outside the scope of this study). Furthermore, comparisons with CCGT plants show that the high upfront capital outlays associated with nuclear investments make them more sensitive to project risks, and any delays and cost overruns rapidly undermine their economic performance and, ultimately, their capacity to attract and secure funding. Completing construction on time and on budget is therefore an essential first step to de-risk nuclear projects and unlock future cost reductions.

As it is clearly necessary to reduce investment costs, the next section provides more detailed cost breakdowns and also prioritises items that should be tackled to achieve significant cost reductions.

Box 3: **Cost of capital and nuclear risk premium**

Most projects are financed through a combination of debt and equity. A common approach to derive the cost of capital consists of computing the weighted average cost of capital (WACC) assigning different weights to the various sources of financing. In this process, all else being equal, private investors put a price on the underlying risk of a specific project; this is known as a risk premium. The perception of risk premium is influenced significantly by the degree of public investor involvement (see Chapter 6).

The risk premium specific to nuclear power (compared with other energy projects under the same market conditions) is based on uncertainty stemming from recent Gen-III final cost and scheduling issues and can also be interpreted as a sort of "nuclear risk premium" (IAEA, 2008). All these factors are reflected in the WACC of a project and tend to increase the cost of capital and hence the LCOE. Given the high capital intensity (USD/kW_e) involved, the impact is particularly acute for nuclear projects (see Figure 10).

2.2 Nuclear investment cost breakdown

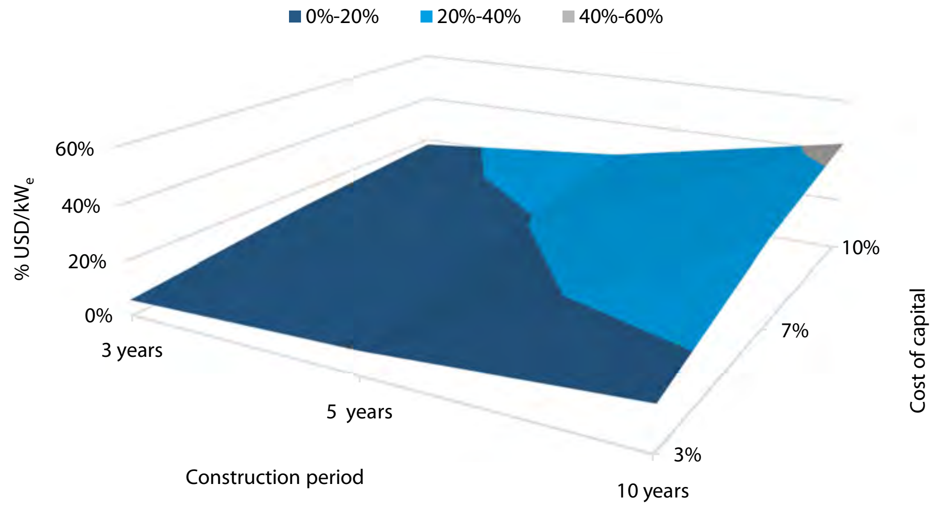
As indicated above, the investment costs of a nuclear power plant comprise all the elements required for its design, construction and commissioning. This covers expenditures for materials, components and equipment and their installation, as well as personnel wages and the cost of the capital involved – representing the total *capital at risk* before operations. Investment costs can then be divided into OCC and capitalised financial costs.

The OCC covers all the costs of building an asset independently of the time necessary for its design and construction. This metric assumes that all expenses are incurred "overnight," neglecting the effect of time in terms of financial interests or any discounted payments. It is the intrinsic cost of a technology without the impact of financial conditions that are, typically, country- and project-specific. This cost category is usually normalised to capacity (e.g. USD/kW_e).

Conversely, capitalised financial costs account for the effect of time on the funding of projects – essentially the interest paid to investors during the construction period (the IDC). Capitalised financial costs therefore increase with the lead time of a project and, as a result, vary significantly from one project to another. The impact of the cost of capital and project lead times on capitalised financial costs is illustrated in Figure 11.

Capitalised financial costs can make up more than 20% of total investment costs per kW_e, especially for projects that take more than five years to construct and have a cost of capital higher than 7% – the case for most nuclear projects under construction in OECD countries. Important financing cost savings can therefore be achieved if capital is accessed under more favourable conditions (i.e. lower cost of capital), for instance with higher government involvement in the financing scheme. The lead-time impact becomes more noticeable as the cost of capital increases.

Figure 11: **Portion of IDC in total investment costs per kW_e as a function of capital costs and construction period**



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

Note: Calculations based on OCC of USD 4 500/kW_e.

The OCC can, in turn, be split into several subcategories. There is no generic way to proceed, as the level of detail and scope of these categories may be adjusted according to the project's characteristics, type of contractual arrangement, accounting rules, and information and cost management systems. Nevertheless, three main categories are typically identified: contingency costs; owner costs; and engineering, procurement and construction (EPC) costs.

Construction contingency costs

Contingencies are a way to deal with the unexpected. The US National Energy Technology Laboratory (NETL) defines project and process contingency provisions as being

> included in the estimates to account for unknown costs that are omitted or unforeseen due to the lack of complete project definition and engineering. Contingencies are added because experience has shown that such costs are likely and expected to be incurred even though they cannot be explicitly determined at the time the estimate is prepared. (NETL, 2011)

The number of contingencies also evolves as projects mature, as information gathered after several construction projects increases the accuracy of new estimates and thus reduces the potential for unforeseen costs. Projects at low levels of maturity usually include contingencies of 30-50% in their estimations of total OCC, whereas for projects at more advanced stages of learning, contingency provisions drop to 10-15% (D'haeseleer, 2013).

High contingency levels can also result from poor risk allocation due to inefficient supply chain contracts schemes. A University of Chicago study found that the OCC escalation observed in recent US nuclear projects could be explained, to a large extent, by the accumulation of contingencies arising from several companies at different levels of the supply chain working in an insular manner with their own scope of risks, trying to avoid the penalties of further losses

(EPIC, 2011) (this situation is explored in more detail in Chapter 3). Contingencies can also be applied to other cost parameters, such as IDC costs to account for underlying reactor design/construction schedule uncertainty, and O&M costs to counteract reactor performance unpredictability.

Owner costs

The scope of expenses borne by a project's owner varies depending on the owner's capabilities and thus on the extent of EPC works. The IAEA (2011) comprehensively lists expenses that could be included in the owner's scope:

- general administration, project management, legal and financial advisory services;
- site selection and licensing, environmental monitoring and preparatory works;
- site support infrastructure such as electrical interconnections, water supply, roads and harbours;
- licensing and permitting, interfacing with regulatory bodies;
- public relations;
- taxes and legal fees;
- preoperational costs.

Various authors suggest that owner costs account for 15-20% of OCC (D'haeseleer, 2013).

Engineering, procurement and construction costs

After contingencies and owner costs are subtracted from the OCC, the remaining expenses are the EPC scope. This category includes all activities related to project design, procurement, construction, commissioning and handover to the plant operator. Consequently, this category covers the greatest portion of a nuclear project's OCC and, just as important, most of the risks.

Similar to owner costs, EPC expenses depend on the final extent of EPC activities, which is determined by the capabilities of the owner and the different contract schemes adopted for the project. Elements such as materials, components, on-site equipment and facilities to support construction and civil works, the manpower required for the installation, and project engineering, supervision and management are usually part of the EPC domain.

Based on information and categories detailed above, Figure 14 provides a representative breakdown of investment costs per kW_e of nuclear power plants in OECD countries. EPC claims more than 50% of the total investment costs, followed by IDC (~25%) and owner costs and contingencies (15% each).

The following sections further develop the breakdown of nuclear investment costs. Investment cost evaluations are broken down primarily by:

- direct versus indirect costs;
- labour versus materials;
- components and recurring versus nonrecurring costs.

The first two are static and limited to the EPC scope, whereas the third, covering all investment costs categories, is more dynamic (i.e. it has a temporal dimension) and allows for the identification of potential savings associated with mobilisation of the supply chain.

2.2.1 *Direct versus indirect costs (EPC scope)*

Table 3 presents a generic breakdown of the EPC scope. Direct costs encompass expenses *directly* related to the cost object: for a nuclear power plant, civil works, heavy components and other equipment, and the labour employed in construction (see Section 2.2.2). Indirect expenses concern support activities that cannot be directly traced to the cost object but are indispensable for its delivery. In Table 3, these support activities are referred as services provided during plant construction, related to engineering and design, procurement, project management and field supervision, quality assurance and testing, and commissioning and start-up.

Early (i.e. pre-conceptual, conceptual, preliminary, etc.) design activities, supply chain qualification and certification, and licensing efforts prior to the building of a first plant, are also important indirect cost contributors, especially for the first unit of a nuclear programme (see Section 2.2.3).

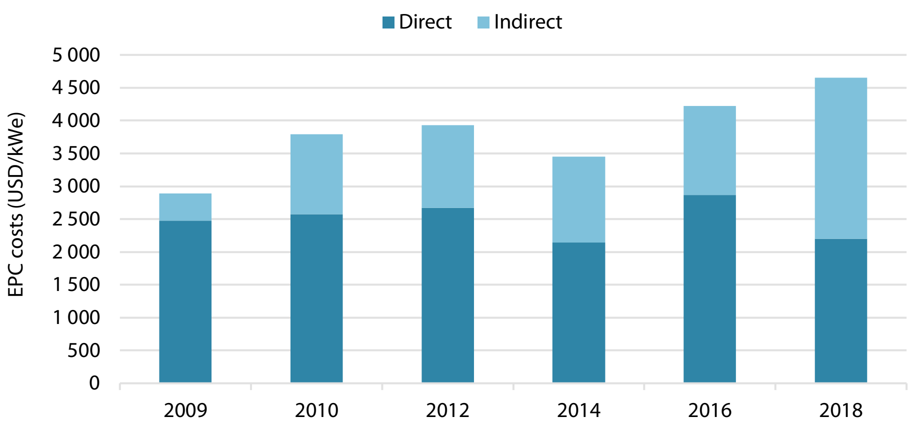
Table 3: **Generic EPC cost breakdown**

Direct costs	Civil structural works
	Reactor plant equipment
	Turbine plant equipment
	Electric plant equipment
	Main heat rejection system
	Miscellaneous plant equipment
Indirect costs	Engineering and design services
	Project management and field supervision services
	Quality assurance and testing services
	Commissioning and start-up services

The Generation IV International Forum (GIF, 2007) provides more comprehensive EPC breakdowns by direct and indirect cost items.

Furthermore, consulting the various public EPC cost estimates performed in the last ten years reveals the distribution and evolution of direct and indirect costs within the EPC scope (Figure 12). Following the investment trend for most recent nuclear projects, EPC costs have been rising steadily but indirect cost are the main driver of these cost overruns.

Figure 12: **Evolution of estimated direct and indirect expenses within EPC costs for nuclear power plants**



This can be explained by the fact that, as part of the technology maturation process described in Chapter 1, indirect expenses have proven to be higher than previously expected. In fact, the rising trend in indirect costs largely reflects additional expenses for engineering work related to design completion, changes during construction and regulatory interactions, as well as to supply chain qualification and development. These cost contributors have been confirmed in the various cases analysed for this report (see Chapter 3).

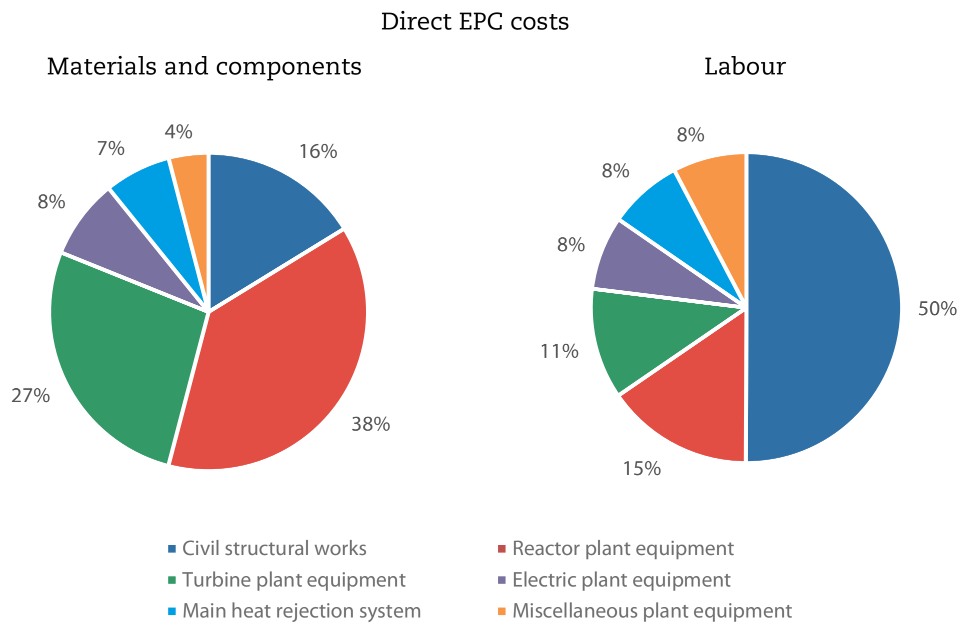
These results show that indirect costs should not be neglected. According to more recent estimates, they may account for an even greater share of total EPC costs than direct expenses do (approximately 53%, compared with 47% for direct costs) (ETI, 2018). This suggests that cost issues associated with nuclear power stem principally from project governance and organisation rather than from system materials and components.

2.2.2 *Materials and components versus labour (EPC scope)*

An alternative way of breaking down EPC costs is to separate the materials and components involved in plant construction from the labour that goes into design, installation, supervision and testing. The results of this analysis, limited to direct costs, is presented in Figure 13.

In terms of materials and components, reactor systems and turbine plant equipment account for more than 60% of total costs. Some materials and components must meet nuclear-grade standards, which raises their final cost significantly.[12] In terms of manpower, civil works are the more labour-intensive activity, making up 50% of total direct labour needs. Overall, around 30% of direct costs are attributable to direct labour and the remaining 70% to materials and components.

Figure 13: **Materials and components vs. direct labour in direct EPC cost breakdown**



A more recent evaluation from the Energy Technologies Institute finds that 40% of direct costs and 80% of indirect costs are labour (ETI, 2019). Using values for 2018 taken from Figure 12, it can be estimated that labour expenses represent approximately 61% of EPC costs,[13] the remaining 39% being essentially for materials and components.

12. Mainly because of the additional qualification tests, quality assurance requirements and documentation necessary to gain nuclear-grade certification. Additionally, nuclear-grade materials do not currently benefit from the volume effect of industrial-grade components due to their specific design and manufacturing process.

13. 47%*0.4 + 53%*0.8 = 61.2%. MIT reports similar figures, with direct labour plus field and home engineering representing 60% of total costs (EPC and owner costs) (MIT, 2018).

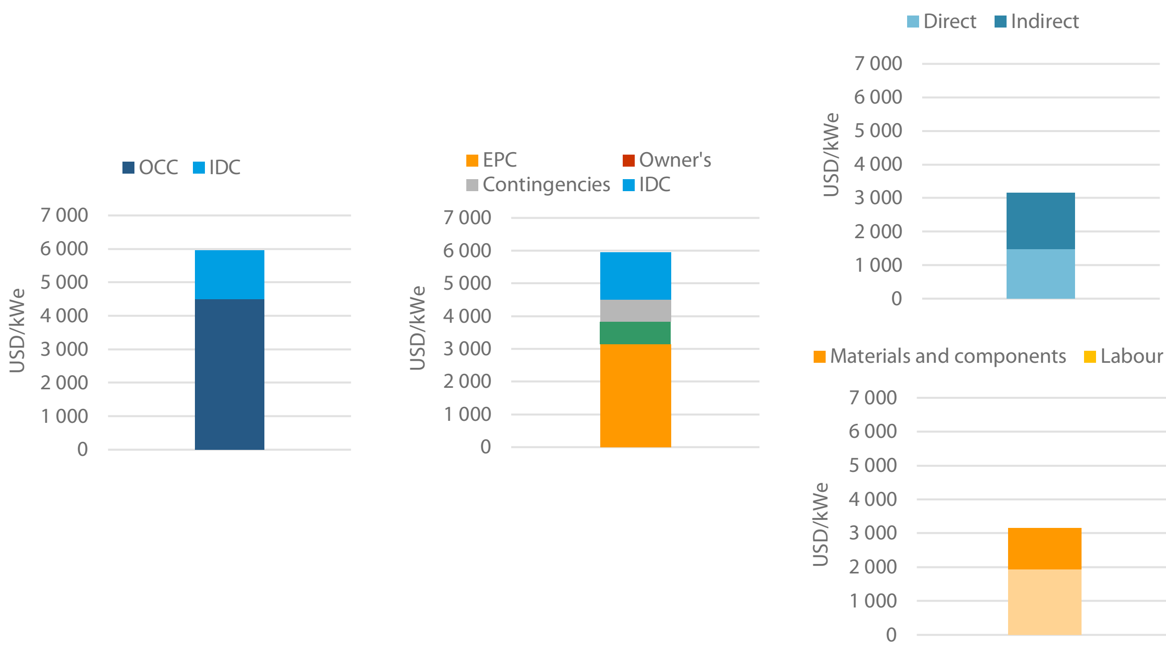
When assessing the impact of labour on nuclear investments, it is necessary to distinguish between salary and productivity. A recent Massachusetts Institute of Technology (MIT) study concluded that "while differences in labour rates play an important role[14] they do not account for all the variations in overnight construction costs observed in nuclear plant projects around the world" (MIT, 2018), suggesting that productivity rates should receive further attention. In fact, the same study illustrates how productivity rates in the construction industry have been falling in western OECD countries compared with other regions such as China or Korea, where rates have been trending upwards.

Closer examination of materials (or commodity) usage indicates that materials may make up almost 12% of direct EPC costs (EPIC, 2011). The most-used materials during nuclear construction are piping, accounting for 30-38% of material expenses, and concrete, responsible for 24-29%. The portion for concrete is even higher if 35% of the steel cost (for rebar) is included (i.e. in which case concrete and rebar together account for 31-37% of the commodity costs).

These cost data illustrate the importance of indirect costs and labour in the EPC scope. D'haeseleer (2013) stresses the dominance of labour in EPC costs, especially because of the need for highly skilled labour (both technicians and engineers) and a substantial portion of additional indirect services (i.e. project-, licensing- and quality-related). The MIT (2018) reaches similar conclusions, with civil works, site preparation, installation and indirect expenses (essentially labour-intensive engineering oversight) representing around 72-83% of EPC and owner costs combined.

A general breakdown of nuclear investment costs including the different EPC breakdowns described above is presented in Figure 14.

Figure 14: **Nuclear power investment cost breakdown per kWe in OECD countries**



Notes: Average costs per kW_e in OECD countries. IDC based on a cost of capital of 7% and construction time of 7 years. Owner costs and contingencies assumed to be 30% of total OCC. EPC costs comprise direct expenses (47%) and indirect (53%). EPC scope also divided into costs for labour (61%) and materials and components (39%). Labour includes both indirect and direct labour. See Figure 13 for a more detailed breakdown for materials and components and their associated direct labour.

Source: IEA/NEA (Forthcoming), *Projected Costs of Generating Electricity* 2020.

14. For comparison, labour rates in China can be ten times lower than in the United States (MIT, 2018).

2.2.3 *Recurring versus nonrecurring costs (all investment cost categories)*

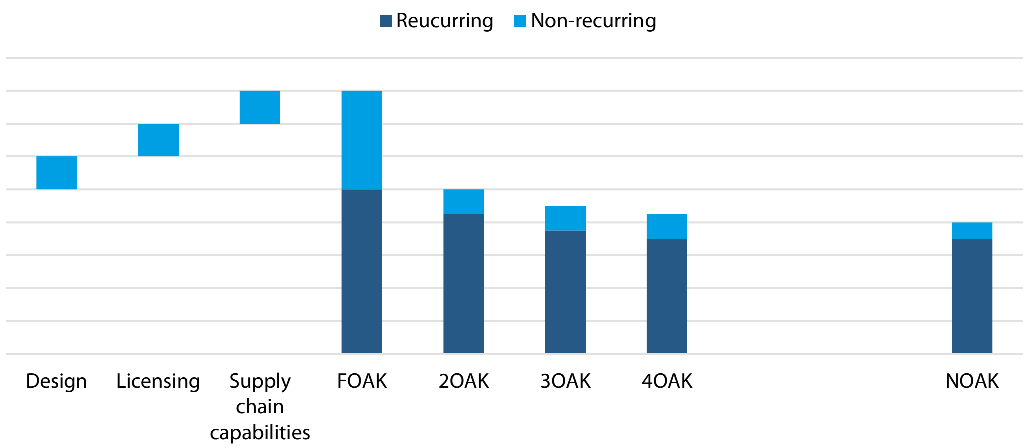
Although the different cost breakdowns presented in the previous section are useful to determine the categories that contribute the most to final nuclear investment costs, they fail to capture the positive effects of the learning-by-doing process that can be expected with the construction of several units with similar characteristics (i.e. the series effect). To better understand these potential benefits, it is necessary to introduce cost categories that take the temporal dimension into account.

Projects in the early development phase of the learning curve (see Box 1) may incur costs inherent to the maturation process of any technology, which are essentially borne by the first unit of the series, also called first-of-a-kind (FOAK). These expenses "should"[15] be incurred once in the learning process and amortised by subsequent replications until extended learning or nth-of-a-kind (NOAK) conditions are reached. These costs can be defined as "nonrecurring"[16] and usually include design and testing, licensing and certification, and supply chain training and qualification, which are essentially of an indirect nature (see Section 2.2.1). Nonrecurring costs can add approximately 30-35% to the OCC of a first reactor (EPIC, 2011), or USD 1 350/kW$_e$ to USD 1 575/kW$_e$ according to Figure 14 cost estimates.

Conversely, as learning advances with the deployment of subsequent units, several activities are repeated with every new construction; the associated costs are therefore defined as "recurring" and encompass both direct and indirect expenses. As highlighted by the REDCOST experts, barring any major structural change to the basic design, recurring cost *should* experience a rapid decline with the deployment of several reactors (both direct and indirect expenses), with each unit carrying a portion of the nonrecurring cost as part of the designer amortisation strategy. Figure 15 illustrates the temporal distribution of recurring and nonrecurring costs.

It is important to highlight that in a changing and unpredictable environment, some nonrecurring cost may become recurring if normal learning process dynamics are altered, leading to cost overruns and delays. This can happen when a new regulatory requirement is introduced, or a design is exported to countries with different regulatory regimes. These situations and potential cost-effective solutions are explored in Chapter 4.

Figure 15: **Temporal dimension of recurring vs. nonrecurring nuclear investment costs**



Source: Based on GIF (2007), *Cost Estimating Guidelines for Generation IV Nuclear Energy Systems*.

15. The difference between what a nuclear plant "should" cost and "could" cost is discussed in Part 2.
16. Or as FOAK costs.

2.3 Assessing areas for nuclear investment cost reductions

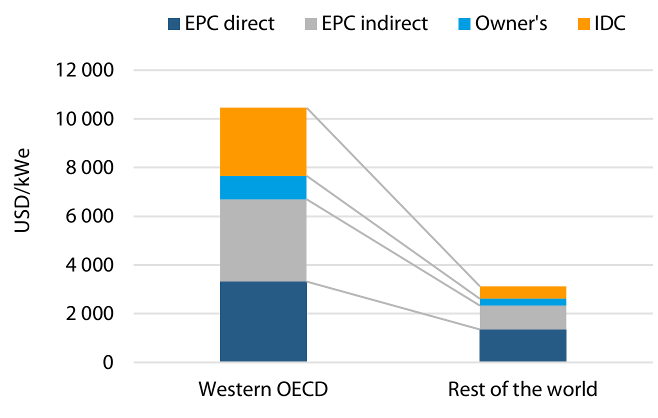
This chapter's analysis permits several areas for nuclear investment cost reductions to be identified:

- EPC costs are dominated by labour: Despite wage variations across the world, productivity rates can be improved and lead to significant cost reductions. Support services (i.e. engineering, project management, supervision and testing, etc.) and civil works can be particularly labour-intensive and should therefore be addressed first.
- Most EPC costs are indirect: Expenses for support services and for overseeing the value processes tend to exceed the cost of the product itself. Better organisation and governance could therefore have a major impact on investment costs.
- From a design perspective, the reactor and turbine plant equipment are the most expensive components: Design optimisation should target these systems first, as well as concrete and rebar, and piping commodity usage.
- As part of the maturation process of any technology, the first unit bears significant nonrecurring costs: These are mostly indirect (i.e. related to detail design, licensing, supply chain qualification, etc.), and could be effectively lowered through the construction of additional units of the same design as long as the environment remains stable.
- Financial costs have a significant impact on levelised capital costs: They can be reduced with a lower cost of capital and shorter lead times.

Figure 16 compares nuclear investment costs for recent projects in western OECD countries (i.e. Europe and the United States) and in the rest of the world (ROW) to convey the magnitude of potential cost reductions. ROW values are based on cost estimates for countries such as the United Arab Emirates, Russia and China.[17]

Indirect EPC costs and IDC are the areas in which higher cost reductions could be achieved in absolute terms. Direct cost reductions are more limited, especially for materials and components, and may require more innovative designs and techniques that could materialise in the longer term.

Figure 16: **Nuclear investment costs in western OECD countries vs. rest of world**



Source: Based on ETI (2018), *The ETI Nuclear Cost Driver Project: Summary Report*.

17. The results of this chart must be analysed with caution. First, conditions in ROW and western OECD countries may be relatively different in terms of labour rates and commodity prices. Second, supply chain maturity differs from ROW to western OECD countries. In fact, conventional nuclear construction in ROW countries has already reached the later stages of the learning curve, while western OECD countries are just at the end of the technology maturation process, as indicated in Chapter 1.

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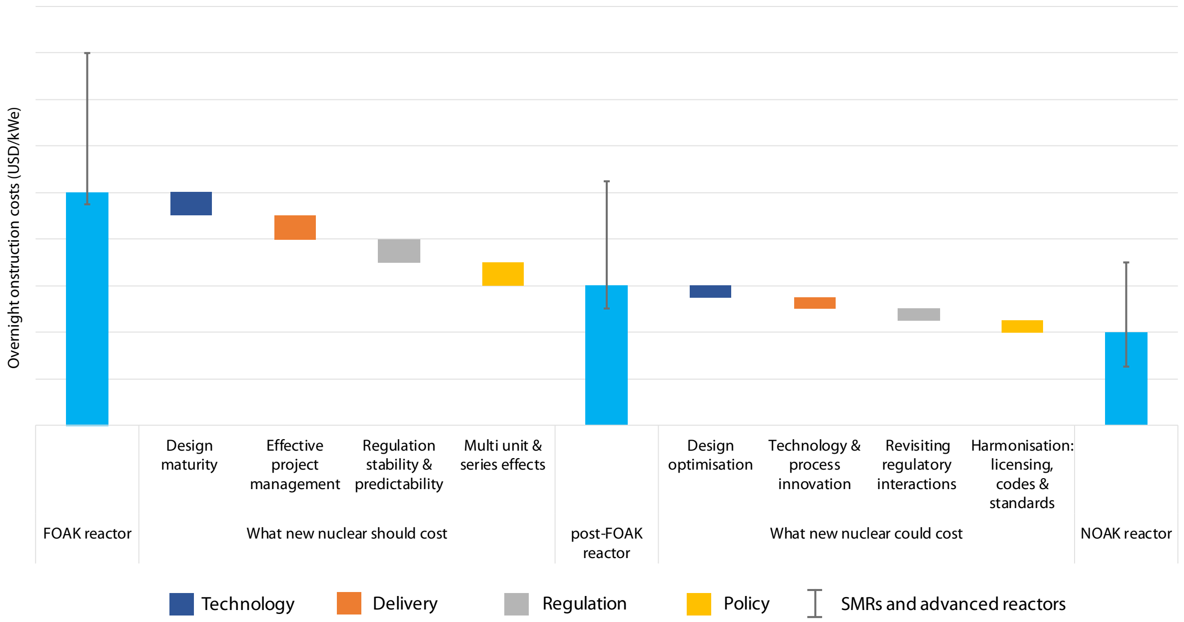
Part 2: Nuclear construction cost reduction drivers

This study identifies eight drivers to reduce nuclear construction costs, as shown in Figure 17. These drivers unlock positive learning and propel continuous improvements to large Gen-III reactor concepts. Implementing these cost drivers will also help attenuate the technological, organisational and regulatory risks associated with new nuclear deployment This part of the study sets out the learning curve for nuclear projects, first drawing on the lessons learnt from recent first of a kind projects, then extracts short term learning opportunities, before identifying longer term cost reductions stemming from innovation and harmonisation.

Figure 17: **Nuclear cost and risk reduction drivers**



3. Core nuclear construction cost drivers: Lessons from historical and recent projects

Important insights can be derived from historical and recent first-of-a-kind (FOAK) project experiences, complementing the cost breakdown analysis of Chapter 2. Reviewing lessons learnt from successful and challenging projects has identified some common cost drivers.

Four categories in particular determine whether there will be delays and cost overruns:

- design and supply chain maturity;
- effectiveness of project management;
- nuclear safety regulation stability and predictability;
- policy framework (in terms of political leadership and multi-unit projects).

These four drivers are not directly discernible in cost-figure analyses, and quantitative scrutiny must be complemented by qualitative analysis of project conditions. Due to the complexity of nuclear projects, these factors are intertwined, so that undertaking a root-cause analysis to quantify the specific role of each driver can be challenging and will eventually require some intuitive judgement.

This chapter is based primarily on lessons learnt from recent FOAK projects that have encountered significant difficulties. Understanding what happened during these projects is critical to assess to what extent their costs overruns and delays can be attributed primarily to cost drivers specific to FOAK reactors, so that mistakes are not repeated. In parallel, lessons from historical experience in selected OECD countries allow for further comparison among difficult projects as well as among those that successfully avoided obstacles. Furthermore, parallels can be drawn and lessons learnt from other industries in which investments in large-scale infrastructure projects (i.e. megaprojects) are happening.

Box 4: What does first-of-a-kind mean?

Many usages are common when referring to Gen-III FOAK reactors, but this report rests on the following definitions:

- Pre-FOAK: phase prior to the construction start of a recent Gen-III reactor.
- FOAK: First projects of Gen-III designs. In some cases they may not strictly be the first reactor built for a given design but, in the absence of a governance model to ensure the effective transfer of learning from one reactor to another, they are also considered as FOAK in this report.
- Post-FOAK: projects that should be able to take advantage of the learning described in this chapter to reduce costs, seizing on opportunities described in Chapter 4.

3.1 Developing a mature design and a supply chain before construction begins

The maturity of the design and of the supply chain before construction begins are among the most significant cost determinants of recent nuclear new-build projects.

Recent FOAK projects offer particularly relevant lessons on the impact of a lack of design maturity on overnight construction costs (OCC). AP1000 and EPR construction projects in Europe and North America especially show that it was one the main reasons for combined delays and costs overruns.

Given the scale and long lead times of nuclear projects, developers are often pushed to start construction before the design is fully completed. In practice, this means that some of the details needed for the later stages of construction will be completed during the course of construction to reduce the lead time between the final investment decision and the construction start date. The same rationale applies to the supply chain.

Recent Gen-III FOAK projects often started with a low level of design maturity or continued with construction despite safety regulation changes that required significant design changes. In addition, a lack of supply chain engagement resulted in manufacturing and procurement challenges that made it difficult to deliver this new generation of nuclear reactors. Optimism bias, which magnifies these challenges by leading developers to underestimate costs at the early design stages, has been identified as a recurrent issue in complex engineering projects (see Box 5).

Box 5: Optimism bias during the design stages of complex engineering projects

For complex engineering projects, cost estimates and their associated uncertainties during the early stages of the design process may be subject to optimism bias. Merrow, Phillips and Meyers (1981) provide insights on the evolution of cost estimates and associated uncertainties as a technology develops. Their study reviews 44 large engineering megaprojects, including chemical plants, public works and nuclear installations. Findings highlight the existence of optimism bias in project cost estimates, as final construction costs were often twice the initial estimates (Figure 18).

The traditional view in cost estimates is to anticipate that cost uncertainties will be reduced as the project develops, but this overlooks the fact that cost reassessments will remain consistently below final costs reported upon project completion.

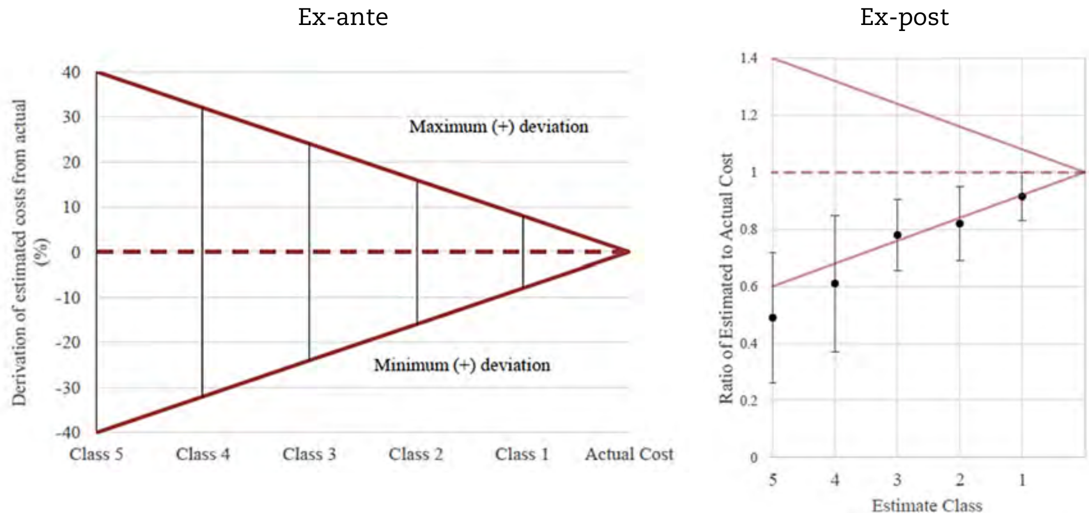
Several complementary factors help explain this trend:

- Difficulty in capturing all the cost uncertainties and in accurately defining project boundaries during the early stages due to the complexity of these large-scale engineering projects.
- Cognitive bias of the engineers in charge of cost estimates and their management, which leads them to attach less importance to potential costs increases.
- Reporting low-cost estimates as a strategic decision to secure early support from stakeholders.

Recent cost estimates from ongoing and future nuclear new-build projects further illustrate this point (MIT, 2018):

- Advertised OCCs for the AP1000 have increased from approximately USD 2 000/kW$_e$, to USD 4 500/kW$_e$, to USD 8 600/kW$_e$.
- Early pre-conceptual cost estimates for NuScale were USD 1 200/kW$_e$ but are now projected to be approximately USD 5 100/kW$_e$.
- The OCC for the FOAK Flamanville EPR project increased from EUR 2 000/kW$_e$ to EUR 7 500/kW$_e$ (Folz, 2019).

Figure 18: **Optimism bias: Ex-ante project cost estimates vs. ex-post costs**

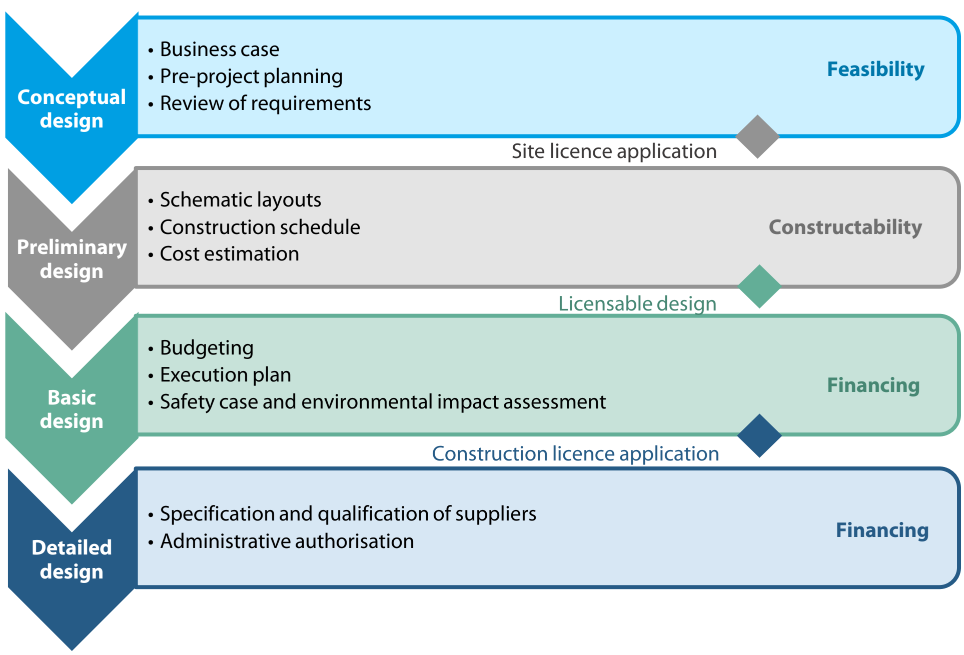


Source: Merrow, Phillips and Meyers (1981), *Understanding Cost Growth and Performance Shortfalls in Pioneer Process Plants.*

3.1.1 *Design maturity before start of construction*

Designing a new reactor takes several years, from conceptual to detailed design. For a nuclear project, this typically requires several million man-hours of engineering studies and certification by the safety authority. Even then, the development of a construction and work plan is required for the design to be considered mature, in order to translate design specifications into detailed supply chain requirements and plans for each construction stage. Each key design stage has associated technical, business and regulatory activities (Figure 19).

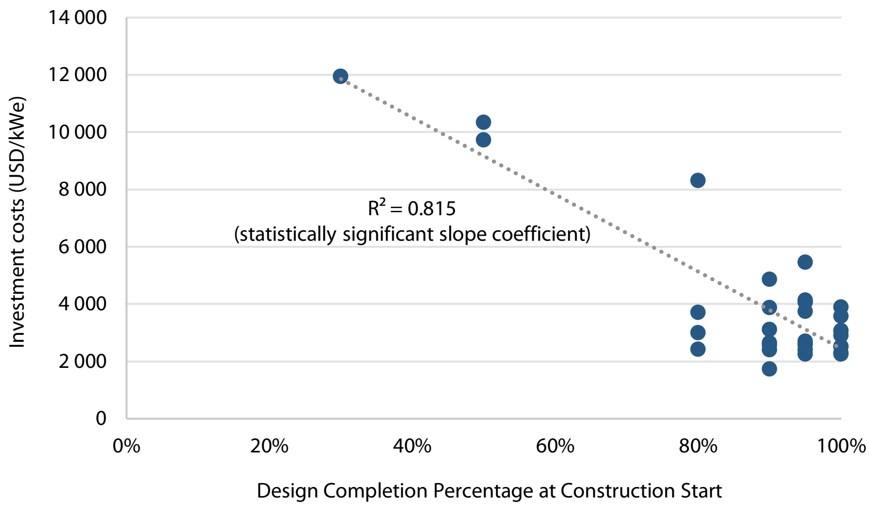
Figure 19: **Typical scope of design activities**



A lack of design maturity can lead to numerous adjustments during construction and, given the complexity and scale of nuclear projects, result in delays and cost overruns. Recent FOAK projects in western OECD countries are a prime example of such risks.

Figure 20 presents quantitative evidence for the correlation between design completion and final OCC for recent anonymised nuclear Gen-III nuclear projects. These data were consolidated by the ETI (2018), which developed a database from recent nuclear projects and identified that design completion ranks as a key cost determinant.

Figure 20: **Percentage of design completed and total capital costs**



Source: Based on ETI (2018), *The ETI Nuclear Cost Driver Project: Summary Report.*

Lessons from EPR projects

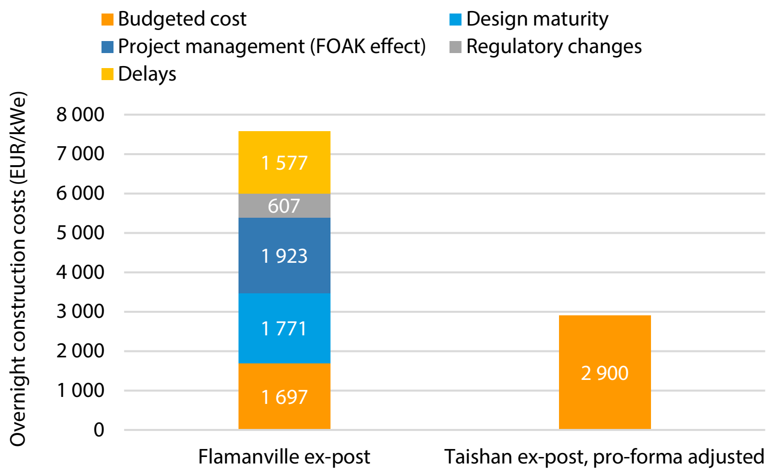
The EPR reactor was initially developed in the early 1990s as part of a French-German consortium led by Framatome (later Areva) and Siemens. In 1992, the beginning of the conceptual design phase aimed to combine technological features from the French N4 reactor and the German Konvoi reactor, with a core focus on safety and lower operational costs through higher availability and increased reactor size. The main technological choices were then jointly approved by the French and German safety authorities, leading to the 1997 publication of a basic design report. Efforts were suspended, however, following changes in public opinion towards nuclear in Germany and, to a lesser extent, France. This resulted in a phase of design optimisation, but with limited progress was made towards a detailed design in the absence of a clearly identified new-build project.

In 2003, Areva and Siemens won a competitive tender to build the first EPR at Olkiluoto in Finland on a fixed-cost turnkey contract of EUR 3 billion. Construction began in 2005 with only part of the design and engineering studies completed, and without an established supply chain.[18] At the time, anticipation of a nuclear renaissance and hopes to benefit from the first-mover advantage in the nuclear new-build market motivated Areva-Siemens to bid at a low price and with an unfinished design (NEA, 2015).

18. www.power-eng.com/articles/npi/print/volume-3/issue-3/nucleus/lessons-learned-from-olkiluoto-3-plant.html.

Similarly, in 2007 EDF began constructing a second EPR at Flamanville at an equally low level of design maturity, leading to numerous design changes during construction. It is estimated that only 40% of the detailed design was complete when construction began (Folz, 2019). In fact, detailed engineering studies had only just been initiated for safety, fires, external hazards and material qualification. At the same time, differences in the licensing frameworks and requirements of the French and Finnish authorities meant that both designs were completed in parallel with limited opportunities to learn lessons and share experience between the two projects.

Figure 21: **Key drivers of Flamanville 3 EPR cost overruns**



Source: Based on Folz (2019), "Rapport au Président Directeur Général d'EDF: La construction de l'EPR de Flamanville."

This lack of design maturity was one of the key reasons for the delays and costs overruns experienced by these two EPR projects. It compromised construction feasibility, made supply chain requirements unclear, and caused considerable reworking and design adjustments throughout construction. For instance, it is estimated that more than 4 500 design modifications were made for the Flamanville EPR project (Folz, 2019).

Conversely, construction of the two EPRs in Taishan, China, which began in 2009, benefitted from the lessons of the Flamanville project as EDF was involved in both projects.

Lessons from AP1000 projects

The same pattern is observed in FOAK AP1000 construction in the United States. The two AP1000 projects (Vogtle and VC Summer) were launched with incomplete designs,[19] particularly in terms of design specification of key component manufacturing by the supply chain (Bechtel, 2016).

The decision to start construction with an incomplete design can be partly explained by the timing of US policy incentives that provided tax credits for nuclear new-build projects;[20] this accelerated the steps to construction even though the design was not completed. It is therefore critical that governments and policy makers consider the issue of design completion when establishing deadlines and milestones.

19. www.world-nuclear-news.org/C-US-governor-releases-report-on-VC-Summer-flaws-06091701.html.

20. In 2006, the US federal government decided that up to 6 000 MW_e eligible for production tax credits would be divided pro-rata among applicants filing combined construction and operating licence applications by the end of 2008, who had commenced construction of new nuclear units by 2014, and whose units entered into service by 2021.

In addition, similar to Europe, the FOAK nature of both these nuclear projects required relaunching of a domestic nuclear supply chain. Both projects were also FOAK implementations of a new modular construction methodology relying on off-site construction and the shipment of very large prefabricated modules constructed at a dedicated facility. This facility, which had mainly serviced the nearby petrochemical industry, had difficulties[21] adapting to nuclear-grade construction standards for some of its deliverables.

Lessons from other Gen-II and Gen-III designs

Conversely, recent VVER projects in Russia and APR1400 projects in South Korea provide examples of new nuclear projects launched with sufficient design completion. Korea's nuclear industry especially has – like Japan – a long track record of starting new-build projects with 70-80% of the detailed design complete (Choi et al., 2008).

For instance, the Kashiwazaki-Kariwa 6-7 nuclear reactors in Japan illustrate that FOAK projects can be built on time and without cost overruns when construction begins with a high level of design and supply chain maturity. This FOAK advanced boiling water reactor (ABWR) project has one of the best lead-time performances in the nuclear industry, with a record construction period of less than 52 months. The lessons learnt from this project in terms of prerequisites are (NEA, 2015):

- detailed engineering and planning studies before construction start;
- prudent design change controls based on the test-before-use principle;
- detailed procurement programme at an early stage with all the necessary engineering documentation;
- advanced construction methods based on previous lessons learnt, including to mitigate the impact of weather events on the construction schedule and to expand the scope of modular and factory-based fabrication for large blocks.

3.1.2 Supply chain competences and capabilities

For recent FOAK projects, design maturity challenges have often been compounded by shortfalls in supply chain competences and capabilities.

For instance, in the case of the EPR projects, no nuclear power plants had been built in Europe over the previous 20 years, leading to erosion of competences and capabilities across the supply chain. The low-competence situation was complicated by the fact that the workforce involved in constructing previous nuclear reactors was reaching retirement or had moved into other industries in the absence of new-build nuclear projects. Regarding capabilities, important challenges also arose in reviving the European nuclear supply chain and implementing new requirements with innovative designs and changes in safety regulations.

Similarly, the AP1000 projects had to develop a new supply chain in the United States and internationally, relying on companies with limited experience in the nuclear sector. The projects also faced specific challenges as they depended on new construction techniques, such as modular construction, that – combined with the lack of design maturity – made it more difficult to address the need for design adjustments and reworking during construction.

Conversely, recent projects in Asia (primarily China and Korea) have benefitted from the fact that these countries have kept sufficiently active nuclear programmes to maintain and develop domestic supply chains.

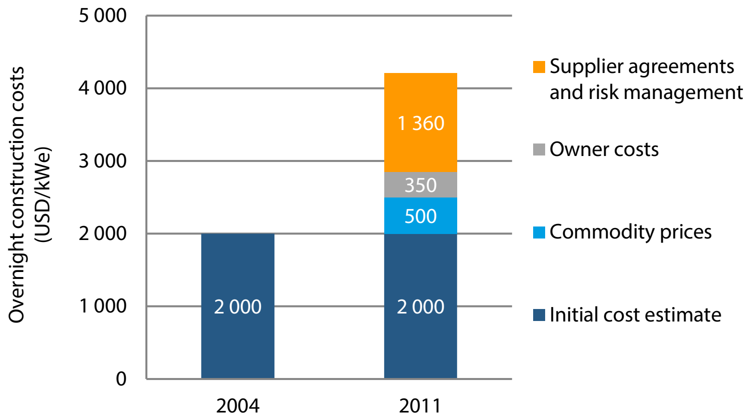
21. www.enr.com/articles/43325-witness-to-the-origens-of-a-huge-nuclear-construction-flop.html.

3.2 Effective project management and procurement framework

Project management encompasses all the organisation and planning steps required for the construction of a new nuclear power plant. The procurement (or contracting) strategy can be viewed as part of this overall framework to the extent that the project management structure will affect procurement decisions.

The importance of project management and procurement frameworks cannot be overstated. An EPIC (2011) study of costs in the US market estimated that overnight capital costs for a FOAK plant more than doubled from USD 2 000/kW$_e$ to USD 4 210/kW$_e$ between 2004 and 2011 (Figure 22). The study concluded that rising commodity prices contributed an additional USD 500/kW$_e$ to OCC, and owner costs a further USD 350/kW$_e$. However, the largest contributing factors were design maturation (the additional cost of adapting designs to US requirements), vendor and supplier agreements and risk management.

Figure 22: **Factors that increase overnight capital costs**



Source: NEA based on data from EPIC (2011), *Analysis of GW-Scale Overnight Capital Costs*.

The study does not fully quantify the breakdown of design maturation, vendor and supplier agreements and risk management, but it quotes outside expert views attributing the bulk of these rising costs to fixed- or firm-price engineering, procurement and construction (EPC) contracts, viewed as the primary reason for escalating nuclear capital costs. While such contracts provide a degree of certainty for the plant owner, it comes at the price of a significant premium due to caution on the part of EPC contractors. This is exacerbated by the fact that EPC contractors then seek to pass on the risk by negotiating similar contracts with their own suppliers, layering cost contingencies with margins built on margins.

3.2.1 *Transaction costs and the role of project management*

The choice of industrial organisation is central to the management of large-scale, complex infrastructure projects such as new nuclear plants. The economic theory of transaction costs developed by Coase is a useful tool to understand the rationale for different types of contractual frameworks (Coase, 1937).

In concrete terms, transaction costs are factors that are not immediately quantifiable as goods or services themselves but that must be taken into account in costs estimates. They constitute a residual category that includes the often unaccounted-for, if not unquantifiable, costs of managing contractual arrangements between stakeholders. One of the most important components of transaction costs is the cost of monitoring and enforcing the quality and precise technical specifications of goods that have been outsourced to other companies. Given the quality requirements in the nuclear industry, this issue is of considerable importance.

A key consequence of transaction costs is the strategic behaviours that may arise among those involved in a contract through two major factors:

- Contracts cannot be permanently renegotiated since negotiation itself is costly, leading to moral hazard. In many ways, contracts have economic characteristics akin to irreversible capital investment. They engage participants over a certain period, so there is an inevitable tension in the contractual relationship over pre-delivery investment and post-delivery performance.
- Information is costly and asymmetrical. Neither side knows exactly what the other is really doing or capable of.

These two factors coalesce into a third one. Since information is costly and the future is uncertain, contracts are always incomplete. No contract can possibly specify conditions for all possible contingencies. In addition, both monitoring and enforcing contract performance are costly. This situation can provide both sides with the possibility of a "hold up" – the ability to interpret, exploit or even deform the contractual relationship in a manner that lowers its cost or increases its profits such that the other side is willing to pay for monitoring and enforcing the original contract.

This situation creates what is known in economic theory as the principal-agent problem.[22] In addressing this issue, contract design is key to align goals, primarily through offering incentives and monitoring the other party's actions. In practice, the principal-agent problem is at the heart of the challenges new-build nuclear project management must address. It primarily affects the contractual framework governing the project, but also reinforces the role of managerial and planning processes to mitigate some of the transaction costs.

Box 6: **The importance of soft costs and the organisational dimension in nuclear power**

To build a room, only walls, doors and windows are needed; they represent the physical (tangible) assets of the room. However, the space inside (intangible) is what really matters and makes the room useful. Soft costs relate to the space inside the room, but they are usually overlooked by project governance schemes and have also received limited academic coverage.

In fact, one of the main complications concerning soft costs is the lack of a clear definition. One key characteristic is their intangible nature. NEA, (2015) considers aspects such as "trust", "experience", "shared vision" and "leadership" as soft issues of project management. Mckinsey (2017) refers to soft issues in megaprojects as the "art" of project management, which involves a blend of leadership, organisational skills, mindsets, attitudes, behaviour and organisational culture. Conversely, the "science" of megaprojects – the processes, principles and theories – is generally well understood.

Soft costs could therefore be defined as expenses, usually not properly accounted for by traditional cost management methodologies, incurred by the interaction of personnel with the processes, structures and mindsets within an organisation or project. As such, they depend on human capital resources – thus intangible by nature – not directly "owned" by the firm, but that can be managed properly if the right processes, structures and corporate culture are in place. Transaction costs, which are usually under-evaluated and depend on project structures, can be considered a category of soft costs according to this report's definition.

22. Also known as agency dilemma, the principal-agent problem occurs when one person or entity (the "agent") is able to make decisions and/or take actions on behalf of, or that impact, another person or entity: the "principal." This results in a conflict of interest between the two parties, as the agent acts solely in his/her own interests.

Box 6: **The importance of soft costs and the organisational dimension in nuclear power** *(cont'd)*

This definition highlights the importance of organisational and management approaches in limiting the soft costs of nuclear power projects.

Kotter (2012) provides insights into the organisational models needed to stay competitive in environments characterised by constant turbulence and disruption. Within a firm, different types of organisational structures cohabit. Traditionally, hierarchical structures, built on optimisation and specialisation, have been established to increase productivity. Although hierarchies perform well under predictable environments, they fail to effectively handle mounting complexity and rapid change. The introduction of a dual operating system that combines traditional hierarchies with network-like structures can be a way to address this shortcoming. While hierarchies co-ordinate day-to-day activities in an efficient way, networks provide higher levels of collaboration, diversity and dynamism needed for rapid problem-solving in complex and uncertain environments. Of especial importance is the role of networks to sustain knowledge.

However, safety issue in the nuclear sector may set some limitations on network-like organisational approaches. Regulations require order, standards and quality control rules that cannot be provided effectively by a network. In addition, safety is at the core of nuclear activities and processes. Although safety is the overarching priority, its logic does not efficiently mobilise resources within a firm. In a recent publication, NIRAB (2019) indicates that, to increase nuclear sector productivity, a well-balanced safety and high-performance culture may be beneficial. A certain emphasis on high performance within an organisation is necessary to challenge current processes and foster their continuous improvement, without necessarily compromising safety. In practical terms, it could be possible to find the right balance between hierarchical and network-like structures to minimise soft costs and hence maximise safe performance.

3.2.2 *Project management in practice: Key lessons from recent FOAK projects*

In practice, project management for large infrastructure projects, such as new nuclear plants, is faced with the trilemma of costs, quality and delivery time (WNA, 2018). It is the overall objective of contractual and procurement frameworks to balance these three components.

This balance is challenging to achieve due to the occurrence of transaction costs that require incentives to be established and collaborative frameworks to be set up to align the interests and goals of all stakeholders. Organisational choices, particularly at the project team level, are especially important to address these challenges.

Recent FOAK projects reveal how transaction costs can lead to hold-up problems that effective project management needs to address.

Leadership and the role of the project team

The importance of leadership in managing nuclear new-build projects cannot be overstated.

The scope of responsibility for the project team and the project owner/operator covers a range of organisational and contractual arrangements. The project team will take the role of the owner/operator in the case of split/multi-package procurement, and it will be responsible to the reactor vendor and/or project consortium in the case of a turnkey contract. Regardless of the procurement approach chosen, given the scale and complexity of a nuclear new-build project, it is very important to develop a dedicated project team structure with sufficient resources and empowerment to enable competent leadership and ensure timely decision-making.

First, the project owner/operator (i.e. in most cases the future utility) is central to the acquisition strategy, and its active involvement needs to be maintained throughout the project. A systematic approach to acquisition especially helps the owner to be prepared to react to changing situations. If a competitive acquisition process is used, nuclear power plant (NPP) vendors may change their strategy during the bidding process, or the bidding process may lose its value due to a lack of real competition or to the unwillingness of NPP vendors to participate in a challenging new-build project under the given terms and conditions. Plus, partnerships and alliances may change during the acquisition process, which could create dramatic changes during the ongoing NPP acquisition process. Finally, contingency plans should always be ready for the owner.

Second, it is essential to establish a strong and dedicated project team to ensure leadership throughout all stages of the project and efficiently address challenges. The project team will be responsible for developing the detailed design, securing the safety case and planning the procurement and construction schedule (RAEng, 2012) It will also have to establish collaboration with the supply chain and with external stakeholders (particularly the local community) – for instance to address emerging environmental and social issues (WNA, 2018). The project team requires a strong team leader reporting directly to the organisation's top-level management.

Although recent FOAK nuclear projects have followed a variety of organisational and procurement approaches, they share a number of lessons applicable to future nuclear projects.

- Lessons from AP1000 projects in the United States

US AP1000 projects – Vogtle (ongoing) and VC Summer (cancelled) – highlight the importance of a solid and experienced project team. Indeed, for both projects the main construction contractor– Stone & Webster (S&W), part of the Shaw Group – originated as an engineering company in the oil sector, with no previous nuclear experience. Consequently, the company's senior management initially underestimated the challenges of new nuclear construction, particularly the quality requirements, and their lack of experience contributed to recurring quality assurance issues (Bechtel, 2016). In the case of VC Summer, it also led to a situation in which the plans and schedules were not reflective of the actual project situation.

Experiences with these projects also underscore the need for plant owners to establish an experienced project management organisation to ensure that the consortium's contractors are fulfilling their contractual obligations. The projects' initial lack of resources in this area contributed to conflict between the EPC consortium led by Westinghouse and the plant owner, which hindered rapid and non-litigious adjustments to unanticipated changes in requirements or subcontractor performance. This amplified the contractual challenges presented in the next section.

- Lessons from EPR projects

A key lesson learnt from the Flamanville EPR project is the need to clearly define and separate the roles of project owner and project manager. Historically, a separate division within the EDF was in charge of project management for the construction of the French nuclear fleet, but because there were no new nuclear plants built in the 1990s this division was eventually incorporated into the EDF nuclear operations division.

This organisational change resulted in the lack of a clearly identifiable project manager, as project oversight was shared by several teams – which changed several times. Plus, many of the teams were not located on-site. Furthermore, the successive managers responsible for the Flamanville project held this role as part of a broader management position and did not report directly to the EDF CEO – a clear disconnect, considering the importance of the project.

According to Folz (2019), this had major consequences as it hampered the ability to mobilise resources internally and to take rapid and effective decisions on-site. The low level of design maturity in particular resulted in a high number of design modifications that needed to be addressed, but the absence of an integrated project team meant that each design change was treated incrementally and separately – often not by teams based directly on-site – without due consideration of the overall impact on project planning. It was only late in the project that sufficient resources were allocated to manage these design modifications.

Conversely, the EPR units in Taishan were delivered with a well-defined project management structure, both in terms of the role of the project team and its direct reporting to the company's top management. The same applies to current EPR construction in the United Kingdom (Hinkley Point C).

- Lessons from APR1400 projects in Korea

The Korea Electric Power Corporation (KEPCO) led the APR1400 project from design development to the completion of construction. Unlike the previous OPR1000 new build projects, the utility took responsibility for the design of the APR1400: under its leadership, APR14000 design was undertaken co-operatively with a well-integrated supply chain. KEPCO Engineering and Construction was in charge of architecture/ engineering (A/E) and nuclear steam supply system (NSSS) design, while Doosan Heavy Industries & Construction Co. was responsible for fabrication design and KEPCO Nuclear Fuel Co. for initial core design. The Korea Atomic Energy Research Institute (KAERI) led the development of FOAK items for APR1400, and the regulatory body developed safety regulation requirements.

As soon as the design was completed, with its standard design certification obtained in 2002, the utility (now the Korea Hydro & Nuclear Power Co Ltd [KHNP]) prepared for construction. Its main task was to complete preparations for all contracts – for A/E services, equipment and material manufacturing, and for construction, including construction permits (Oh, 2019) – and it successfully orchestrated the transition from design to construction.

Last, the utility also directed the construction phase. The company signed a series of contracts for the supply of main facilities and comprehensive design service in 2006, and for the construction in 2007.

Contractual and procurement frameworks

As highlighted in Box 7 below, several procurement approaches can be considered for nuclear new build that will result in different outcomes in terms of risk allocation. In that respect, procurement plays a central role in order to align the interest of the different stakeholders, and in particular incentivise the different contractors.

In addition, these contractual frameworks can further transfer some of the risks through different pricing structures, of which three are often used (NEA, 2015):

- Fixed pricing: the stated price is fixed for some portion of the work throughout the term of the agreement (subject to typical change orders, such as those requested by the owner, force-majeure events or legal requirements).
- Indexed pricing: the stated price for some portion of the work (which also depends on typical change orders) is subject to adjustment over the course of the project based on change in one or more indices.
- Target pricing: the contractor is reimbursed for all costs it incurs plus a fee (profit), subject to a sharing mechanism wherein the contractor receives a bonus if the final project costs are below (or a penalty if the costs are above) a pre-established target price. Target pricing often puts an absolute limit on the contractor's exposure to project cost overruns regardless of fault.

Both the AP1000 projects in the United States and the EPR projects in Europe illustrate how contractual framework and pricing structure choices in nuclear construction projects can contribute to delays and costs overruns if the goals of all parties are not well aligned. An inappropriate contractual framework can amplify the consequences of lack of design immaturity and supply chain challenges faced by FOAK projects.

Lessons learnt from the AP1000 and EPR highlight the counterproductive effect fixed-cost contracting can have on nuclear new-build projects. While the primary goal of this type of contract is to reduce project risk, shifting some of the risk to subsequent subcontractors means that each party has a risk margin. This can snowball, however, with risk margins being added to risks margins. In such a situation, the final cost would reflect a misallocation of risks rather than actual production costs. Owners need to understand that fixed-price contracts mean qualified contractors must include more contingencies for project risk.

At the same time, if these risks do materialise (as happened with recent FOAK projects), this type of contractual framework does not provide the incentives to tackle construction challenges, and instead leads to litigation that makes the situation worse.

Box 7: **Organisational and contracting approaches for new nuclear plant construction**

Constructing a nuclear power plant is highly complex, requiring the co-ordination of a wide range of activities: design development based on detailed technical assessments and regulatory requirements; procurement of equipment; civil engineering and construction; testing and installation of components; and commissioning of the power station. Plus, contractor and subcontractor co-ordination is necessary at all these stages.

How a project's equipment, materials and services are procured and the relationships with and among contractors significantly affect supply chain development. Many options are available for responsibility-sharing between the ultimate operator of a nuclear power plant and the principal supplier. The three main categories of contracts normally used for nuclear new-build projects are (NEA, 2015):

- Turnkey, wherein a single contractor or a consortium of contractors takes overall responsibility for the construction work. A turnkey approach to NPP contracting involves a single large contract between a customer and NPP vendor (or a consortium led by such a vendor), covering the supply of the entire plant. The vendor or consortium subcontracts any elements of the project it cannot supply itself. The contractor thus takes full responsibility for delivering the plant to the customer.
- Split package ("island"), wherein overall responsibility is divided among a relatively small numbers of contractors, each in charge of a large section of the plant. At its simplest, this approach divides a plant into two packages: the nuclear island and the conventional or turbine island. More complex split-packages separate off civil construction work as well as other major electrical and mechanical systems. In such an approach, it is necessary to allocate overall responsibility for design and licensing, and for reintegrating the various packages to ensure that all the plant's systems work together efficiently. Such overarching responsibility could be taken by the plant owner or the main contractor.
- Multi-contract, wherein the plant's owner or architect-engineer assumes overall responsibility for detail engineering and plant construction. The architect-engineer typically prepares the contracts, which are then placed by the owners. This approach gives the customer maximum oversight of plant design and construction, but also the most responsibility for project success. Only a few large nuclear utilities have this expertise in-house, so often when this approach is adopted, an external A/E company will first be contracted to manage the project overall. Breaking the project into a large number of separately supplied components and systems can maximise the choice of supplier as well as competition, but it is likely to make the architect-engineer's task of co-ordinating the project more onerous.

▪ Lessons from AP1000 projects in the United States

In the case of the US AP1000 projects, the partnership between Westinghouse and S&W[23] contributed to a lack of incentives to resolve construction challenges and eventually resulted in a series of litigations. As these litigations often took place during critical periods of construction, they further hindered the project. This also resulted in lower mobilisation of company resources, and lower worker morale reduced site productivity.

23. In the years since the EPC agreement, these contractors have gone through multiple acquisitions by larger companies. At the time, S&W was an operating company of Shaw Group LLC, a Louisiana-based infrastructure company initially specialised in the oil and gas industry. In 2012, the Shaw Group was acquired by Chicago Bridge & Iron (CB&I), a large infrastructure company and energy conglomerate. In addition, Westinghouse, which in 2008 was partially owned by the Shaw Group, was subsequently bought by Toshiba, a Japanese industrial conglomerate, but later went into bankruptcy and was taken over by a private equity group, Brookfield Business Partners.

For the two AP1000 projects, Westinghouse and the Shaw Group, which owned S&W, set up an EPC consortium and agreed with the utility owners on a "guaranteed substantial completion date",[24] with damage provisions in case of delays. Westinghouse was primarily responsible for the design, manufacture, and procurement of the nuclear steam supply system, while S&W was to tackle on-site construction and procurement of auxiliary equipment.

As explained in the previous section, these two projects were FOAK implementations of a new modular construction approach using off-site construction and large prefabricated modules manufactured at (and shipped from) a facility operated by Shaw-Chicago Bridge and Iron (CB&I), S&W's parent company. This facility, which had mainly serviced the regional petrochemical industry, found it challenging to adapt to nuclear-grade construction standards. There were also issues with reactor site constructability due to lack of design maturity, particularly concerning integration and the on-site assembly of prefabricated modules. In addition, changes in US Nuclear Regulatory Commission (NRC) regulations led to further design modifications during construction.

These technical difficulties were exacerbated by contractual challenges, both within the consortium and between the consortium and the owner utilities:

- Contractual challenges within the EPC consortium: The series of technical difficulties affected the working relationship between the designer authority, Westinghouse, and the builder, S&W. In turn, instead of mobilising resources to resolve these unanticipated issues, both parties revolved to commercial disputes.[25] This situation was further amplified by fixed-price contracts aimed at shifting construction risks to the subcontractors.

To address this form of hold-up problem, some significant changes in EPC project management took place in 2016, with this role being transferred to one sole experienced EPC company. In parallel, Westinghouse decided to acquire the nuclear business of CB&I, including S&W. This form of vertical integration allowed Westinghouse to become the sole construction contractor, thereby resolving the commercial dispute with CB&I over delays at the two AP1000 projects.

This illustrates the importance of avoiding fixed-price contracts for risky parts of projects: due to transaction costs, contracts remain incomplete, which increases the risk of litigation in cases of technical difficulty. At the same time, vertical integration and the selection of a single experienced EPC contractor were found to strengthen project management and effectively reduce transaction costs.

- Contractual challenges between the consortium and owner utilities: The initial contractual framework between the owner utilities and the AP1000 project consortium at both Vogtle and VC Summer has also been identified as a factor amplifying the construction difficulties of these two projects. Both projects were signed under fixed-cost contracts, which shifted most of the construction risks to the EPC consortium.

The Huston expert review (2016) argued that this could have counterproductive consequences in the case of a nuclear project, with more incentives to focus on cost management than on quality. In addition, the multiplication of design changes (due partly to regulatory changes and therefore the responsibility of the owner utilities) led to further commercial litigation over responsibility for the projects delays and associated cost overruns. As argued by Bechtel (2016), in the case of VC Summer this led to a situation in which the contractual framework was no longer aligned with the project goals. To a large extent, this can also be considered another layer of hold-up problem due to transaction costs and incomplete contracts.

24. www.powermag.com/how-westinghouse-symbol-of-u-s-nuclear-power-collapsed/?printmode=1.

25. For instance, as the Huston expert report (2016) documents, at the Vogtle project, CB&I refused to incorporate a number of Westinghouse design modifications into module fabrication. The internal consortium dispute hence had a direct impact on the project's timeline. According to the Bechtel report (2016), a similar situation occurred at the VC Summer project and reduced onsite worker productivity.

Conversely, the new EPC contract signed in 2017 between Georgia Power and Bechtel to manage completion of the Vogtle project is not based on a fixed-price contracting framework and instead includes specific incentive payments for on-time, on-cost completion.[26]

- Lessons from the Flamanville 3 and Olkiluoto 3 projects
  - Contractual challenges between the consortium and the owner utility: The Finnish EPR project shared some similarities with the US AP1000 projects in terms of contracting framework, with the use of fixed-term contracts producing similar lessons.

In 2003, an Areva-Siemens consortium signed a EUR 3-billion fixed-price turnkey contract with the Finnish utility Teollisuuden Voima Oyj (TVO) for construction of the first EPR at Olkiluoto. Low design and supply chain maturity caused design changes that resulted in delays and a rapid escalation of construction costs. This led to a series of commercial disputes and litigations, with both sides claiming compensation for the cost overruns and associated extra delay costs (STUK, 2016). In 2008, Areva claimed compensation of about EUR 1 billion for TVO's alleged failures, and TVO, in a January 2009 counterclaim, demanded EUR 2.4 billion in compensation from Areva for project delays. This legal dispute lasted for several years until a final arbitration in 2018 in which TVO was awarded a EUR 450 million settlement.[27]

This settlement also included some changes in the contractual framework with incentive payments. The supplier consortium would be entitled to receive an incentive payment of up to EUR 150 million in the case of project completion according to a new agreed timeline (end-2019). Otherwise, the consortium would be expected to pay a penalty to TVO for such delays, proportional to the actual time of completion of the OL3 EPR project and up to a maximum of EUR 400 million.

  - Incentivisation of lead contractors: In the case of the French EPR project, EDF acted as owner and architect-engineer, contracting directly with suppliers through a multi-package approach. In this respect, this project did not face the difficulties associated with fixed-price turnkey contracts used in other FOAK projects, but this does not mean that EDF avoided all contractual framework challenges. Compared with its previous projects, the EDF aimed to reduce the number of first-rank contractors and limit the complexity of interface management while incentivising suppliers to be responsible for their scopes. In the end, however, most of the risks were still borne by EDF, which was required to be much more involved in contract management than anticipated.

Project planning and scheduling

Project planning and scheduling are especially important, as early decisions in these fields have a long-lasting impact on the project. The ability to influence the success of a project is gradually reduced after the planning phase while accumulated capital expenditures increase, especially after the start of construction.

While this trend applies to any large-scale engineering project, its impact on new nuclear construction is probably unique. Project complexity and high regulatory oversight further limit opportunities to review and alter some areas of planning once construction has started without significantly affecting the rest of the project.

To a large extent, project planning and scheduling hurdles are similar to, and strongly linked with, the design and supply chain maturity challenges highlighted in Section 3.1. For example, including the supply chain early in project planning and in detailed design studies will both help to ensure constructability and tackle equipment qualification issues. Similarly, the optimism bias that impacts costs estimates when design maturity is low (see Box 5) also affects project planning and scheduling. Recent FOAK projects have been characterised by notoriously unrealistic initial planning and scheduling, which has amplified the impact of design changes during construction.

26. www.enr.com/articles/42734-how-bechtel-limits-risk-on-possible-big-plant-vogtle-role.

27. www.nucnet.org/news/tvo-says-450-million-settlement-with-olkiluoto-3-suppliers-has-come-into-force.

Finally, it is worth stressing that while successful project planning and scheduling is in large part a matter of organisational choice and resources, the availability of innovative methods and especially a system engineering approach are also important factors. These will be presented in detail in Section 4.2. as part of short-term cost reduction opportunities.

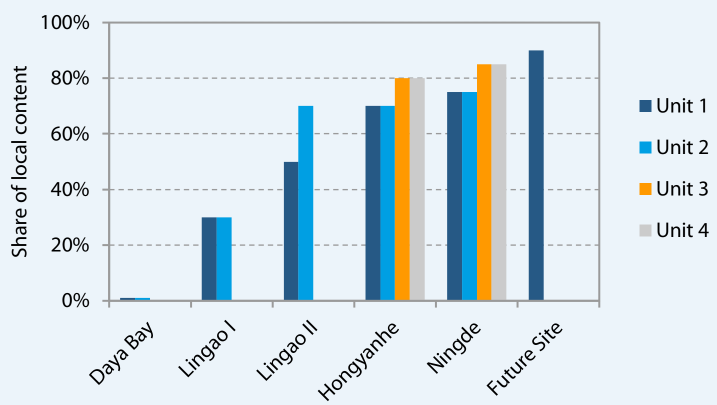
Box 8: The opportunities and challenges of localisation strategies: Insights from the Akkuyu project

When a nuclear power plant is exported, a localisation strategy in the supply chain externalises some of the activities of the construction of a nuclear power plant to the local industry.

Construction of the first nuclear power plant in a country will generally require a turnkey contract with an experienced international vendor, at least for the nuclear island (IAEA, 2011). As local industry experience develops, the local content of subsequent new builds also tends to increase. If the size of the national programme is sufficiently large, host countries may have a strong interest in participating in activities with higher value in the supply chain, such as manufacturing, engineering and design. In this case, localisation strategies are usually accompanied by technology transfer agreements. This is the model supporting successful indigenous nuclear industrial plans in France, Japan, Korea and, more recently, China.

A localisation plan may provide different type of benefits depending on the stakeholder. From the consumer (host country) perspective, greater localisation offers opportunities for economic growth and employment in the region. It may also raise the productivity of local industries and foster long-term business relationships with leading global companies. Building in-house capabilities also makes economic sense, especially for large nuclear programmes.

Figure 23: **Progress on local content of different Chinese CPR-1000 reactor**



Source: NEA (2015), *Nuclear New Build: Insights into Financing and Project Management.*

For the technology vendor, localisation also provides diverse opportunities. First, it reduces political risks and opposition by strengthening relationships with the government and local communities. Secondly, CAPEX savings can be realised thanks to less costly local procurement, lower transport costs and keener competition.

Nevertheless, technology vendors also face several additional risks with localisation. The local industry may be less productive and may lack the necessary capabilities and skills, putting the project's budget and schedule at risk. The qualifications of local suppliers to manufacture nuclear-grade components should be properly investigated and monitored. Risks related to currency exchange rates should also not be neglected. Furthermore, the number of project interfaces increases with greater organisational complexity, raising transaction costs. The cultural differences between vendors and host countries may also add to soft costs (see Box 6).

Box 8: **The opportunities and challenges of localisation strategies: Insights from the Akkuyu project** *(cont'd)*

To mitigate these potential risks, vendors may adjust and refine their localisation approaches. Among the best practices, assessing the capabilities of local suppliers and setting up qualification and oversight processes are of high importance (WNA, 2019). The Akkuyu project provides interesting insights on the opportunities and potential of localisation strategies.

The Akkuyu project

The Akkuyu project involves the construction of four VVER-1200s (4 800 MW_e total capacity) in Turkey, following the signature of an intergovernmental agreement (IGA) with Russia in May 2010. The Akkuyu project is the first nuclear power plant ever built in Turkey and the first new-build project based on the build-own-operate (BOO) contractual model.[28] According to the IGA, Russia (with Rosatom at the head of the project) is responsible for the planning, construction, operations, maintenance of the plant as well as its decommissioning and waste management. This scope also includes the project financing, estimated at USD 20 billion (NEA, 2015).

One of the key aspects of the project is the necessity to raise significant funding, particularly export credit agency (ECA) funding. Estimates from 2015 indicated potential ECA needs of USD 1.6 billion (NEA, 2015). Rosatom's strategy involves adjusting the contracting approach through a split-package and multi-package mix to maximise localisation opportunities and, consequently, the chances of attracting ECA funding.

The selected localisation process requires elaboration of a detailed plan of localisation resources and their division (i.e. internalisation versus externalisation) in collaboration with a key local experienced partner. More specifically, for the resources of the Akkuyu project (i.e. equipment, materials, workforce and machines), around 7 500 items have been identified for monitoring their prices in Turkey in detail.

At the same time, an audit of the capabilities of potential manufacturers and suppliers is being performed with the involvement of key partners, certification authorities and duly accredited testing laboratories. The outcomes of the audit are used to define the final resource division plan. For the Akkuyu project, most of the materials and components not subject to special safety requirements (i.e. low or no safety-class components) are being procured in Turkey and other countries, whereas safety-class components and other steel structures are generally manufactured in and delivered from Russia.

In addition, the audit may help identify key local suppliers and potential qualification needs. The qualification of a new supplier remains a challenge. In some cases, the local industry may be reticent to accept the high level of qualification and standards that nuclear manufacturing processes require, especially in the absence of subsequent projects. To accelerate the localisation process, it is advisable to identify a local party able to guide and assist the various partners through the qualification process.

Alternatively, one of the solutions adopted for the Akkuyu project involves the publication of standards similar to Russia's in the Turkish standardisation system; these standards are then included in the project's licensing database. Open dialogue and communication with the local business community is also an effective tool to expand the pool of potential suppliers and their optimisation.

28. The BOO model is similar to the turnkey contract, except that there is a major difference in ownership. Consequently, a foreign investor has to plan, construct, operate and provide financing for the NPP.

3.3 Stability and predictability of the regulatory framework

A number of factors related to the regulatory framework can impact nuclear construction costs. First, the level of safety requirements can be a cost driver. Gen-III nuclear reactor developments since the Three Mile Island (TMI) and Chernobyl nuclear accidents have resulted in enhanced safety standards that have affected design and supply chain requirements, often resulting in cost increases. Examples include the double-containment wall and the core catcher used in several Gen-III designs as well as an increased number of redundancy systems.

In many instances, however, historical and recent construction experiences highlight that a key factor in constructions costs – and in costs overruns especially – is not the level of safety requirements per se, but rather their stability and predictability.

3.3.1 Stability of the regulatory framework

Having a stable regulatory framework does not mean that safety standards do not evolve to reflect lessons learnt, scientific progress, and overall revaluations of safety objectives. Rather, it is crucial to anticipate those modifications to the safety framework prior to the beginning of a new nuclear construction project, as they can have significant cost and delay implications.

Lessons from historical projects in the United States

A key driver of cost overruns in the United States has been changes during construction, typically imposed by the regulatory body as regulators progressively learn more about the safety of nuclear facilities, and about the best practices in reactor construction with regards to safety.

In general, changes after construction has been initiated are very damaging to the cost of facilities (Ganda et al., 2016), primarily because the original contracts, negotiated through competitive bidding, become untenable when changes to the original scope of work are requested. Typically, rebidding at that point is also impractical, so that historically the original fixed-price contracts were switched to cost-plus contracts, impacting contractors' incentives to complete the work efficiently and within a set budget.

Additionally, several other drivers of historical cost escalations are related to reworkings:

- The completed work has to be removed/altered, often with ripple effects on nearby systems.
- The construction sequence has to be altered and so do equipment delivery schedules, potentially leaving groups of workers idle and leading to lower labour productivity.
- The increased construction duration can create a positive feedback loop by exposing the project to greater risk of regulatory turbulence, raising interest costs and disrupting construction logistics.

A similar conclusion was reached by a United Engineers and Contractors' analysis for the US Department of Energy (DOE), discussed in ORNL (1988). In fact, "[cost overruns were] due more to decreased productivity than to increased amounts of material and equipment being installed." Nuclear construction productivity has two components (ORNL, 1988):

- Within workers' control: "related to their competence, thoroughness, organisation and incentive to do quality work."
- Outside workers' control: "related to *rework* [emphasis added] (design changes, interferences, inadequate lead times) and delays (extended schedules, quality assurance hold points, inspections)."

ORNL (1988) found that the second component, related to reworking and delays, was the dominant cause of labour cost escalation between 1978 and 1988: "It is the second component that appears to predominate in the causes for decreased productivity."

As an example, Basset (1978) studied the cost overruns of the Davis-Besse power station in Ohio and found that the cost escalation (from the original budget of USD 136 million in 1967 at the approval of construction, to USD 650 million in 1977 at the end) was primarily linked with "NRC modifications and their chain effects", accounting for USD 398 million of the total USD 650 million.

Lessons from the recent AP1000 project in the United States

Since the early 2000s, the NRC has taken many steps to make the regulatory framework for nuclear new-builds more stable, including streamlining licensing by implementing combined licence applications (COLAs) that cover both construction and operations for new reactors.

However, in the case of Vogtle 3 & 4, the COLA licence affected the AP1000 generic design licence. A new standard was introduced in 2009 for shield building requirements, seven years after Westinghouse had applied for approval of its AP1000 design.[29] The new requirements resulted in unanticipated engineering challenges at a late stage of project planning, and were only met by the company in 2011, contributing to both delays and costs overruns.

Lessons from historical projects in France

Analysing the construction costs of the French nuclear programme produces similar conclusions. Average costs as well as the variability of the French construction programme were substantially lower than for the United States. This performance can be attributed primarily to the lack of changes during construction, as well as to "rigorous quality and cost control by EDF" (Grubler, 2010). The lack of changes during construction was partly a result of deliberate efforts to preserve engineering stability and partly owing to a regulatory environment that avoided imposing changes during construction.

In addition, Rangel and Lévêque (2012) notes that despite the stability of safety rules, EDF integrated progressively more stringent safety features into new reactors.

Lessons from APR1400 projects in Korea

The APR1400 received standard design approval in May 2002, within five months of completion of its design development.

First, from the basic design stage of the APR1400, the Nuclear Regulatory Agency developed the regulatory requirements and guidelines to be applied to the APR1400 by examining those applicable to existing nuclear power plants, as well as past operational experience. The Agency also evaluated new safety systems, ergonomic considerations and the reliability of critical systems and devices. It adopted a preliminary approval review system to facilitate co-operation between design development and regulatory evaluation and discussed major safety issues with designers (Oh and Park, 2004).

Next, the Agency introduced a system to approve standardisation of the APR1400 design. After reviewing the US case and gathering a wide range of opinions on the necessity and direction of the system, the Agency established a standard design approval procedure adapted to the domestic situation. In this case, KEPCO signed an agreement for the preliminary safety review of the APR1400 with the Agency in 1999. It was agreed that the preliminary review results would be reflected in the subsequent official licensing process. In the preliminary review process, the utility answered roughly 2 100 questions raised by the Agency (Choi et al., 2001).

As a result of these efforts, the bill to introduce the system for licensing standard design was enacted in 2001 under the Atomic Energy Act and related sub-regulations. Standard design approval is intended to improve the efficiency of regulations by applying a simplified licensing procedure to allow repetitive construction through a single design review of the standard design part. Designs with standard design approval were given a ten-year legal validity period.

In July 2001, KHNP applied for standard design approval with a standard design safety analysis report, standard design description, performance verification plan for design and construction, and emergency operations procedure. The Agency focused its review on man-machine interfaces related to main control room design, new safety injection system performance, and countermeasures against severe accidents. APR1400 standard design approval was granted in May 2002 (Oh and Park, 2004), and the utility received a construction permit for the first APR1400 in 2008.

29. www.reuters.com/article/us-toshiba-accounting-westinghouse-nucle-idUSKBN17Y0CQ.

3.3.2 *Predictability of the regulatory framework*

Predictability of when new standards or rules will be introduced is also critical, especially because the new regulations may not be directly translated into the detailed technical requirements needed to inform engineering studies.

Lessons from the EPR project in France

The implementation of a new regulation for nuclear pressurised equipment in France, and its impact on the Flamanville 3 project, illustrates the importance of this issue. In 2005 the regulation introduced new requirements concerning qualification, resistance to hazards, material properties and welding procedures, as well as quality control, quality assurance, and surveillance by third parties. It then took 4 years for the licensee and the safety authority to reach a common understanding on interpreting these new technical requirements. The requirements were further updated in 2012, and the regulation itself was further revised in 2015.

All of this happened at the same time as large components were being manufactured for the Flamanville EPR, requiring the industry and certification bodies to interpret and agree upon the evolving requirements.

The issues involved in qualification of the Flamanville pressure-vessel head illustrate how this lack of predictability – and to some extent stability – of safety regulations, combined with challenges in supply chain capabilities, can lead to delays and therefore contribute to costs overruns:

- Although the reactor's pressure head was forged in 2006, prior to the new regulation on pressure equipment, Framatome had agreed to comply with the imminent regulation.
- However, as one of the largest forged nuclear components, it proved especially challenging for the industry and the safety authority to reach a common understanding for the qualification process. Initial discussions were completed only in 2011.
- Further tests were then requested, which resulted in identification of non-compliance with the new specifications in 2014.
- This led to a large-scale programme that lasted until 2017 to further demonstrate the safety case, despite the identified non-compliance.
- Eventually, in October 2017, the French safety authority qualified this component for a reduced period until 2024.

3.4 Policy framework and the mobilisation of stakeholders in a new-build programme

Successful nuclear projects require strong and consistent political leadership to offer sufficient visibility and certainty to mobilise the different stakeholders, particularly in the supply chain. The development of a nuclear new-build project as part of a long-term programme can be a strong driver of cost reductions, as it limits nonrecurrent costs among units and supports the series effect.

3.4.1 *The role of political leadership in spearheading nuclear new-build projects*

Historical lessons from France's nuclear programme

Historically, the success of France's nuclear programme depended on a government-led plan and the country's goal to build power generation infrastructure that would support economic growth, ensure energy independence, and quickly achieve technological self-reliance. Having clear visibility over the size of the programme (initially 13 reactors) allowed the industry to organise itself under the strong industrial leadership entrusted to the state-owned electric utility by the government, and more generally by the community.

This context enabled the mobilisation of capabilities from other industries, including by means of conversions from declining sectors such as coal mining and steel and aluminium production. It also made it possible to optimise the standardisation effect across the largest fleet ever built and operated by a single utility. The difficulties encountered at the time were mainly related to the high pace of implementation[30] and the pressure on domestic industrial capabilities, as well as on financial markets. The rhythm slowed as the initial forecast of 100 GW_e of nuclear by 2000 was adjusted to meet demand and 63 GW_e were eventually put into operation.

Lessons from the Flamanville and Taishan EPRs

In the early 2000s, however, several of the elements of France's nuclear programme had disappeared, making it a challenge to build the first French EPR at Flamanville (Folz, 2019).

Although the government authorised the Flamanville EPR as a demonstration project aimed at validating the design and renewing industrial capabilities for a potential future renewal of the fleet, the industry was not given the programme visibility it had received 30 years earlier. Instead, the Flamanville EPR was built within the context of political and media focus on renewables development, as well as on public debates about lifetime extensions of the existing fleet and reducing the share of nuclear in France's electricity mix.

Financial and human investments were inadequate to overcome the project's challenges, as the sense of project ownership and its long-term vision for the community were left to the operator, EDF. At the same time, EDF involvement in the community had shifted. It no longer had its historical function as a fully state-owned company in charge of the electricity monopoly following an initial public offering (IPO) in 2005 and initiation of electricity market liberalisation in the early 2000s.

In this context, EDF and its supply chain were under pressure to legitimate their project and nuclear new-builds more generally by proving their ability to achieve the announced targets. Extreme scrutiny was emphasised by increasing political, financial and media attention to short-term concerns. As a result, too much focus was placed on technical difficulties encountered in project execution and their impact on the budget, the schedule and the forecast commercial operations date (COD), at the expense of a shared vision of the project's contribution to long-term energy policy.

A similar project in a different context – Taishan, China – demonstrates that focusing instead on successive milestones, keeping a clear perspective of the project's aims, and relying on the dynamics of a programme, create the best conditions to optimise the performance of an infrastructure project, especially in a FOAK context.

Lessons from Korea's nuclear programme

Since Korea's first long-term nuclear power development plan was established in 1968, government policy has consistently affected all nuclear power development businesses and processes, from the technology transfer of foreign designs and localising with the OPR1000, to further advancement with the APR1400. This government policy provided not only a domestic market but also supported the development of Korea's indigenous technological capabilities for key nuclear power programme functions, including design, manufacturing, construction, and operations and maintenance. Hence, the Korean government has directly invested in technological learning and regulated domestic market conditions throughout the course of nuclear power plant development. It has actively played a pivotal in Korea's nuclear power programmes, especially in terms of promoting synergistic interactions between technology development and market demand.

In the early 1980s, the government formulated strategic plans for technical self-reliance on nuclear power plants. As oil crises swept the globe in the 1970s, the Korean government devised policies to foster energy independence – like France and other energy-poor countries – and decided to expand national nuclear power generation capacity.

30. As many as 8 units were commissioned in one year (1981), with a total of 54 units in 15 years.

In 1984, the government established a Technical Self-Reliance Plan targeted at localising 95% of Gen-II-type nuclear power plants by 1995, building up indigenous NPP technological capabilities and localising the design and manufacturing of NSSSs. A joint-design approach was adopted as a way of learning under the contract of international technology transfer.

Development of the APR1400 design was also directed and supported by government policy as part of the country's economic development strategy, which involved 11 projects aimed at helping Korea succeed in world-class technological innovation and competitiveness by the early 2000s. The Korean government therefore strongly supported development of the APR1400 design, placing it at the top of the national agenda.

3.4.2 *Benefits of multi-unit projects and series construction*

For countries considering the construction of several nuclear power plants, multi-unit and serial construction can significantly reduce construction costs. These reductions are achieved through well-identified levers (NEA, 2000; SFEN, 2018):

- First, through the reduction of indirect construction costs. This includes design documentation, safety approvals associated with the design, and supplier qualification. For multi-unit projects on the same site, additional cost reductions are also possible, as nonrecurrent site-specific regulatory, planning, and supporting infrastructure costs are shared across several units.
- Second, through mobilisation of the nuclear supply chain as experience is transferred among the various projects. This applies particularly to construction methods that can be easily repeated once validated. Transferring experience also reduces construction duration, which further cuts financial costs (interest during construction [IDC]).

Multi-unit effect

Constructing several reactors of the same design on the same site reduces the nonrecurrent costs of infrastructure development per reactor. This includes site preparation (e.g. earthworks, road access) as well as some infrastructure (e.g. grid connections, water intake) and annex buildings that can be shared.

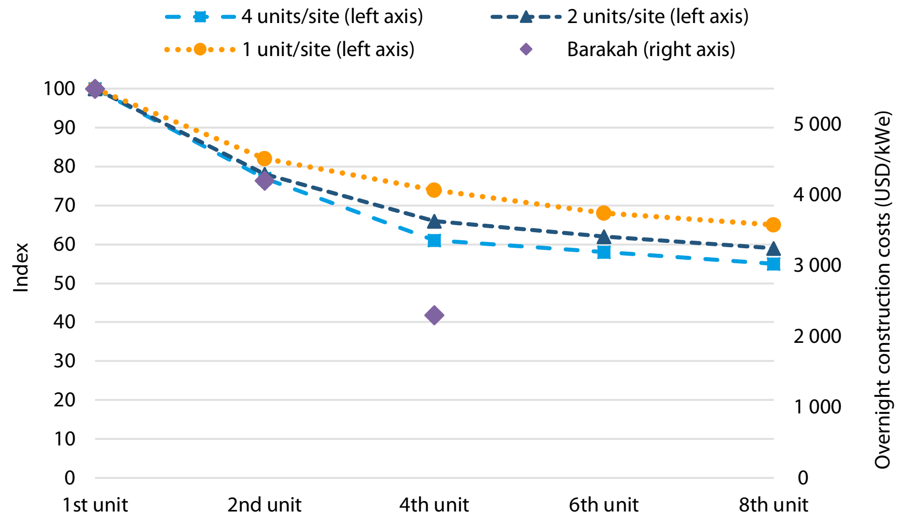
In addition, a twin project facilitates more efficient allocation of resources that can be optimised between the two units, reducing the risks and impacts of delays. For instance, in the case of delays on one unit, teams can be reallocated to the other. Similarly, considering that there will be a lag of a few months between construction of the two units, if a spare part is needed for the first unit, it can be sourced from the second, thereby avoiding the risk of delays.

Overall, it is estimated that constructing reactors in pairs reduces the cost of the second reactor by about 15% (NEA, 2000). An additional 5% cost reduction could also be expected for the second pair.

The recent Barakah 4-unit project in the United Arab Emirates demonstrates that such cost reductions can be even more rapid for the most successful projects (Figure 24). This project implemented construction and contracting best practices: an at-home multi-unit reference project, a proven supply chain, and strong overall project governance. According to Gogan (2019),[31] costs fell more than 50% between the first and the fourth units.

31. Building on data from the ETI Nuclear Cost Database.

Figure 24: **Average cost of one unit in a programme of n units**



Sources: Based on NEA (2000), *Reduction of Capital Costs of Nuclear Power Plants*; and Gogan (2019), "The potential for nuclear cost reduction."

Series effect

Construction of the French fleet clearly benefitted from the series effect, with the average construction cost (EUR/kW$_e$) 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 (Berthélemy and Escobar Rangel, 2015). To create a series effect, the technical standards, codes and norms that will be used in the design, licensing and construction of all units of the series must be stable. When there is any deviation from these conditions, for example with construction projects that involve more than one country (and are therefore subject to different safety authorities and regulations), or that have different industrial assembly lines, series effect benefits are likely to be lost.

The series effect is influenced by two distinct factors: the programme effect and the productivity effect (SFEN, 2018).

- The programme effect originates in the strategic decisions of the architect-engineer (the 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 a series. These nonrecurring costs are both 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.
- The productivity effect is seen mostly 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.

The impact of series construction of standardised reactors on OCC is quite substantial, with cost savings of 15-20% (NEA, 2000). The impact on time-related costs (IDC) is also significant (costs could decrease by more than 60%) because the construction period is substantially shorter. When time-related cost savings are combined with OCC reductions, total costs can be 25-40% lower.