), as well as the energy strategies of its European neighbours, as part of an increasingly interconnected electricity system.

In the short-term, continued operation of existing nuclear reactors ('*Grand carénage*' refurbishment programme) will provide France with low-carbon electricity, produced locally and at a competitive price.

> In the long-term, between 2030 and 2050, France is expected to progressively replace part of its existing nuclear fleet by new means of production.

In the long-term, between 2030 and 2050, France is expected to progressively replace part of its existing nuclear fleet by new means of production. While technical and economic progress is expected, significant uncertainties remain concerning the feasibility, reliability and cost, as well as the specific limits of a system that is heavily, possibly exclusively, reliant on intermittent renewable energy coupled with storage, biogas, and/or fossil fuels with carbon capture and storage.

Given the uncertainties and the urgent need to significantly and rapidly reduce global CO_2 emissions, the International Energy Agency[1] states that nuclear energy is indispensable, and complementary to the development of renewable energy, for a CO_2-free energy mix. This should in all likelihood be the case for France, which is a world reference for use of and industrial expertise in this technology.

In order to avoid significant climate (maintaining or opening new fossil fuel plants, resulting in increased CO_2 emissions) and economic (increased electricity production costs) risks, France must consider the option of replacing part of its nuclear fleet by EPR-type third generation reactors.

In recent years, the first third generation reactor projects have encountered issues during construction. However, it is important not to allow initial cost overruns to overshadow two key considerations. Firstly, these issues have been overcome and the first EPR will be connected to the grid in the next few months. Most importantly, these projects have revived the French and European supply chains, which are now ready to build new units. The nuclear sector, the third industrial sector in France with 2,500 companies and 220,000 highly qualified professionals, has the right tools to succeed.

1 – IEA ETP 2017 Report, 2DS and B2DS Scenarios.

Technical Note Objective

This technical note looks at the conditions that will allow France to keep the nuclear option open for 2050.

More specifically, it helps to explain the:

- costs of construction of new nuclear power plants.
- drivers required, in terms of construction and financing, to ensure the long-term competitiveness of the sector.

This note is based on lessons learned from other industries, as well as from the EPR projects launched in France and abroad (Finland and China).

Its focus is the third generation EPR-type reactor, which is commercially available and is being optimised for commissioning by 2030.

NB: While research is also looking into new concepts, such as Small Modular Reactors (SMR) and fourth generation reactors, their industrial readiness does not match this timescale.

This note has been produced by the SFEN's *Energy Economics and Strategy* Expert Group.

Preliminary remarks

The drivers identified for reducing the cost of the next EPR reactors are neither unique to nuclear technology, nor to France, but apply to all complex large infrastructure projects. They involve the industrial organisational structure as much as governance, which is embodied in contracts and financing costs (risk allocation). In terms of strategy, these large projects require significant involvement of the State.

For an EPR to be commissioned at an optimised cost by 2030, a clear industrial programme must be in place 10 years prior to the project launch. This timescale corresponds to the periods covered by France's next Multi-Year Energy Plan (PPE - *Programmation pluriannuelle de l'énergie*): 2019-2023 and 2024-2028.

> For an EPR to be commissioned at an optimised cost by 2030, a clear industrial programme must be in place 10 years prior to the project launch.

The competitiveness of each means of production will be increasingly impacted by the price of CO_2, and can no longer be considered in isolation. Interdependencies in the electricity system will have to be taken into account (share of intermittent sources, limitations of storage solutions and other sources of flexibility), alongside the electricity market structure.

Consequently, nuclear energy, a low-carbon technology, which is dispatchable, flexible[2] and available 24/7[3], can only be compared to other technologies with the same characteristics, in terms of service provision to the electricity system and their contribution to the fight against climate change.

2 – The power of a nuclear plant can be adjusted by up to 80% within a few minutes.

3 – The average availability of electricity production from nuclear was 75% between 2010 and 2017.

Context

In 2016, the international market for new nuclear was strong, with the commissioning of 10 nuclear reactors[4], representing the largest activity in two decades.

The sector is transitioning towards a new generation of reactors: the third generation.

These technologies offer enhanced performance in terms of safety and availability, as well as environmental impacts. France, with the EPR, as well as Russia, the United States, and China are developing their own technology, especially for export.

4 – World Nuclear Performance Report 2017.

1. The first third generation reactor projects have encountered challenges inherent to new projects. France has overcome these and now has a revitalised and operational supply chain ready to build new EPR.

A review of the First-of-a-Kind (FOAK) third generation reactor projects shows that they have overrun their initial budgets.

This situation is common to complex large infrastructure projects, an example being the Channel Tunnel whose final budget was double the initial estimate. Numerous studies make reference to 'optimism bias'[5] in project forecasts prior to launch. They also draw attention to phases of 'rapid learning' in subsequent projects[6].

This technical note highlights the significant differences between third generation reactor projects in the following countries:

- Countries that are actively building a series of reactors, either because they are extending their nuclear build programme (China), or because they are replacing part of their fleet (Russia). Indeed, it is of note that the first third generation reactor to go online was in Russia, and the first EPR to startup will be Taishan 1, in China.
- Countries that had stopped building reactors (France, Finland, United States). These countries have been doubly disadvantaged, both by uncertainties associated with FOAK projects and having to upgrade their supply chain to the standards required for Gen-III reactors.

Having overcome these issues, the first units are now in the startup phase, and France once again has a supply chain capable of building new reactors (large components, expertise, professional skills, industrial equipment, research capabilities). There is a risk that the returns on this investment will be lost should France once again stop building reactors at home.

5 – Working Paper on Risks n°52, *A risk management approach to a successful infrastructure project*. See also, E. M. Merrow, P. E. Phillips, and C. W. Meyers, *Understanding Cost Growth and Performance Shortfalls in Pioneer Process Plants,* Santa Monica, CA: Rand Corporation, 1981.
6 – PWP Ltd., *Pelamis: experience from concept to connection*, *Phil. Trans. R. Soc. A* (2012) **370**, 365–380.

2. Construction costs are the main contributing factor to overall production costs of a nuclear reactor. These costs can be controlled, provided that France commits to an industrial programme.

The cost of a nuclear reactor is in large part dominated by investment costs in the construction phase which, depending on the discount rate used, represents between 50% and 75% of the total electricity production cost over the facility's operating period.

A review of the first French programme, and other countries' programmes, clearly demonstrates that construction costs can be reduced. This requires development of an industrial programme which generates an economic series effect, and integrates lessons learned from previous construction projects, as well as the latest innovations.

Taking advantage of the economic series effect

The economic series effect refers to the fact that the average investment cost for a series of standard units is less than that for a single unit of the same type, designed and produced separately.

This primarily requires systematic construction of pairs of reactors on the same site, resulting in benefits from several combined effects:

- **'Programme' effects:** assessments and qualifications will be valid for a large number of units.
- **'Productivity' effects:** suppliers can make productivity gains when producing a series of identical items, which they can reflect in their prices.
- **'Pace' effects:** the number of units ordered must ensure a continuous minimum volume for all industrial stakeholders, from design studies to manufacturing, this being achievable through correct management of project costs, lead-times and processes.

Making use of learning-by-doing effects and the latest innovations

- **Improving design:** sharing of lessons learned from Olkiluoto 3 (Finland) and Flamanville 3 (France) has already been of benefit to the Taishan 1 & 2 project (China). The process of EPR design optimisation adopted in 2015 has also led to a simpler design, improving ease of construction and industrial-scale component production.

- **Using the latest methods and techniques:** several innovations have improved performance. Examples include reinforced concrete, 'modularisation' of specific parts of a plant, and the use of engineering methods to improve communication between the different parties involved in a project.
- **Revitalising Europe's supply chain:** the nuclear sector has strict requirements in terms of quality assurance, material purity, component behaviour under irradiation, long-term wear, etc. The whole European supply chain[7] had to be qualified to a 'nuclear quality' level for construction of the Olkiluoto 3 and Flamanville 3 EPR. Future projects will benefit from this restored supply chain, resulting in reduced costs.

Combining these measures will lead to improved project and lead-time management, a key component of economic efficiency.
There are several expected outcomes:
- Time savings by project teams.
- Reduced fixed construction costs.
- Reduced financial costs related to interest over the construction period (as it is shorter).
- Earlier electricity production (which greatly increases the value of the project).

7 – The European supply chain involves several hundred companies distributed across 10 countries.

3. Project financing and expected returns on investment have a major impact on the cost of a project. The State has a key role to play. France can learn from discussions in the UK.

Private investors expect a return on investment for nuclear projects of the order of 9% to 10% in terms of WACC[8]. In addition to the risks associated with the project, these rates reflect market risks (changes in average electricity price), political risks (project called into question by a change of government) and risks related to regulatory changes, which are likely to result in increased costs and project lead-time.

The State's interest in nuclear projects is twofold, as they must ensure the security of electricity supply whilst also reducing CO_2 emissions. In light of this dual objective, new nuclear power plants, as well as existing ones, represent strategic infrastructures, which help to ensure the security of electricity supply and provide low-carbon energy. The State can play a key role in 'removing' project risks or in spreading risks among stakeholders.

In relation to this last point, several lines of approach are possible:

- **Reduce market risks:** the average price per kilowatt hour on the European wholesale market has been halved in the last decade. Many stakeholders are dissatisfied with the current market set up, which does not favour low-carbon energy sources, and are calling for improved visibility for investments. The CFD (*Contracts for Difference*) mechanism used in the United Kingdom attracts investors by guaranteeing returns on investment, for renewable energies and nuclear, based on the services provided.
- **Spread risks more evenly among stakeholders:** a recent report by the UK's National Audit Office[9] draws attention to the considerable sensitivity of electricity prices to the expected rate of return for a project, which is directly linked to contractual arrangements between private investors (high returns), suppliers (high profits) and the State (low returns, owing to longer term objectives, and risk mitigation through investment in several different large projects). For example, the cost of a kilowatt hour for Hinkley Point C (UK) doubles when the discount rate changes from 3% to 10% (value close to EDF's cost of capital for the project).

8 – WACC: *Weighted Average Cost of Capital.*

9 – Department for Business, Energy & Industrial Strategy, *Hinkley Point C*, National Audit Office, HC 40 SESSION 2017-18, 23 JUNE 2017.

Recommendations

Review the supply chain and financing mechanisms for reducing the cost of third generation nuclear power

The cost of third generation nuclear power is based on two factors: construction costs and financing costs. The SFEN has estimated that significant savings are possible compared to the first projects: of the order of 30% on construction costs, due to economic series and learning-by-doing effects, and up to 50% on financial costs, particularly in contractual arrangements.

There are numerous ongoing projects looking to make the most of these savings and ensure that third generation nuclear is one of the most competitive sources of dispatchable generation. This would mean a cost at the lower end of that for combined-cycle gas power plants with a carbon price (of the order of €20-30/tCO_2).

The State has a role to play

The SFEN suggests engaging with public bodies in a review of the supply chain and financing mechanisms for reducing the cost of third generation nuclear power. A key factor is optimising the allocation of roles amongst the public bodies and the industrial players involved in implementing a project. It falls on the State, which guarantees national strategic interests, to maintain a baseline supply of decarbonised electricity, which is flexible, competitive and predictable, up to 2050.

Timescale

This review must be completed without delay before 2020, in order to meet the objective of getting the first pair of reactors online by 2030. The first pair will be part of an industrial programme for a series of EPR, for which lessons learned will contribute to the designs of at least another three pairs of reactors.

Expected benefits

Using this industrial programme approach will provide the whole supply chain, from large groups to small and medium-sized enterprises (SME), with the visibility and timescales required for investing in production lines and competences, as well as for taking advantage of the series effect right from the first construction projects. This industrial programme will enable France to keep the nuclear option open, for managing the decarbonisation of its economy and the renewal of its electricity mix by 2050.

Consequences of not taking action

Without this, France will lose control over strategic components of its reactors, for which relying on a foreign supply (from China or Russia) would represent a major economic and geopolitical concern and, no doubt, a permanent loss of technological and energy sovereignty.

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Technical Note

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Contents

1. Introduction

A previous SFEN Technical Note covering production costs of France's existing nuclear fleet concluded that it is highly competitive in terms of cash cost (€32-33/MWh).
In light of the debate surrounding the renewal France's nuclear fleet in the coming decade (with decisions to be made as part of France's Multi-Year Energy Plan - *Programmation pluriannuelle de l'énergie* -which is currently being drawn up), the objective of this technical note is to:

- Understand the cost of production of one or several new means of production: what are the key cost components, what are the drivers for reducing it, who builds the reactors, with what structure for risk allocation, and with what market structure? How will these parameters influence the cost of the project?
- Examine the competitiveness of a means of production as part of a mix: this must no longer be considered in isolation as it is dependent on the electricity system (% non-dispatchable sources), and the electricity market structure (including externalities and services provided).
- Determine the competitiveness of new nuclear in different scenarios, with hypotheses about changes in the electricity system and market structure.

The cost of nuclear reactors and electricity production must be considered in context, which is characterised in particular by:

- European electricity market failure: over-capacity, low wholesale price. Currently, no new means of production is built without a guarantee on future revenues (purchase price).
- Changes in the electricity system's structure: an increasing number of non-dispatchable and distributed energy sources.
- Highly criticised European 'Energy & Climate' policies: see European Court of Auditors[1], reports by France-Stratégie[2] and Mc Kinsey[3] on the Energiewende.

In this context, the global nuclear sector (i.e. French, American, Russian, Chinese, Korean, etc. vendors) have prepared for a change of reactor generation, moving from the current generation ('Generation 2') towards a new generation ('Generation 3'). The startup of these reactors has proved more difficult than anticipated, with the first projects seeing delays and significant costs overruns. The credibility of nuclear power as a key technology in the fight against climate change remains high in Asia, for example in China. In Europe, however, confidence in nuclear power has been declining over the last decade. In the US, nuclear power cannot compete with shale gas. The two main challenges for new nuclear are, therefore:

- Startup of the very first third generation units.
- Reducing costs and keeping to construction schedules for the next reactors.

The aim of this technical note is, therefore, to contextualise the current efforts being made towards reducing costs.

2. Costs and timescales for third generation nuclear new build

2.1. Arrival of third generation nuclear reactors: a new phase
In previous decades the construction of reactors has been highly cyclical in nature. Second generation reactors were mostly built between 1970 and 1990, as shown by Figure 2.1 below. The pace subsequently slowed significantly, with the exception of China, whose development programme is in full swing resulting in the 2015-2016 spike (of Generation 2 reactors).

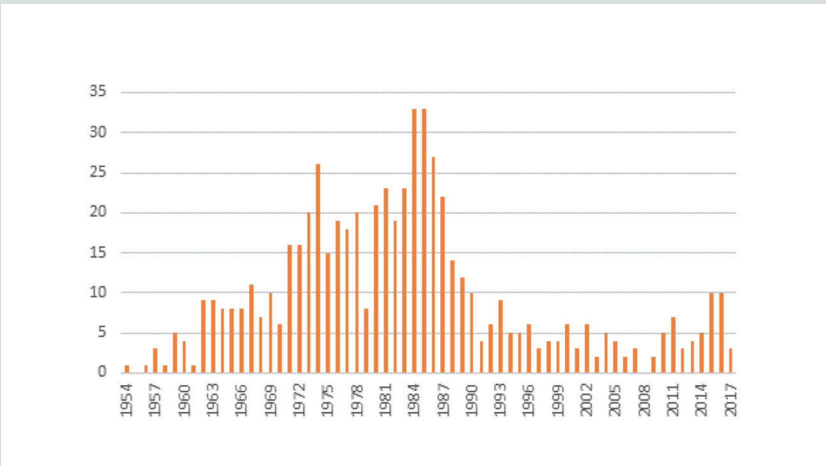

Figure 2.1. Number of units connected to the grid each year. (Source: IAEA/PRIS data on reactors under construction, 1950-2016).

It is important to note the very different contexts for each of the industries involved (engineering, civil engineering, reactor core supplier, equipment manufacturers, etc.) specific to each country's:

- History and position taken by authorities.
- Structural organisation and current programmes.
- National Safety Standards.
- Operational capacity and nuclear qualification of suppliers (supply chain).

1 – See: https://www.eca.europa.eu/en/Pages/DocItem.aspx?did=41824
2 – See: http://www.strategie.gouv.fr/publications/crise-systeme-electrique-europeen
3 – See: https://www.mckinsey.de/energiewende-deutschland-die-kosten-steigen-weiter

In 2016, the global market looked to have taken off with the commissioning of 10 nuclear power reactors (mostly second generation), which had not occurred for over two decades. By the end of 2016, the total number of reactors reached 448 with a net global capacity increase of 8 GWe; 61 reactors were under construction. The market, however, is increasingly dependent on China, which accounts for half of all construction projects. We can also see a pause in new project launches in China (with the exception of the first concrete poured for Tianwan 6) in 2017. In the United States, 2016 saw the startup of Watts Bar 2, the first connection to the grid in 20 years, although this was a reactivated project.

Since the 1990s, industry has been developing new reactor concepts, in order to integrate technological developments resulting from accumulated experience, and advances in technologies and materials, as well as for improving safety (accident probability and impact in terms of radionuclide emissions in the event of a major accident). The main concepts developed and now available on the global market include the EPR (Framatome), the AP1000 (Westinghouse), the ATMEA1 (Framatome-Mitsubishi), the VVER-1200 (Rosatom), and the Hualong 1 (CGN-CNNC partnership in China). The APR (KHNP/Korea) could almost be added to this list, but this concept does not incorporate all of the features of third generation reactors. In this technical note we have classified all of these new concepts as 'Generation 3', an umbrella term for a wide range of solutions developed to achieve similar objectives.

The technical objectives set for all of these Generation 3 concepts are as follows:

- Core-meltdown probability of <10-5 per year, calculated based on probabilistic studies at the design phase.
- In the event of a major accident, minimum impact on the population by ensuring containment integrity.
- Enhanced protection against external threats (natural and manmade).
- Availability >90% for at least 20 years.
- Operating lifetime of 60 years incorporated in the design.

2.2. Construction of the first third generation reactors: very different contexts

Construction of the *First-Of-A-Kind* (FOAK) third generation reactors has taken place in different country-specific contexts. At the beginning of the 2000s, whilst substantial construction projects had been launched in China and South Korea, no new projects had started in either Europe or the United States in nearly two decades. This resulted in a loss of competence in parts of the supply chain (with bottlenecks for specific components), at a time when regulatory standards were being extensively revised. It has, therefore, been necessary to revive these activities to meet orders from utilities in a period of strong growth, but also turbulence, in the energy markets. Construction of the first EPRs in Europe and AP1000s in the United States has been impacted by this, adding the burden of re-building and re-qualifying the supply chain to the inherent uncertainties of FOAK projects.

We can observe the following developments for four reactor models:

- EPR, with 6 reactors under construction in the world. Four are to be connected to the grid in the coming months in China, France and Finland. Two other construction projects were launched in 2016 at Hinkley Point (United Kingdom).
- The new Russian AES 2006 model of the VVER-1200 reactor, with the first plant connected to the grid in August 2017 at Novovoronezh II, and others to follow at Leningrad II and internationally.
- The new Chinese Hualong 1 1000 MWe model, whose construction has recently been launched at home and is being offered abroad.
- Westinghouse's AP1000, under construction in the United States and China, has encountered several issues, resulting in the cancellation of two units under construction in the United States (VC Summer 3 & 4). The first AP1000 is scheduled for startup in China in 2018 (Sanmen).

It should be noted that Russia has already commissioned a Generation 3 reactor (AES 2006 at Novovoronezh II-1), 8 years following the start of construction. In Russia, Generation 2 construction projects were not interrupted, unlike in Europe and the United States. South Korea has also kept its Generation 2 model, AP1400 at Shin-Kori 3, on schedule.

The Chinese programme includes various reactor types, using French (EPR), American (AP1000), Russian (VVER-1000) and Chinese (Hualong 1) technology. The size and structure of its market has enabled a substantial diversification of models. Construction projects have made satisfactory progress, even if delays have been reported at the end of construction phases. For example, at Taishan where construction of two units started in 2009, and for which the startup had been scheduled for end 2017 and the first half of 2018, has now been pushed back to 2018 and 2019. Taishan 1 should be the very first of Framatome's EPRs to be commissioned in the world, before Flamanville 3. This is also one of the main reasons for its delay, startup having been scheduled without input from lessons learned on the European EPRs.

Conversely, in the United States, nuclear has only recently made a comeback. New AP1000 (Vogtle 3 & 4 and Summer 2 & 3) construction projects have encountered delays and cost overruns, to such an extent that construction of Summer 2 & 3 has been abandoned: part of the US electricity market does not offer much opportunity in the short-term, with low electricity prices due to low unconventional gas prices.

In Europe, the two EPR projects (France and Finland) have encountered significant delays for similar reasons: the French context will be discussed in more detail hereafter.

Construction lead-times have shown that a minimum of 6 years is required for completion, which remains an achievable target, for the South Koreans with their second generation model at Shin-Hanul, and for the United Arab Emirates (to be confirmed in 2018), and for the Chinese for all reactor models built at home.

Table 2.1. Third generation reactors, connected or under construction, worldwide in 2017.

Technology	Reactor	Country	Capacity (MWe)	Construction start date	Initial startup date	Revised startup date	Initial cost of construction ($US/kWe)	Revised cost of construction ($US/kWe)
EPR	Flamanville 3	France	1600	Dec-07	2012	2018	2,063	6,563
	Olkiluoto 3	Finland	1630	Aug-05	2009	2018	2,025	(More than) 5,215
	Taishan 1	China	1660	Oct-09	2014	2018	1,960	3,150
	Taishan 2		1660	Apr-10	2015	2018		
AP1000	Summer 2	United States	1117	Mar-13	2017	Cancelled	4,387	6,267
	Summer 3		1117	Nov-13	2018	Cancelled		
	Vogtle 3		1117	Mar-13	2017	2019	5,565	6,802
	Vogtle 4		1117	Nov-13	2018	2020		
	Haiyang 1	China	1000	Sept-09	2014	2018	2,650	?
	Haiyang 2		1000	Jun-10	2015	2018		
	Sanmen 1		1000	Apr-09	2015	2018	2,650	2,807
	Sanmen 2		1000	Dec-09	2016	2018		
VVER 1200	Novovoronej 2.1	Russia	1114	Jun-08	2015	2016	2224	?
	Novovoronej 2.2		1114	Jul-09	2016	2018		
	Leningrad 2.1		1085	Oct-08	2013	2018	2,673	3041
	Leningrad 2.2		1085	Apr-10	2016	2019		
HUALONG 1	Fuqing 5 & 6	China	1090	May-15	2020	?	2800	3500
	Fangchenggang 3 & 4		1090	Dec-15	2020	?		

Sources: WNA website for the most part, completed with additional published data. The costs indications are not 'guaranteed' or necessarily comparables in terms of what they include.

2.3. Construction costs of reactors under construction

The construction costs in the previous table (Table 2.1) provide a general overview, as they have been taken from various sources and are, as such, difficult to compare:

- They have been estimated using exchange rates at the time of their publication, which fluctuate and are not direct measures of purchasing power or real wages within countries.
- They should, in principle, be 'pure' construction costs which do not account for expenses related to construction times (interest during construction).
- It is not possible to verify that they cover exactly the same scope from site preparation up to and including startup.
- The specific contexts and regulations of each country and site can lead to differences.
- Independent of reactor model, domestic or foreign, there is a significant amount of local investment, which results in structural variations in costs, but has the advantage of providing local employment and local value chains in the country of construction.

There remains a difference between costs in Europe and the United States, and those in China and South Korea, of at least a factor of about 2. There have also been cost overruns for all projects compared to initial estimates. The largest cost overruns have been for the two European EPRs, although it is important to note that they were the very first projects to have been launched, in 2005 and 2007 respectively. As such, construction of Olkiluoto 3 and Flamanville 3 were launched within a context of dual risk:

- New Generation 3 reactor concept, integrating innovations (in particular, with higher safety standards), with increased unit power, and for which a detailed design had not yet been finalised.
- No nuclear power plants had been built in France or Europe in over a decade.

Beyond these FOAK effects, the following factors explain the observed cost increases:

- Regulatory changes during the course of the project.
- Delays (various causes, various effects).
- Cost of raw materials, temporarily increasing during the 2010s.
- Issues with sitework planning.
- Issues with planning and delivery in the supply chain.

Progress should be made for each of these factors through learning-by-doing alone.

Of particular note is the effect of delays, which impact costs in numerous ways. Poorly managed construction lead-times result in delayed revenues, with loss of revenues from sale of electricity of the order of several hundreds of millions of euros for a one-year delay, and losses due tied-up capital (see section on financial factors).

There are also some lesser known factors related to contractual arrangements and supply chain profit margins. According to the University of Chicago[4], estimates of overnight costs of a FOAK unit increased by 68% between 2004 and 2011, due to new design requirements, as well as changes in risk management across the value chain. This negative impact could challenge the preference for 'turnkey' contracts, which had been favoured over 'cost-plus' contracts in order to promote competition.

2.4. Controlling the costs of large infrastructure projects

Owing to the amount and complexity of the work required for building Generation 3 reactors, their construction shares characteristics of all complex large infrastructure projects. Common features include both industrial structural organisation and governance of responsibilities, which are embodied in contracts and financial costs. These large projects, owing to their strategic importance, also point towards expectations of increased State involvement.

The table below (Figure 2.2), taken from a study by McKinsey published in 2013[5], gives some illustrative examples.

Example	Budget vs actual € billion (Planned / Actual)	Delays and start-up problems	Incorrect capacity and revenue plans	Total value lost vs plan € billion
Eurotunnel	7.5 / 15.0	▪ 6-month delay ▪ 18 months of unreliable service after opening	▪ Overestimated market-share gain in freight and passengers by 200%	~7.5
High-speed rail Frankfurt-Cologne	4.5 / 6.0	▪ 1-year delay of construction ▪ Legal and technical issues	▪ Unforeseen capped government funding	~1.5
Betuwe Line NL (cargo rail)	2.3 / >5.0	▪ 1.5-year[1] delay of construction ▪ Technology choices still not finalized	▪ Annual revenue shortfall of €20 million	~3.0
Kuala Lumpur Airport	2.0 / 3.5	▪ Initial issues with connectivity to downtown area ▪ Complaints about facility hygiene levels	▪ Handles only ~60% of current capacity ▪ Losing market share to Singapore	~1.5

1 Project still not finalized and costs could go even higher.
Source: Annual reports; Reuters; Jane's Airport Review; McKinsey analysis

Figure 2.2. Cost comparisons of initial budget estimates and final project cost (Source: McKinsey, 2013).

An early Rand Corporation study of 44 construction projects for factories for the chemical industry[6] clearly showed evidence of optimism bias in project cost estimates. Final construction costs were twice those of initial estimates. Re-assessment of cost during the project also remained below final costs reported on project completion. The findings are summarised in Figure 2.3 below:

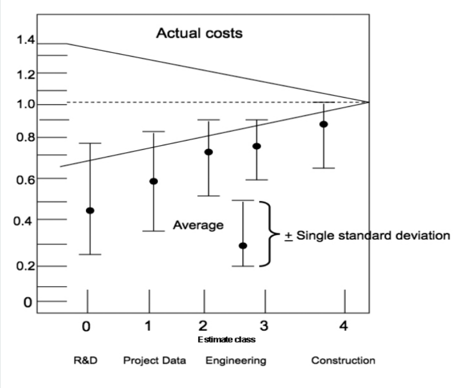

Figure 2.3. Diagram of changing project cost estimates
(Source: Merrow, Phillips and Myers, 1981)

In the energy sector, Pelamis Wave Power (PWP) published a study in 2012[7] on the development of their wave energy converter, which led them to suggest the following typical cost curve (Figure 2.4) for changes in the cost of a new technology. The curve shows a peak in cost for the *First-of-a-Kind*, with reference to the first commercially operational unit. This peak corresponds to Merrows, Phillips and Myers' Phase 4 (construction; Figure 2.3). PWP then show that a *rapid learning* phase directly follows commissioning of the first unit.

4 – *Analysis of GW-scale Overnight Capital Costs*, EPIC Technical Paper, University of Chicago, 2011.

5 – *A risk-management approach to a successful infrastructure project*, McKinsey Working Paper on Risks n°52, 2013.

6 – E. M. Merrow, P. E. Phillips, and C. W. Myers, *Understanding Cost Growth and Performance Shortfalls in Pioneer Process Plants,* Santa Monica, CA: Rand Corporation, 1981.

7 – PWP Ltd., *Pelamis: experience from concept to connection*, *Phil. Trans. R. Soc. A* (2012) **370**, 365–380.

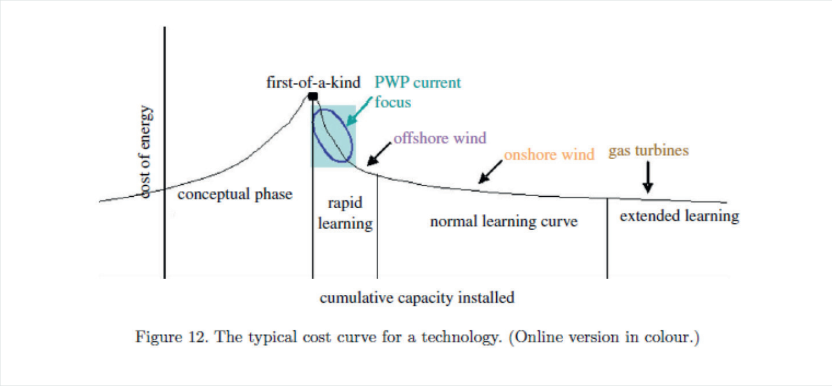

Figure 2.4. Typical cost curve for different technology development phases
(Source: PWP, 2012)

2.5. Conclusion

After a pause in nuclear new build in most countries (except China and South Korea), construction has since picked up again, and is increasingly for Generation 3 designs, with significantly improved performances in terms of safety. These reactors are often built in difficult conditions: parts of the supply chain inactive with only limited orders, more complex reactors (required upgrades), new regulatory procedures, temporary increases in cost of raw materials, etc. It is difficult to compare published data for the Generation 3 reactors currently under construction. It is clear, however, that the costs vary somewhat (up to a factor sometimes exceeding 2). This is mainly due to construction delays. The reasons for these costs overruns are covered in the following sections, with a particular focus on EPR reactors.

3. Influence of reactor construction costs on total electricity production costs

3.1. Cost definitions

The cost of a product or service is more complex than appears at first sight. The factors taken into account depend on the point of view (for example, the consumer, the network operator, the taxpayer, etc.). Cost also depends on the period under consideration: 10-year timeframe, entire operating lifetime of a facility, period covering all cashflows before and after operation, etc. Another factor is the current worth or present value of cashflows given a specified rate of return (discount rate).

Cost estimates are of particular interest when comparing two competing alternatives. It is, therefore, best to provide a reliable cost estimate to inform the decision-making process. The cost of decision-making can be explicitly established with a fair degree of certainty, by reporting all the expenditures and revenues arising from the decision. The cost of investment decisions in new nuclear must be compared with the cost of alternative decisions.

In this technical note, we look at the decision to build a new production unit, and compare this with the previous SFEN technical note on existing nuclear, mainly through comparison of the Levelised Cost of Electricity (LCOE). The LCOE is explained in more detail in the following sub-sections.

3.2. Levelised Cost of Electricity (LCOE)

The LCOE is an average value of the total cost, discounted or levelised, over the lifetime of the operation, divided by the discounted production. The total cost comprises 4 main inputs:

- Investment cost which is a fixed cost, independent of the future operation of the power plant, and includes:
  - Overnight construction costs (i.e. all costs required for commissioning of the power plant, non-levelised, were the plant to be built in one night), covering construction and engineering costs; as well as all other costs prior to commissioning, covering owners' costs (mainly spare parts, pre-operating costs, administrative procedures and taxes, first fuel load and cost of site acquisition if applicable).
  - Interest costs during construction, which takes into account the discounting of scheduled overnight construction costs over the construction period.
- Operations and maintenance costs, covering all costs in relation to operation and maintenance, as well as operating taxes: taxes and royalties directly related to the operating facility.

- Fuel costs, which for nuclear cover the whole cycle: front end operations (natural uranium, conversion, enrichment and fuel fabrication), and back end operations (transport, spent fuel reprocessing and waste management and storage).
- Dismantling and decommissioning costs.

3.3. Discount rate

In order to take overall economic variations over time into account, the discount rate is commonly used, which accounts for social preferences: individuals prefer to own something today rather than tomorrow. Another consideration which proves necessary when a decision-maker is from industry, is to demonstrate that the rate includes interest rates and risk premium (in reality an access to capital rate, which involves slightly more complex calculations; see later reference to the *Weighted Average Cost of Capital* - WACC).

With typical rates of the order of 5-10% (private rates), it is the first years which have most influence on the calculations, which is disadvantageous to nuclear reactors which have a long construction time compared to other electricity sources.

The discount rate used can come mainly from a public (defined by the State) or a private (defined by the company, depending on access to capital) process:

- **Discounting by the State:** in general we use a 'standard' rate which is specific to the sector and type of investment. For electricity production, the French Energy Ministry currently recommends a rate of 8% for the first 30 years, with a rate of 3% for subsequent years. Different options are, however, looked at regularly in order to test the robustness of decisions at a range of rates.
- **Discounting by the company:** the *Weighted Average Capital Cost* (WACC) is calculated as the weighted average of the cost of equity and debt, after tax, for a given company's financial structure, and represents the value of time and payment of returns on investment for the accepted risk level.

The public rate is, in general, lower than private rates by several percentage points. This is for two main reasons: firstly, the State is relatively protected against bankruptcy risks for each project (when the size of the project remains moderate compared to the State's budget); secondly, the State operates for the common good, taking a longer term view than the private sector (which results in lower rates). The notion of the common good, for which the State is responsible, is of particular relevance to large infrastructure projects. Energy strategy also depends on other objectives, such as energy security or development of industrial sectors. This is notably the case for decisions concerning nuclear.

One issue is how to combine the two approaches, public and private. A project which is economically sound, based on a public rate, may prove unattractive to the private sector. This is when the public authorities (those we call the '*Strategist State*' in Section 8) must correct the market or contribute to a framework which transfers part of the risk to the State or final consumers, bringing the project more in line with the interest of the common good.

3.4. Main items of cost for nuclear power and order of magnitude

As is the case with new renewable energy projects (wind, solar, hydro) and, more generally, the majority of large infrastructure projects, nuclear costs are for the most part dominated by capital expenditures during the construction phase. As such, the discount rate used (see previous section) has a first-order effect on the WACC.

For nuclear, data collected periodically by the OECD (IEA/NEA, 2015) show the sensitivity of cost items to the discount rate used[8]. For a discount rate of 7%, construction expenditures represent about €45/MWh, or 73% of the total cost of production. This is reduced to 55% for a discount rate of 3%, with construction costs of about €20/MWh.

Other cost items, however, are not as sensitive to the discount rate used. According to the OECD, excluding the effects of tax, operating and maintenance costs are estimated at €10/MWh, fuel-related costs (uranium and front end activities) at €5.3/MWh, and costs of decommissioning and waste management at €1.7/MWh.

8 – The last IEA/NEA report, from 2015, is based on an overnight construction cost (i.e. excluding financial costs) of €3,800/kWe. This value is for a new EPR reactor in France in 2030 with a capacity of 1630 MWe. This point is further discussed in later sections..

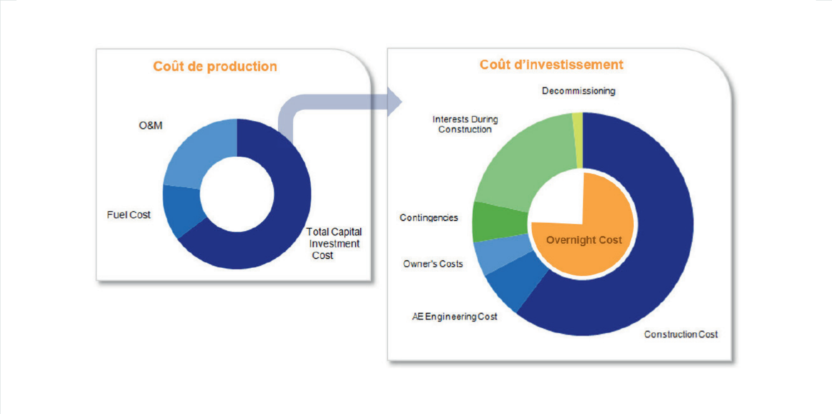

Figure 3.2 Breakdown of costs of generating electricity from nuclear energy (Source: OECD).

Under ‘standard’ conditions, capital costs represent about two thirds of the production cost, of which construction costs make up to about 40% of the production cost.

In addition, capital costs can quickly become a significant fraction of the construction costs if capital costs and/or construction times increase[9] and if expenditure profiles vary. Thus, for capital costs of 10%, a doubling of construction time will increase the contribution of capital costs as a fraction of the total construction cost from 22% to 40%.

	Construction time		
	1 year	5 years	10 years
Capital cost 5%	2%	12%	22%
Capital cost 10%	4%	22%	40%
Capital cost 15%	6%	30%	54%

Tableau 3.1 Capital cost as a fraction of total construction cost (Source: L. W. Davis 2011[10])

3.5. Focus on capital costs

Capital costs, at the commissioning of a facility, comprise the following items:

Operator items

- Cost of safety assessments and certification prior to construction permits.
- Site preparation.
- Training for operators and pre-startup tests.
- Interest during construction: related to initial financing and covering the period between investment and startup.

Facility and Fuel Supplier items

- Engineering studies and project management.
- Civil engineering.
- Components (nuclear and conventional) and assembly.
- Instrumentation and Control.
- Fuel (first fuel load).
- Pre-startup tests.

As indicated in the previous paragraph, construction costs represent a significant proportion of production costs. The main components of construction costs that can be optimised are:

- Engineering studies
- Civil engineering
- Systems (including Instrumentation & Control)
- Standardisation of components
- Construction methods and techniques

All of these areas are undergoing different types of development, which are looked at in later sections of this technical note. Considerable savings are also possible through project management and coordination of contractors and construction phases, in particular, in relation to lead-time.

3.6. Conclusion

Construction costs, lead-time and capital costs (equity and debt) are a major fraction of the total cost of a kWh of nuclear energy. Furthermore, the risk of cost overruns for the first two items increases the cost of capital by introducing a risk premium. The following sections cover the steps that are required and current efforts to optimise these three factors in future EPR projects.

9. See: http://www.energie.sia-partners.com/20170905/le-financement-est-il-devenu-une-limite-au-developpement-dun-projet-nucleaire

10. Davis, L. W., *Prospect for US Nuclear Power after Fukushima,* Energy Institute at Haas, Berkeley, California, August 2011.

4. Historical construction costs for second generation nuclear reactors show that they can be managed

Historical construction costs of nuclear reactors have for the most part been published and reviewed in official reports (French National Audit Office - *Cour des Comptes*, 2012[11]) and academic articles (Grubler, 2010[12]; Lovering *et al*., 2016[13]; Berthélemy and Escobar, 2015[14]; Duquesnoy, 2013[15], d'Haeseleer, 2013[16]). These studies use data from both the French fleet and most of the nuclear countries within the OECD.

4.1. Technical and economic analysis of construction costs for French nuclear reactors

The French National Audit Office's report provides a sound statistical baseline for the construction costs of France's current fleet of 58 reactors, expressed in nominal and real terms (using a GDP deflator). A review of the data shows that including the series effect, a strategy of standardisation for the French fleet, a vertically integrated industrial organisation (in particular with architect-engineer responsibility of the Operator, EDF), as well as economies of scale resulting from an increase in the size of reactors, are all important factors that have contributed to reducing construction costs.

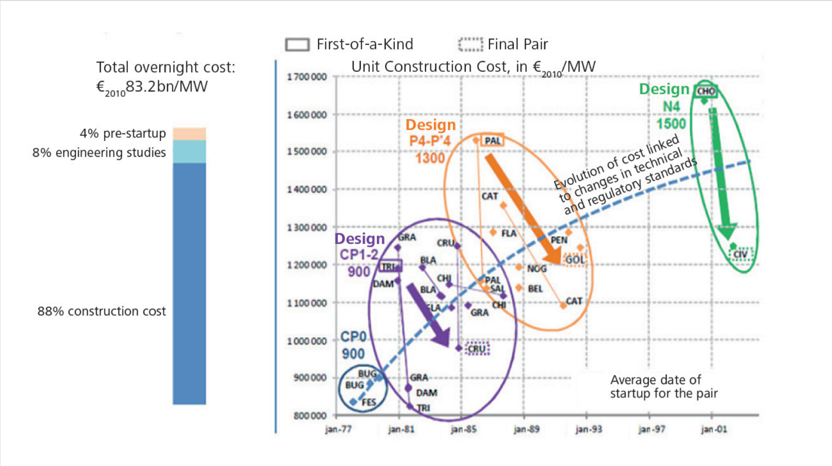

Figure 4.1 Construction cost boundaries for French nuclear reactor units, according to design. (Source: French National Audit Office - Cour des Comptes, 2012).

4.2. Econometric analysis of international cost data

Another method for correcting empirical data for First-of-a-Kind or pair effects (for example), is to carry out an econometric analysis. The causalities identified in the previous sub-section can be assessed in more detail using this method. Construction time is shown to be the key factor by which organisational factors influence construction costs.

When a workforce and specialised equipment, which cannot immediately adapt to potential project delays, are temporarily held-up there is a significant impact on construction costs. Delays affecting a sector workforce, or changes to the reactor or in the permit application procedures for specific phases of construction, can result in disruption of the schedule for the whole project, and the risk of increased costs in a number of areas.

A comparison of the French and American experience illustrates the role of construction time particularly well (Figures 4.2 and 4.3). Construction costs in the United States increased rapidly in the 1970s and 1980s as a direct result of longer construction times, which were largely due to organisational failures in an American nuclear sector that lacked standardisation. Costs increased eightfold between the start and the completion of construction of the US fleet, alongside a fourfold increase in construction time.

11 – See: https://www.ccomptes.fr/sites/default/files/EzPublish/thematic_public_report_costs_nuclear_%20power_sector_012012.pdf

12 – Grubler, A., *The costs of the French nuclear scale-up: A case of negative learning by doing*, Energy Policy, N°38(9), 2010, 5174-5188.

13 – Lovering, J. R., Yip, A. & Nordhaus, T., *Historical construction costs of global nuclear power reactors,* Energy Policy, N°91, 2016, 371-382.

14 – Berthélemy, M., & Escobar, L., *Nuclear reactors' construction costs: the role of lead-time, standardization and technological progress*, Energy Policy, N°82, 2015, 118-130.

15 – Duquesnoy, T., *Coût de construction des réacteurs REP : évolution des conditions économiques ou accroissement de la complexité?*, La lettre de l'I-tésé, N°18, 2013.

16 – See: https://www.mech.kuleuven.be/en/tme/research/energy_environment/Pdf/wpen2013-14.pdf

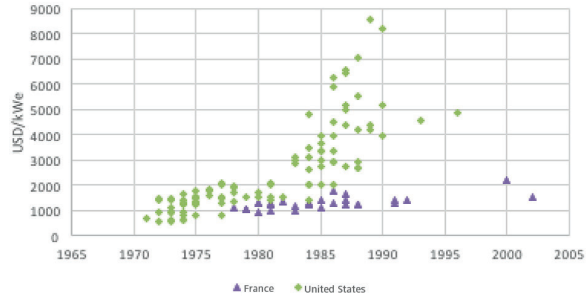

Figure 4.2 Construction costs of reactors in France and the US.
(Source: Berthélemy and Escobar, 2015).

The following figure (Figure 4.3) shows construction times, which are strongly correlated with construction costs.

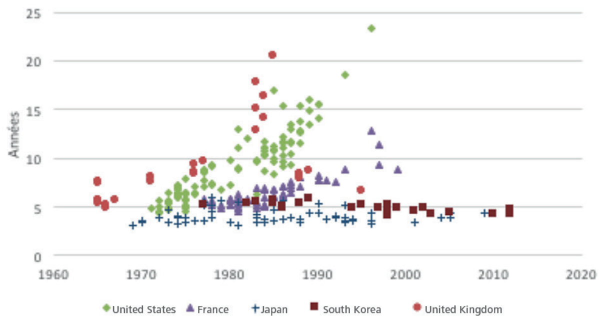

Figure 4.3 Construction time of nuclear reactors. (Source: Berthélemy and Escobar, 2015).

Series effect or learning-by-doing

A series effect was clearly observable during construction of the French fleet, with the average construction cost (€/kWe) of a series of standardised units being less than for a single unit with the same features designed and built separately.

The series effect, a term covering all the effects related to delivering large projects, has been demonstrated in several econometric studies[17].

In order for there to be a series effect, there is a need for stable technical standards, codes and norms to be used in the design, licensing and construction of all unit of a series. As soon as there is a deviation from these conditions, for example on construction projects in different countries (different safety authorities and regulations), or with different industrial assembly lines, the benefits of a series effects are likely to be lost.

The series effect is influenced by two distinct factors: the programme effect and the productivity effect. The pace of construction work (frequency and volume of annual orders in the supply chain) is a component of the productivity effect.

Programme effect

This effect originates in the strategic decisions of the architect-engineer (company managing the project and supervising reactor construction, for example EDF in France). The programme effect arises from the uniformity of studies, developments, qualifications and testing of materials for one reactor model built in series. The corresponding costs are independent of the number of units involved and are fairly independent of unit size (rated power). They are, however, strongly impacted by the level of innovation and degree of complexity introduced in a new design.

Productivity effect

This effect is mostly seen in the supply chain, with suppliers passing on gains in productivity in their prices. It is highly dependent on the visibility given to suppliers with a guaranteed order for a series of identical components. This visibility means that the planning, and use of resources and production tools, can be optimised.

Unit costs are also sensitive to the pace effect, which leads to greater frequency and impacts annual volumes.

Pace effect

The pace effect exists for all stakeholders, and is closely related to the series effect. It reflects the fact that the beneficial series effect is a function of the associated pace of commitment, within the range allowed by the existing supply chain potential. For this effect to be significant there must be enough units to maintain a minimum ongoing activity, both in terms of engineering studies and equipment manufacturing. The continuity of commitments is an essential condition, as the pace of construction is directly related to a volume effect. Fixed costs (plant amortisation, maintenance of skills) can be significant for low annual volumes. For example, the number of computer scientists, while the use of computers has increased significantly over the last 20 years (with associated productivity gains), has remained largely fixed.

The series effect is enhanced when several reactors of the same design are built on the same site: site development works, as well as some infrastructures and annex buildings, are shared, and the resulting pair effect leads to a cost reduction of about 15% for the second reactor[18]. By combining this effect with the need for new power capacities (replacement of the fleet, with the possibility of a slight reduction in installed capacity), and providing the supply chain with a degree of visibility for about fifteen years would mean committing to a programme of 3 to 4 pairs.

17 – See: Berthélemy and Escobar, *op. cit.*, and Escobar & Lévêque, *Revisiting the Cost Escalation Curse of Nuclear Power Generation: New Lessons from the French Experience*, Economics of Energy and Environmental Policy, Vol. 4, 2015.

18 – In 2000, the OECD/NEA costed the pair effect at 15% for the second unit on a site, and at an additional 5% for construction of two pairs. Source: https://www.oecd-nea.org/ndd/pubs/2000/2088-reduction-capital-costs.pdf

By way of illustration, EDF expects a 20% construction cost saving on its offer of two EPRs for Sizewell C by taking advantage of lessons learned on the Hinkley Point project[19]. EDF is confident that they can remove most of the £2 billion (€2.25 billion) needed for the pre-construction site preparation work at Hinkley Point C. Other significant savings are to be made by using sub-contractors already working on the site and equipment that has already been through the required certification process for use at a nuclear site.

4.3. Conclusion

Historical cost analysis shows that, in France, construction costs of second generation reactors are generally well managed. For other countries, however, success in managing costs has proved more variable, especially comparing the United States, whose performance has been poor, and Asian countries (South Korea, Japan), which have kept costs down. Two of the most important factors are sound management of project timelines and having a structured programme in place (pace of construction and industrial policy).

19 – Source: EDF (The Times, 3rd January2018).

5. Projected costs of future EPRs

Section 2 of this technical note describes the international context. The challenge for France lies in its ability to reduce the costs of future EPRs, based on lessons learned from current projects, primarily that of Flamanville 3.

5.1. Projected costs of future EPRs: findings from the OECD/IEA-NEA study

The recent OECD/IEA-NEA (2015) study on electricity generation costs, focusing on construction costs of new units starting around 2020-2030, compiles estimates for EPRs from different European governments (Belgium, Finland, France, United Kingdom), resulting in a cost range of €3,800 to €4,500/kWe. This shows a cost reduction of the order of 30% compared to the first EPRs coming into operation in 2018, at a cost of €5,200 to €6,560/kWe. The following table provides country-specific estimates:

ONGOING PROJECTS	Olkiluoto 3	Flamanville 3	Hinkley Point C
MWe (net)	1630	1600	3300
Construction time	13 years	11 years	6.5 years
Overnight construction cost	>€8.5 billion	€10.5 billion	€23 billion*
€/kWe	>5200	6563	7000
IEA-NEA Study 2020 projections	**Finland**	**France**	**United Kingdom**
USD/kWe	4896	5067**	6070
€/kWe***	3672	3800	4520
Cost reduction	**-28%**	**-40%**	**-36%**

Table 5.1. Construction cost estimates for future EPRs (Source: IEA-NEA 2015).
*£19.6 billion (EDF, WNN 3/7/2017) for 2 units.
**For a series by 2030.
***With $US 1 = €0.75 = £0.64

The challenge in OECD countries is to bring costs down compared with those of current constructions. For 2020 onwards, the projected cost reduction varies according to the country, with France's data including the series effect. The French scenario is based on partial replacement of its current fleet, with a first series of EPRs to be commissioned from 2030.

A cost reduction of 30% in France seems achievable through a combination of:

- An improved design in terms of lower construction costs (in progress); and
- Optimised construction methods.

A nuclear industry with enough visibility for new build projects will generate a series effect linked to programme (visibility, continuity) and productivity (industrial structural organisation, standardisation) effects.

5.2. Lessons learned and optimisation of EPRs

The former-Areva NP, now Framatome, has been working since 2009 to gather feedback from current construction projects. The Taishan 1 & 2 projects have already benefited from such feedback (from Olkiluoto 3 and Flamanville 3). Here, construction time between pouring of the first concrete and installation of the dome was reduced by half (24 months instead of 47) between Olkiluoto 3 and Taishan.

The following examples clearly demonstrate the gains to be made from integrating lessons learned (Source: Areva NP now Framatome):

- A significant reduction in the number of hours for engineering studies, and therefore the associated costs, for the nuclear steam supply system (-60% between Olkiluoto 3 and Taishan).
- A significant (-40%) reduction in the manufacturing time of large components, through increased efficiency of production processes (for example, Taishan's steam generator production time was reduced by one year, of which 4.5 months through use of a forged component instead of a series of welds for part of the steam generators).
- Increased adherence to construction schedules resulting from fewer supply-related delays (65% reduction of delays, on average, between Olkiluoto 3 and Taishan).
- The overall lead-time (between first concrete and first criticality) should be 30% lower.

The number of hours worked by the engineering teams is 60% lower for Taishan than for Olkiluoto 3, which illustrates the benefits of standardisation:

- First complete plans of piping and instrumentation systems reduced from 14 to 9 months; this step is required for completing the layout plan and for the civil engineering work.
- Number of detailed plan modifications reduced from 10 to 3.
- Procedures for installing the instrumentation and control systems were made available in 20 rather than 30 months.

In addition, the ongoing construction of the 4 EPRs has made it possible to set up a well-structured supply chain for the design of new EPR reactors:

- An engineering and project team of over 6,000 people:
  - Including more than 1,000 experienced project managers.
  - Project managers at the Taishan site had previously worked on Olkiluoto 3 or Flamanville 3.
- Increased expertise in procurement and qualification of companies supplying equipment and engineering services.
- Established and reliable internal procedures for collecting feedback and analysing the lessons learned. It is estimated that more than 1,600 lessons learned were recorded during these construction projects.

The EPR optimisation approach, was jointly launched in 2015 by EDF and Areva NP (now Framatome) engineering teams, to take advantage of lessons learned from the EPRs currently under construction. It incorporates lessons learned from the concept itself, particularly in terms of design simplification, improvement of its constructability and industrialisation of its equipment. It also implements system engineering techniques to improve the performance of professionals working on the project, and takes into account the latest techniques and methods, particularly in civil engineering and numerical modelling.

The main technical options that have been retained following integration of lessons learned are:

- **Reactor core of the same rated power as the latest EPRs** (thermal power of 4,590 MWth) optimising reuse of the primary equipment of the EPR. This choice makes it possible to keep the same equipment specifications as for previous projects, and thus to limit, as much as possible, the risks related to their qualification and supply.
- **Single-wall containment with liner** ensuring both containment of radioactive materials in the event of an accident and protection against external threats, which significantly simplifies construction.
- **Three independent emergency cooling systems.** This choice aims to simplify the design as much as possible, and incorporates the lessons learned from the Fukushima accident most effectively, by further separating the facilities used to prevent core meltdown from those used to mitigate this type of accident.
- **Optimisation and simplification of the construction process based on lessons learned by suppliers,** leading to significant reductions in procurement costs and lead-time for construction work:
  - Simplification of the building architecture.
  - Optimisation of concrete reinforcement.
  - Optimisation of electromechanical assembly using more prefabrication and reducing the number of hydraulic tests.
  - Standardisation of equipment through the use of catalogues based on industry standards.
  - Size optimisation of the main control unit, by reducing the amount of data transmitted from the instrumentation and control equipment to the control unit.

– Development of system engineering solutions specific to complex projects.

These options focus on short-term, ongoing optimisations. Many additional options are also the subject of studies and research for the longer (and very long) term.

5.3. Optimisation of nuclear construction sites

One of the areas identified for optimisation - already being implemented or studied - concerns the overall structural organisation of the construction project, in order to reduce construction times and, therefore, costs. In particular:

- **Use of advanced construction techniques,** with optimised logistics choices for heavy components.
- **Pre-assembly or 'modularisation' of reactor parts** when the overall benefit is greater than the overall cost of the modification.

Some of these organisational changes may require minor design adjustments, but this would not change the overall design, safety level, or performance. The **development of numerical simulation of construction sites** is also an important advantage, as it can be used to optimise the coordination of different contractors.

Areas of technical progress being explored include simplifying the design of reinforced concrete (percentage of steel, concrete thickness), supporting the development of new construction methods (modularity, prefabrication, self-supporting structures), and developing digital tools to support the decision-making process (from design to operation). The integration of new solutions will allow future reactors to benefit from new technologies for taking measurements, high-performance computing, augmented reality, etc.

5.4. Reviving the European nuclear supply chain

Until recently, no nuclear reactor project had been launched or commissioned in Europe for about two decades. As the nuclear industry is characterised by very strict requirements in terms of quality standards, purity of materials, behaviour of equipment under irradiation, long-term behaviour, etc., the entire industrial supply chain had to be revived to build Olkiluoto 3 and Flamanville 3. Framatome has now qualified more than 600 suppliers of equipment and services, and has made significant progress in the quality and the delivery times of supplies.

The entire industrial supply chain - systems, services and components - must be qualified at the 'nuclear quality' level, with quality standards defined and controlled by certified and independent bodies. Many suppliers have had to develop competences, through recruitment or internal training programmes, in areas specific to nuclear power.

The map below shows a geographical distribution of Europe's revived supply chain (as of June 2015). While France and Germany account for a high proportion, eight other countries have between 11 and 100 companies involved in the sector's supply chain.

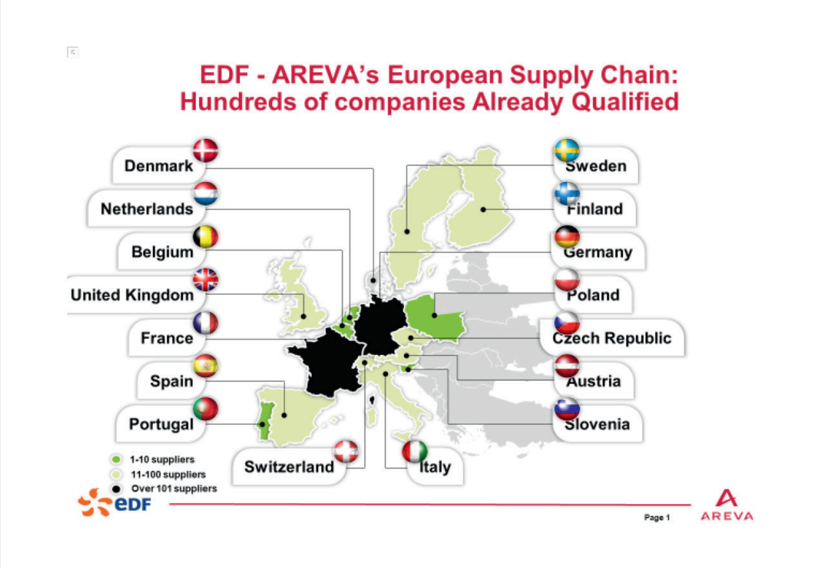

Figure 5.1 EDF and Framatome's (ex-Areva NP) European supply chain.
(Sources: EDF and Framatome).

Future projects will benefit from this revived supply chain, with resulting costs reductions.

To guarantee the capability of France's nuclear industry, in terms of capacity, competences and competitiveness, to deliver new projects in the future, and in order to benefit from a series effect, a construction development programme must be defined, alongside a structured supply chain.

5.5. Integration of nuclear exports objectives

Constructing and selling EPRs in other countries adds additional constraints and targets, for which today's lessons learned are already proving useful.

- Flamanville 3 is now used as a reference, having already integrated feedback from Olkiluoto 3, being a sound reference for safety options. This concept does not, however, eliminate the need for modifications which meet specific construction site constraints, as well as the specific requirements of national safety authorities. As more EPRs are built in different countries/sites, the need for modification will be increasingly reduced.
- A supply chain and project management structure capable of meeting the localisation and training challenges for successful project completion, and for preparation of the Operator, is a basic requirement for each project. Even if the industry has vast experience, objectives may vary from one project to another and can be impacted by cultural factors. It is clear that having a supply chain and project teams working on the construction of several reactors in parallel is not comparable to a supply chain that has to be revived.

- Tools and working methods to fully integrate cultural factors, communication and other areas, in order to create a safety culture for the future Operator, as well as high performance during plant operation, are essential aspects of complex projects. Many of the lessons learned have already been integrated, and work at the Hinkley Point site will help in the development of new tools and systems. In this respect, additional ongoing improvements in performance are still possible.

5.6. Conclusion

Cost reduction programmes are being implemented worldwide (United States, France, United Kingdom, etc.) and shared, in particular within the OECD's Nuclear Energy Agency. This industrial optimisation is possible now and must be carried out in the short-term, for reactors commissioned by 2030 at the latest.

The drivers of investment cost reductions have been well identified: i) feedback from current construction projects, and ii) benefits resulting from a structured construction programme.

The reduction of associated risks is primarily linked to process control and supply chain mobilisation as part of an industrial programme (for example 6 optimised EPR reactors). The success of current projects (with the commissioning of the Taishan EPR in early 2018, followed by Flamanville in late 2018/early 2019) will be a key factor in risk reduction, as it will demonstrate the viability of the reactor design.

In France, the objective is to reduce the overnight costs of a future pair of EPRs by up to 30%. With improved financing conditions, which in turn are linked to reduced project risks (including cost and time-to-investment risks), this objective will make a decisive contribution to reducing the levelised costs of a series of standardised new nuclear reactors, in order to remain competitive with the cheapest dispatchable power plants: in this case the lower end of the range of production costs for a combined-cycle gas plant with carbon pricing (about €20-30/tCO_2).

6. Other cost items of nuclear power are a limited source of risks

In addition to the construction cost, which is the main item of the cost per kWh for a new reactor, variable costs must also be considered. These are the operating and maintenance, fuel cycle, and decommissioning costs.

According to the OECD/IEA-NEA 2015 report, for future EPRs in France the operating costs are around €10/MWh, and the cost of the fuel cycle (including waste management) is around €7/MWh, while the cost of decommissioning is less than €0.3/MWh. When compared to the investment cost (€45/MWh with a discount rate of 7%), these cost items represent a relatively small fraction of the total costs.

6.1. Characteristics of the additional cost items

Operation and maintenance costs

These costs cover a variety of plant-related items such as sitework management, training, support services, operating costs, engineering costs, etc.

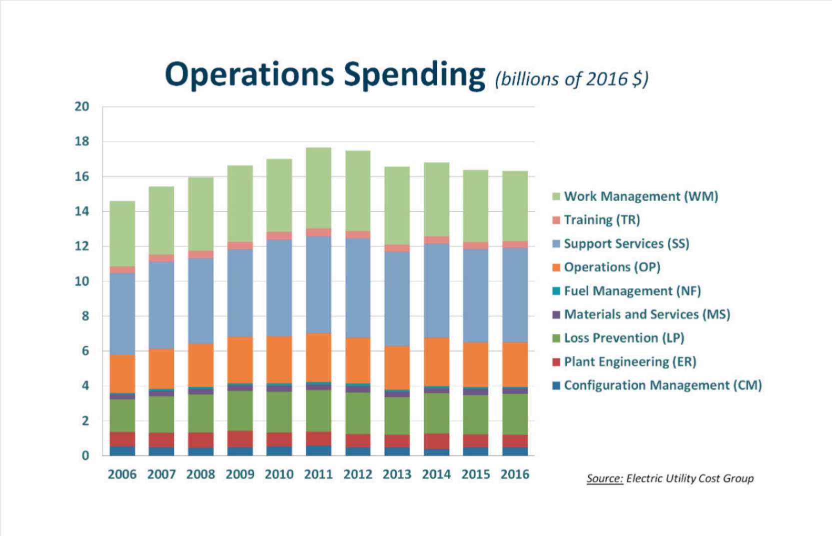

Figure 6.1 Operational spending for nuclear reactors: examples from the United States up to 2016. (Source: NEI[20]).

20 – Electric Utility Cost Group, cited by the NEI White Paper on *Nuclear Costs in Context*, August 2017.

Operating and maintenance costs can be quite variable from one country to another depending on the scope and the overhead costs of the nuclear utility. The OECD/IEA-NEA report (2015) shows costs in the range of US$10-21/MWh for European countries, with the highest costs in the United Kingdom. For France, the operating cost of US$13.33/MWh is for a series of EPR reactors commissioned from 2030, and is lower than for the current fleet.

The new reactor models, with greater efficiency and reliability, are designed for high availability factors, of 91% or more, which lowers fixed operating costs per kWh. In addition, technical improvements, such as neutron reflectors in the reactor pressure vessel, or improvements in the efficiency of the steam generators, reduce production losses and therefore increase the electrical power recovered per unit of fuel consumed.

As with any industrial activity, performance targets and the need to be competitive in electricity markets incentivises nuclear utilities to optimise production costs in compliance with safety standards. Costs variations are therefore limited.

Decommissioning costs

The 2015 OECD/IEA-NEA report[21] uses a default value set at 15% of the overnight cost where no data regarding a country's decommissioning provisions for nuclear are provided. This value is added to the cost of the reactor and is discounted over the operating lifetime of the reactor (60 years) in the calculation of the levelised cost. As these expenditures occur long after the production of the kWh, their contribution to the cost of the kWh is very small.

Fuel cycle costs

In the OECD/IEA-NEA 2015 report[22], the average values for European countries are between $9 and $11/MWh regardless of whether the country operates with an open or closed fuel cycle. This report uses the following values:

Open fuel cycle	Costs US$/MWh	Additional Information
Front end	7	Mining, conversion, enrichment, fuel fabrication
Back end	2.33	Removal of spent fuel, interim storage and final disposal

Table 6.1. Examples of the different components of fuel cycle costs. (Source: OECD/IEA-NEA)

The general consensus is that fuel cycle costs represent about 15-20% of the total production costs. The 2012 OECD/NEA report[23] states that the fuel cycle accounts for about 20% of the levelised cost per kWh, including 15% for the front end of the fuel cycle (including fuel fabrication), and 5% for the back end.

Impact of the price of uranium

At the front end of the fuel cycle, uranium supply accounts for about half of costs. At current spot prices this represents less than €2/MWh, since the price of uranium has fallen sharply on the world market, to below $30/lbU3O8. The global supply and demand forecasts (source: WNA) suggest that the price will only rise significantly in about a decade's time. However, in the longer run, lack of investment in mining is expected to affect the uranium price, which is likely to double to $60/lbU3O8 or more. The impact on the total cost of production will, however, remain limited: €2 to €3/MWh.

Impact of the other front end activities

For the other front end activities, the transition in recent years from gaseous diffusion enrichment technology, that consumes a lot of energy, towards gas centrifuge techniques, which are much more efficient (by a factor of around 50), should be noted. This global technological change is resulting in lower costs for the Separation Work Units, which in turn further reduces current front end costs. It is a structural reduction in the cost, but one which only affects part of the costs of the cycle.

6.2. Conclusion

Operating, fuel and decommissioning costs present low risks and their impact on the levelised cost per MWh remains limited. For operations, the example of the US nuclear fleet also shows that productivity gains can be achieved for an older fleet than the French fleet.

For all of the different generations of nuclear technologies, as the fuel cycle share of the cost per MWh is low, it is insensitive to changes in the cost of uranium and related services. Similarly, decommissioning and waste management costs remain low compared to total costs.

21 – See above reference.

22 – See above reference.

23 – *Trends in the Nuclear Fuel Cycle: Economic, Environmental and Social Aspects*, OECD/NEA 2012.

7. The importance of nuclear new build financing and the interplay with risk management

New nuclear financing directly affects the levelised cost per kWh. This financing is strongly influenced by the nature of the risks (high risks leading to a high expected rate of return on investment and, therefore, a higher cost of capital), and the organisational framework, which distributes the risks across the different stakeholders. Governments have a central role to play in this respect, as they may decide to carry a greater or lower share of the risk themselves (to set up the conditions for the development of selected technologies or to support a national export strategy). Governments can also put strategies in place to transfer risks to the final consumers.

7.1. Attracting investors

In addition to the inherent risks involved in carrying out the project (cost, lead-time, performance, regulation, etc.), investors face other risks related to the market and its predictability. The main risks are a fall in prices and a lower value for production than expected. Others are of a political nature (see below).

The rate of return required by the investors will be higher with increased expected project risks. Currently, a potential investment in one (or two) EPR in Europe - and more generally in a new nuclear unit – would be subject to several sources of risk:

- **Market risk:** the average price per kWh on the European wholesale market has been halved over the last ten years (from €60 to €30/MWh), under the combined effect of falling coal prices, excess capacities due to subsidised investments in renewables and stagnant demand.
- **Political risk:** potential review of a nuclear project following a change of majority in Government, opposition movements leading to construction delays.
- **Technical risk:** possible delays and construction costs overruns as observed for Olkiluoto 3 in Finland, Mochovce 3 & 4 in Slovakia, and Flamanville 3 in France.

The investment payback period is greater than 10 years for these projects. Their long-term economic value increases their sensitivity to political risk and price risk. The cost of capital (WACC) is closer to 10% (as is the case for the Hinkley Point C project in the United Kingdom). In comparison, the WACC is between 3% and 6% for ground-based solar power projects in France, due to low risks.

An EPR project concentrates various different types of risks in a multi-billion euro project, whereas a €15 million solar project, supported by purchase power agreements will have lower and more mitigable risks.

This situation can potentially create a vicious circle: the higher the perceived risk, the more the WACC increases and the financing becomes expensive, the more the total cost of the project increases and the more the market risk increases. For example, the levelised cost per kWh of Hinkley Point C in the United Kingdom is doubled when the discount rate goes from 3% to 10% (value close to EDF's WACC for the Hinkley Point project).

The level of financing for this type of project may require several sources of funding, but may also allocate a risk to the balance sheet of the company in charge of the project. Thus, one way to attract investors for the construction of nuclear reactors is to reduce the WACC by mitigating some risks or by transferring all or part of the risks.

7.2. Project risks: the role of construction lead-time on the levelised costs of the Flamanville project

This is a key factor. Figure 7.1 shows the impact of a 3-year delay on the payback time (when revenues cover expenditures). Previous sections have shown that an increase in the lead-time has a strong impact on costs, and results in losses due to interest accrued over the longer period. In addition to this, the reactor starts generating electricity at a later date. These two effects lead to a significant shift in the payback time. In the figure below, the lag is ten years for a 3-year delay. Management of project schedules, and/or specific risks (transferring all or part of the risk to a third party) are decisive factors in the risk mitigation strategy for nuclear projects, and therefore in their feasibility.

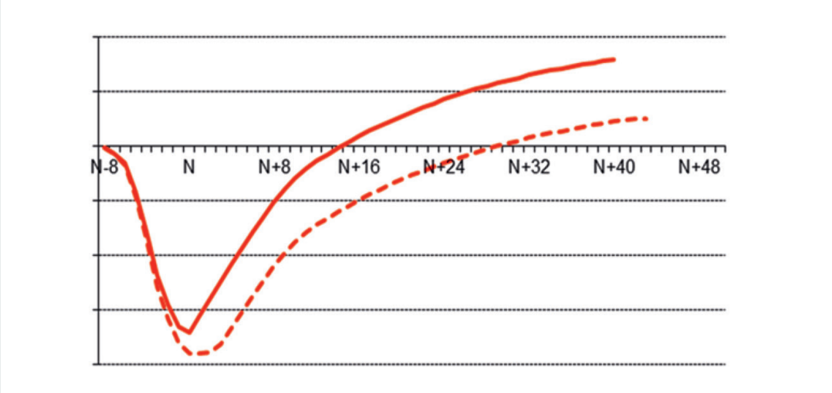

Figure 7.1 Impact on the payback time of a 3-year delay in the commissioning of Flamanville 3. (Source: EDF).

7.3. Price risks in the EU electricity market

Market risk is the vendor's risk of encountering a situation that differs significantly from initial expectations, such as a fall in prices. Electricity markets are often complex and vary depending on local regulatory conditions.

In Europe, part of the market remains regulated, but an increasing share is open to competition and derives its revenue from wholesale markets. Current market rules are likely

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to require major adjustments in the future given the extent of existing market failures, including the lack of long-term price signals for investors.

7.4. The Finnish response: the Mankala model

The Finnish company TVO, which was the first in the world to invest in an EPR, has a special status. While it is a private company, which sells its electricity on the competitive wholesale market, it also has two key specificities: it is a cooperative, whose shareholders are mainly large consumers of electricity, and must therefore not generate a profit. These shareholders commit to purchase TVO's electricity at cost (LCOE) either for their own needs (paper manufacturers, chemical industry, etc.), to offer it on the wholesale market (Fortum, a 25% shareholder in TVO), or to supply it to its inhabitants (City of Helsinki, 8% shareholder, and other municipalities). This scheme, the so-called 'Mankala model', is not unique to TVO; in 2010 it applied to 42% of Finnish national electricity production. It provides shareholders with the following advantages:

- A stable long-term price, not subject to price volatility on the wholesale market, and with security of supply; this is important for large electricity consumers from the industrial sector (electrolysis for example).
- The sharing of investment risk between several investors-consumers, which is of particular benefit to small stakeholders that would not otherwise be able to invest alone in a large production unit (whether it is a nuclear, hydro, or coal power plant).
- As a result, an excellent valuation by rating agencies which take solidarity among shareholders into account.

The Olkiluoto EPR project was 75% financed by loans issued by TVO, its shareholders, and the French export credit agency, with the remaining 25% provided by shareholders' equity. The resulting cost of capital (WACC) has not been made publicly available, but economic studies published in Finland (Lappeenranta University) on the competitiveness of nuclear power suggest a discount rate of about 5%. The status of TVO, which limits some of the risks, makes it possible to deliver a competitive cost of capital.

7.5. Impacts of project risks on the cost of capital: lessons from Hinkley Point C

The decision-making context for investment in two EPRs at Hinkley Point can be summarised as follows:

- Low political risk due to the consensus between political parties on energy policy and the broad public acceptance of nuclear power in the UK.
- Limited market risk due to the *Contracts for Difference* (CfD) mechanism applicable to all low-carbon energy projects, guaranteeing the electricity price through compensation of price variations on wholesale market.
- High technical risk, a significant factor in a project, related to delays experienced by the other EPR projects and the need to upgrade the British nuclear industry.

The *Contracts for Difference* (CfD) mechanism set up between the producers of low-carbon electricity and a centralised purchaser, an *ad hoc* company created by the State, frees the project from risks related to price volatility on the wholesale market. The long term price (£92/MWh over 32 years for Hinkley Point C), the 'strike price', is set either through a tender process which awards the contract to the lowest bidder, or by negotiation between the project owner (EDF Energy for Hinkley Point C) and the State, where a tender process is not feasible.

The following figure (Figure 7.2) illustrates the high degree of sensitivity of the Hinkley Point C project's strike price to the expected rate of return for the investor. When there is a public investor (i.e. the British Government), it is possible to set a rate of about 2%, leading to a strike price of £20-30/MWh. The private status of the investor (consortium led by EDF), and the nature of the associated risks, have led to an expected rate of return of almost 10%, and a strike price of around £100/MWh. This highlights the importance of the contractual arrangement and the nature of the risk borne by the stakeholders. These are strategic projects, which require backing from the State, resulting in modest rates, or (which is equivalent) a reduced sensitivity of electricity revenues to cost of construction (see lefthand part of Figure 7.2).

As such, the UK National Audit Office's analysis shows that, in most scenarios, significant costs overruns would not undermine the current agreement with increased costs for the final consumers.

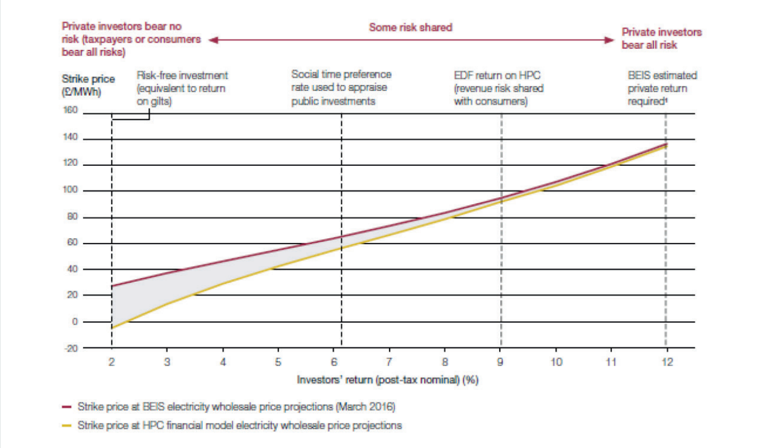

Figure 7.3 Strike price sensitivity to investors' rate of return. (Source: UK National Audit Office[24]).

24 – Department for Business, Energy & Industrial Strategy, "Hinkley Point C", National Audit Office, HC 40 SESSION 2017-18, 23 JUNE 2017.

We are dealing here with a broader concept of 'economic value' that goes beyond 'profitability'. This has been emphasised by the British authorities in order to justify a higher strike price at Hinkley Point C, compared to those of onshore wind projects and certain large ground-based solar projects:

- Intermittent production units require additional network (connection) and balancing costs (need for back-up, flexible power plants) in order to produce the same quantity of electricity.
- The economic value of nuclear projects must take into account the implicit values linked to: the *reliability* of a means of production, which provides a capacity that can be predicted for 60 years; the *diversity* of technologies used in the mix, which contributes to security of supply; and the *option value of the first pair of reactors* paving the way for subsequent projects.
- Other low-carbon technologies (offshore wind, fossil fuel plants with carbon capture) can have higher costs.

This concept of economic value, which goes beyond the strict framework of the project and its shareholder, is a justification for the State or other stakeholders to bear part of the risk.

7.6. Implications for future nuclear projects in France: the need for a Strategist State

The current decision-making context in France, with regards to future EPRs and fleet renewal, can be compared to that of the Hinkley Point C project as follows:

- Higher political risk: a higher proportion of the population currently supports a nuclear phase-out.
- Higher market risk: without improvement in the European market (€30/MWh) and/or without introduction of mechanisms similar to UK CfDs.
- Lower technical risk: through lessons learned from the four EPRs that will have started up in the meantime.
- Level of investment of the same order of magnitude as Hinkley Point C if a pair of EPRs is built on the same site.

Many stakeholders and analysts are now advocating for an overhaul of the European electricity market, in order to send long-term price signals for investments. They are also calling for a change in the policies supporting renewable energies, which currently circumvent the market, doubling the risk with resulting overcapacity and the collapse of average wholesale prices. However, it is not guaranteed that these reforms will have been fully implemented by the time the decision, for the construction of the first pair of EPRs around 2030, has to be made.

In the 1980s, the French 'Strategist State' decided to launch its national nuclear programme and to finance EDF's nuclear investments in a new way. EDF was, at this point, still a public company and a State monopoly; it made direct and extensive use of international loans, with low interest rates agreed as a result of State guarantees and the company's monopoly. This was the preferred solution, a better alternative to taking loans on the French markets. EDF was unequivocally a national utility applying the energy policy of the French State. This monopoly no longer exists; French energy policy involves other utilities and EDF, like the other producers, is negatively impacted by low electricity prices on the European market.

However, within the context of a European electricity market, the example of the United Kingdom shows that the State can still play a significant central role once it has clearly defined its priorities. In this case, the objective is to combine an ambitious climate policy, with energy security and industrial policy. In France, as in the United Kingdom, all aspects of the economic value of new nuclear projects must be considered, when being compared to renewable projects. In addition to the arguments put forward by the British authorities regarding the Hinkley Point C project (discussed in section 7.5), it is clear that development of the French nuclear industry, the third largest industry in terms of jobs, is a key issue. In order to fully understand this issue, the real export capacity of the sector, in terms of electricity production exports (Europe) and equipment exports (China, India and other countries) must be taken into account.

Planning the renewal of the French nuclear fleet must, therefore, include considering some public-private arrangement in order to significantly reduce financing costs.

7.7. Conclusion

Financing arrangements have a significant impact on the cost of nuclear power. Currently, the rate of return expected by the industry, taking into account the market context, costs, risks, regulations and broader governance, is currently much higher for nuclear projects than for renewable projects, in Europe and the United States. It is therefore important to reduce the overall risks in order to lower expected rates of return.

The main drivers for reducing economic risks, which are further discussed in the following section, are as follows:

- Increasing control over construction costs and lead-time: this will be made easier by a standardised design, learning-by-doing effects throughout the supply chain, and the setting up of a construction programme.
- Long-term price signals on electricity markets, including regulatory incentives for investments in all low-carbon technologies, all of which are highly capital intensive. Nuclear power is part of the solution (e.g. United Kingdom). For these technologies, it seems socially optimal to transfer part of the risk to the State.

8. Reducing market risks to attract investors

In recent years, funding for new nuclear projects has become a major obstacle to its development, particularly in countries that have liberalised their electricity sector. Nuclear energy is, like other low-carbon energies, a technology whose cost structure is dominated by investments during the construction phase. In the absence of incentive policies, these means of production are exposed to market risks (quantity and price risks), which makes it more difficult to finance them.

In addition to this, the European electricity market is in crisis, with a downward trend in prices that fell by almost half between 2008 and 2016, from an average of €65 to around €30/MWh. This is partly related to subsidy policies for renewable energies which, in a context of stagnant electricity demand, have contributed not only to this decrease, but also to a greater volatility of electricity prices[25], notably with the appearance of negative prices. The falling gas prices on the European market have also contributed to this trend. This results not only in an increase in market risks, but also a significant reduction in the stock market valuation of European utilities, which limits their ability to use on-balance sheet financing. These risks, therefore, directly impact the availability and cost of funding sources.

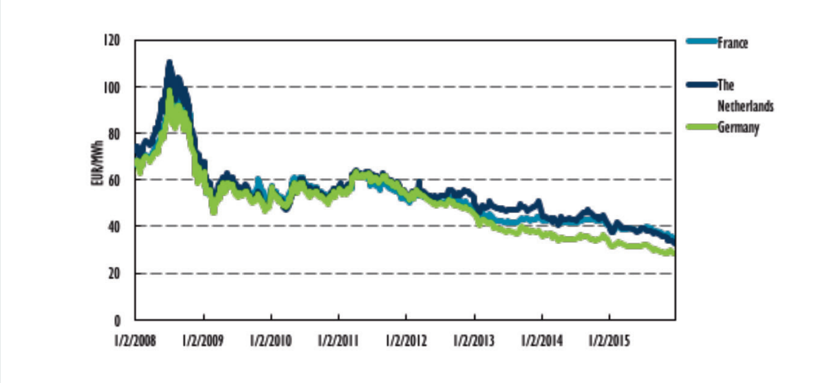

Figure 8.1 Historical European electricity wholesale prices (€/MWh). (Source: IEA)

Therefore, in order to launch the new nuclear (or renewable) projects required to meet targets for greenhouse gas reduction, at a minimal cost, new arrangements that share the risks between investors, consumers and the State must be put in place. This is already the case for solar and wind projects, which benefit from support mechanisms (feed-in tariffs, calls for tenders) that guarantee prices and sales volumes. Nuclear power in France, however, does not benefit from these support measures, resulting in distortion of competition.

In order to set up these risk-sharing arrangements, two complementary mechanisms can be developed:

- **Support for low-carbon investments through creation of a realistic and sustainable CO_2 price** for the electricity sector.
- **Guaranteeing electricity prices through long-term contracts,** in particular based on the model used in the United Kingdom for the Hinkley Point C project.

8.1. Carbon pricing reforms and the electricity system

The EU emissions 'cap and trading' system (ETS) for CO_2 allowances is not currently acting as an incentive to reduce emissions, with a price of about €10/tCO_2. A reform proposal is currently being considered, which would absorb surplus emission allowances established under the initial allocation rules. This proposal includes the creation of a Market Stability Reserve (MSR) and a more stringent emissions cap.

Many experts[26] question the effectiveness of this reform proposal to establish a realistic and sustainable increase in the price of CO_2 in the coming years. In particular, the recent negotiations do not directly integrate the new objectives of the Paris Climate Agreement (COP21). Similarly, the negative impact on the price of allowances of specific policies for energy efficiency or renewable energies, is not explicitly taken into account, and contributes to a surplus of emission allowances[27].

In this context, initiating a realistic increase in the price of CO_2 for the electricity system requires the introduction of a floor price of around €20 to €30/tCO_2 by 2020.

25 – See: http://www.creden.univ-montp1.fr/downloads/cahiers/CC-16-07-115.pdf (Article published in *Revue de l'Energie*, 2016).

26 – For example: https://www.euractiv.com/section/emissions-trading-scheme/opinion/the-case-for-a-price-floor-in-the-eu-ets/

27 – See: https://www.i4ce.org/wp-core/wp-content/uploads/2017/09/17-09-I4CE-Enerdata-IF-PEN_EU-ETS-post-2020-reform-last-call_Policy-Brief.pdf

8.2. Long-term contracts for securing financing for low-carbon energy projects
In addition to introducing a meaningful carbon price, capital-intensive investments such as nuclear power or renewables need visibility on the price of electricity over the operating lifetime of the unit.
To this effect, long-term contracts between supplier and consumer should be established, and should satisfy both parties by providing for a guaranteed purchase price over a long period, thus justifying investment by the supplier and ensuring cost stability for the consumer. The Finnish scheme used by the company TVO goes a step further, involving large electricity consumers (paper industry, municipalities, etc.) who are both customers and shareholders of TVO, with tariffs set at the average cost of production.

The reform of the electricity market in the United Kingdom, with the introduction of a pragmatic *Contract for Difference* (CfD) mechanism, can equally be applied in France in order to reduce market risks related to volatility in the electricity price. The CfD mechanism guarantees a long-term price (for example over the first 30-35 years of operation), with consumer compensation in the event of higher market prices (and vice versa).

8.3. Conclusion
Reduction of market risks in order to enable the financing of investments in nuclear projects (and more generally, all forms of low-carbon energy production) requires, above all, reform of market rules, in order to establish both a realistic and sustainable increase in the price of CO_2 emissions, and to guarantee revenues using long-term contracts (e.g. Contracts for Difference). Such reforms produce a framework that combines the benefits of nuclear power, alongside access to dispatchable and flexible generation with high security of supply, while emitting only limited amounts of greenhouse gases. They would ensure, as previously explained, that the 'decentralised' decision-making of investors corresponds to the social optimum, with the State as guarantor.

9. Implications for investment in future nuclear and renewal of the French fleet

The Energy Transition for Green Growth Law (LTECV - *Loi de Transition Energétique pour la Croissance Verte*) sets out guidelines concerning the French electricity mix, as will its application in terms of a capacity programme, which is currently being defined for the next ten years (Multi-Year Energy Plan or PPE - *Programmation Pluriannuelle de l'Energie*). The main objective of the law is to reduce France's greenhouse gas emissions. With regard to electricity, this will be predominantly achieved by shutting down coal power plants (which should be completed by 2022). Beyond this, the national electricity mix must remain one of the most decarbonised in the world, with greenhouse gas emissions in the range of 10g to 30g of CO_2 equivalent/kWh, so that it can be used to decarbonise other sectors of the economy through increased use of electricity. The law's reference to a desire to reduce the share of nuclear has a different goal to CO_2 emissions reduction: a diversification of the electricity mix.

The long-term objective concerning the share of nuclear power in the national energy mix has not yet been fixed, but a long-term trend towards stabilisation at around 50% seems reasonable at this point[28]. In order to achieve such an objective, it will be necessary to spread the renewal of the current fleet over the next few decades, maintaining a significant share of nuclear in today's mix in order to start actively preparing for its renewal. It is both a question of national sovereignty and industrial policy for a sector that employs 220,000 people[29]. Keeping the nuclear option open requires the construction of new reactors, which raises the question of the timing, the choice of concept and the pace of these constructions.

The timing is mainly related to keeping the nuclear option in the long-term and, thus, to the maintenance of skills in the French industrial sector. Given the current commitments abroad and the commissioning of Flamanville 3 in the near future, it is advisable to order new units without delay. Given the administrative and industrial timescales for transition to the 'post-FOAK' industrial phase, commissioning by 2030 at the latest would be consistent with this strategy. These new reactors will help launch the renewal of the fleet.

28 – A recent study conducted by the University of Athens using the PRIMES model (frequently used by the European Commission), published by the SFEN, estimates the share of nuclear in France, in the very long-term, at about one third of national production.

29 – See, in particular, the SFEN report on employment in the energy transition: http://www.sfen.org/sites/default/files/public/atoms/files/bilan_emplois_de_la_transition_energetique_-_un_argument_a_manier_avec_precaution_-_sfen.pdf, as well as the SFEN report on regional employment in nuclear in France: http://www.sfen.org/sites/default/files/public/atoms/files/sfen-cahier-des-regions-_le_nucleaire_au_service_de_la_reussite_des_territoires-_2017.pdf

The choice of the concept is itself closely linked to that of the timing, as the concept must be amortised. There must also be enough orders for new builds to benefit from economies of scale and stability of orders. In addition, the commissioning date defines the time left for engineering and research to finalise the concept to the required level of detail. EDF and its subsidiary Framatome are working on the optimisation of an EPR, which will come online in 2030. At least 3 pairs of this optimised EPR would represent a good compromise before moving on to the next design.

The pace of construction is primarily related to the need to balance electricity supply with demand, to objectives set for the energy mix and to the pace of reactor shut down.

With respect to adapting construction pace to supply chain capacities, it is considered reasonable to keep the number of construction projects at a relatively stable level, limiting any variations so as to limit pressures on industrial capacity. As previously discussed, the sector will benefit from designing and implementing an organised construction programme, involving all stakeholders, for a series of reactors, which gives rise to the different beneficial effects discussed previously.

France's current reactor export programme is not sufficient in volume, both in terms of the type (only part of the supply chain is mobilised) and the number of reactors per year. While it is difficult to determine an exact minimum volume, feedback from construction projects in France and other countries shows that the optimum period between construction projects is 18 months for construction of two units of the same pair, and 3.5 to 4.5 years for construction of two pairs. As discussed above, building pairs of reactors helps to effectively control costs.

In conclusion, in order to keep the nuclear option in the long-term, at a controlled cost, requires a programme of construction with commissioning of a first pair planned from 2030, followed by construction of a series of reactors. Over a period of fifteen years this programme would provide a total of 3 or 4 pairs.

This programme would satisfy several key concerns raised by stakeholders:

1. For electricity consumers, it is the option of extending the current benefits of a fleet of power plants offering both a low and stable kWh price, compared to the European average, a security of supply at all times and a low-carbon footprint.
2. For the operator, it is the opportunity of maintaining capacity and performance, as well as expertise and excellence in nuclear safety, to have an efficient high-quality supply chain, and to see a return on investments made in Generation 3 technology.
3. For French and European network operators, it is keeping some dispatchable production, that contributes to network stability (in terms of voltage and frequency) whilst also being flexible.
4. For the French State, it is the opportunity of maintaining and developing a strong and globally recognised industrial sector, with all the resulting benefits in terms of: jobs, trade balance, and France's fulfilment of its COP21 commitments (Low Carbon Strategy).

Several issues, however, make it difficult to define the specific programme to be put in place:

- The current state of the European electricity market, where over-capacity has resulted in very low wholesale prices (below €40/MWh). Such levels, which may last for several years as electricity consumption stagnates and subsidised capacity continues to be added, make it difficult to invest significantly in new low-carbon production without a suitable framework (such as guaranteed prices).
- The highly capital intensive nature of nuclear power, which strains companies' balance sheets, at a time when the sector is undergoing a period of restructuring.
- Skepticism with regard to EPR technology (and more generally Generation 3; see AP1000 in the United States), due to time and budget overruns on the Olkiluoto and Flamanville projects.

The first two points are the responsibility of the public authorities. The third falls to the nuclear industry, which must prove that it is capable of commissioning the reactors (the first is set for startup in 2018), and that costs will decrease along with decreasing industrial risks. The State also has a major role to play in carrying risks, as they already do for other low-carbon technologies.

10. Overall conclusions

The first third generation reactors (EPR, AP1000, AES2006, etc.) will soon be connected to the grid[30] and will have to demonstrate their ability to operate safely and efficiently. Operators are confident of success, which will determine whether other reactors of the same type are ordered and built around the world. There have been significant increases in costs during the construction of these first reactors in Europe and the United States. This has been due to both structural and specific factors:

- Broader industry-wide factors (engineering costs, raw material costs, environmental standards) have contributed to these increases over the last 10 years, and have also impacted the gas and coal sectors.
- Factors specific to the nuclear industry have also contributed:
  - The *First-of-a-Kind* (FOAK) effect, inherent to any complex and innovative technology, such as Generation 3 reactors.
  - Specific technological choices that are disadvantageous in economic terms (including safety systems).
  - Supply chain needing to be revived: a pause in the construction of reactors (in particular in the United States, then Europe) over the last 20 to 30 years, has resulted in numerous issues inherent to restarting the supply chain (management of complex project, establishing contractual terms with suppliers, investment and training needs specific to the nuclear industry).

Production costs for future projects must be reduced. This is a focus for all nuclear companies worldwide, who are starting to see results. The three most important components of total cost are:

- The initial cost of construction, based on the design and construction methods.
- Management of lead-time, in particular on-site.
- Project financing.

The areas for progress on the construction costs of the third generation reactors have been clearly identified and are the focus of significant improvement plans. The main areas are:

- Regulation of safety standards and inspection procedures by the safety authority.
- Restructuring of the supply chain.
- Integration of lessons learned from projects nearing completion.
- Use of new techniques and methods to re-optimise the concepts.
- New contractual arrangements to ensure that the most appropriate party bears specific types of risk, and generally supervised by the State.

Other cost reduction factors will contribute, as observed historically:

- Pair effect for the next EPRs (United Kingdom, France), compared to single units like Olkiluoto 3 and Flamanville 3.
- Series effect, a result of visibility and pace of construction.

The overview provided in this technical note shows the importance of developing a structured and stable programme in order to benefit from the cost reductions induced by series effects. This programme includes a first pair by around 2030, then 2 to 3 more pairs in the same decade.

There are many solutions which can contribute to reducing the cost of financing:

- *Contracts for Difference* as per the English model, or 'premiums' (similar to what is widely practiced for renewable energy) added to market prices (mechanisms that make it possible to reduce risks for investors, whatever the means of electricity production).
- Reducing the expected rate of return for the project, when risk is lowered or shared by the State, through a policy of providing access to low-interest loans for all low-carbon energies.

In order to evaluate the contribution of each technology sector, other costs and benefits must be taken into account:

- 'System costs' within the electricity mix (network connections, voltage and frequency balancing, back-up, storage, etc.) are very low for nuclear power.
- Contribution to security of electricity supply.
- Environmental footprint, and above all greenhouse gas emissions.
- Impact on employment.

Reforms of the rules of the electricity markets are essential for proper payment for services provided by each technology, including the need for a higher price of CO_2 emissions.

30 – Note that the Russian VVER-1200 concept has already been connected to the grid.

The SFEN believes that in France, with an optimised EPR design being developed by EDF, a reduction in overnight investment costs of up to 30% is achievable. Some of the most significant cost reductions can be made simply by reducing reactor construction time, which depends on the site on which the units are to be built, by several years in comparison to Flamanville 3. Building pairs of reactors also has a direct impact. Other items contributing to the cost of production (mainly operation, fuel) can be reduced, but to a lesser extent. In addition, if risk reduction and tailored financing are implemented, decreases in the cost of capital by up to a factor of around 50% make it possible to measure the progress that can be made.

Many programmes are being implemented to maximise potential savings. These will, in future, be combined (at least in part), with the aim of reducing the costs of a series of standardised nuclear reactors, so as to remain competitive with the cheapest means of dispatchable generation: in this case the lower cost range of combined-cycle gas (CCGT) power plants, by incorporating a carbon price of a few tens of euros/tonne of CO_2[31]. Furthermore, third generation nuclear power maintains a dispatchable base in the electricity mix, which is highly flexible and a very low-level emitter of greenhouse gases, and can be combined with renewable energy sources, such as solar and wind, supporting the development of these intermittent energies.

The decision to launch a programme for the construction of a series of reactors must also be considered from an insurance point of view in a highly uncertain environment. The electricity mixes of France and Europe in 2050 depend on a large number of technical, economic, social and geopolitical factors that are very difficult to predict. In economic and technical terms, which are of interest to us here, we are confident that the capacities of the nuclear industry can, for the most part, meet the objectives described above (with a 10% margin of error, but not more). In comparison, uncertainties for other energy sources are of a much higher order, even if there is little doubt that the costs of renewable energy will continue to fall. Nuclear power ensures stability; it is present in the long-term in many global scenarios, such as those of the IEA; and it provides a set of readily available technologies, which otherwise would be limited to intermittent renewable technologies. Keeping the nuclear option open is achievable, at a very reasonable and much lower cost than that of other low-carbon energies[32]. This decision is essentially the responsibility of the State.

The State is, as such, a key player in decarbonising the energy system. This is already the case for alternative energies, and is also the case, historically, for the nuclear industry, which initially formed part of a highly strategic public approach to energy independence and cost stability. Added to this are objectives for CO_2 emissions and pollutants, as well as being part of a national industrial strategy[33].

In summary, new nuclear makes it possible to guarantee a supply base of decarbonised, flexible, dispatchable and competitive electricity in France for 2050. The objectives described in this technical note, to develop this safe and competitive new nuclear, based on solid historical results and lessons learned over the last 5 to 10 years, are achievable, but under certain conditions. To achieve them, the authors draw attention to the importance of making a decision quickly with regards to establishing a reactor construction programme in France[34], with commissioning of a first pair around 2030, and 6 to 8 reactors by 2040. Revision of the contractual arrangements will also be necessary, which is also largely the responsibility of the State. Should it not be decided to build this 'nuclear insurance', either the nuclear option will become impossible in the long-term, or the future reactors built in France and Europe will depend on hypothetical conditions of access to the world's remaining nuclear sectors, probably Chinese and Russian.

31 – For example, with a carbon price of between €30-50/tCO_2, and a gas price of between €6-10/Mbtu, the total cost of producing combined-cycle gas would be between €70-100**+**/MWh. Given this range, new nuclear is easily competitive.

32 – To further illustrate this point, the annual cost of Germany's energy transition is of the order of €25 billion, which is equivalent to the cost of building about 4 re-optimised nuclear reactors. At this rate it would be possible to build a 'zero carbon' electricity system in France within 10 years.

33 – In particular, through the creation of the Nuclear Sector Strategy Committee (CSFN - *Comité Stratégique de la Filière Nucléaire*), backed by the State.

34 – Of the order of 6, that is 3 pairs. Such a programme, based on the new EPR concept that Framatome is finalising, would allow the industry to reach a rate of more than one unit per year, given the expected exports. This pace appears very reasonable in comparison to the achievements of the 1980s (significantly faster than 3 units/year). It will allow the start of the renewal of the fleet, while leaving significant room to adapt the power of the new fleet (by 2050) to the technical, economic and social realities of this still distant future.

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In light of France's Multi-Year Energy Plan, - *Programmation pluriannuelle de l'énergie (PPE)* - the SFEN has reviewed the conditions which will enable France to keep the nuclear option for 2050. This technical note provides a detailed overview of the EPR production costs items and the cost drivers which will guarantee long-term competitiveness.

The State has a role to play - The SFEN suggests engaging with public bodies in a review of the supply chain and financing mechanisms for reducing the cost of third generation nuclear power. A key factor is optimising the allocation of roles amongst the public bodies and the industrial players involved in implementing a project. It falls to the State, which guarantees national strategic interests, to maintain a baseline supply of decarbonised electricity, which is flexible, competitive and predictable up to 2050.

Timescale - This review must be completed without delay before 2020 in order to meet the objective of getting the first pair of reactors online by 2030. The first pair will be part of an industrial programme for a series of EPR, for which lessons learned will contribute to the designs of at least another three pairs of reactors.

Expected benefits - Using this industrial programme approach will provide the whole supply chain, from large groups to small and medium-sized enterprises (SME), the visibility and timescales required for investing in production lines and competences, as well as for taking advantage of the series effect right from the first construction projects. This industrial programme will enable France to keep the nuclear option open for managing the decarbonisation of its economy and the renewal of its electricity mix by 2050.