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Unlocking Reductions in the Construction Costs of Nuclear:

A Practical Guide for Stakeholders

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Nuclear Technology Development and Economics

Unlocking Reductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders

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Foreword

Unlocking Reductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders completes a series of recent OECD Nuclear Energy Agency (NEA) publications addressing the cost of the electricity provision in all its dimensions. In contrast to *The Full Cost of Electricity Provision* (NEA, 2018) and *The Costs of Decarbonisation: System Costs with High Shares of Nuclear and Renewables* (NEA, 2019) which focused on the external and system costs, respectively, the present report assesses the construction cost reduction opportunities arising at the plant-level. Although the publication *Nuclear New Build: Insights into Financing and Project Management* (NEA, 2015) provided an evaluation of a number of recent nuclear construction projects, the reduction of new nuclear construction costs is a topic that had not been studied in detail under the auspices of the NEA since 2000.

As highlighted by the NEA's sister-agency, the International Energy Agency (IEA), nuclear power is an integral part of future low-carbon energy portfolios that meet the decarbonisation objectives of the Paris Agreement. However, over the last decade significant cost overruns and delays in a number of OECD countries have challenged the competitiveness of nuclear power and are driving up the risk perception of future projects. Several studies have been recently published on the matter that shed light on specific cost drivers and risks associated with the construction of nuclear power plants. The present report builds on these works and brings a new perspective highlighting the role of the different stakeholders – and in particular policymakers – to unlock a positive learning trend in nuclear construction.

After a long nuclear construction hiatus in OECD countries, recent nuclear projects have served to rebuild supply chain capabilities. While the industry has also made major efforts in terms of organisational restructuring and integration of a number of recent technological advances, governments hold the key to significant construction cost and risk reductions by committing to the next set of new build projects. With several projects under completion in OECD countries, the next decade offers a window of opportunity to capitalise on the experience accumulated to improve the economic performance of both traditional large reactors, as well as new, innovative designs such as various small modular reactors.

More recently, the COVID-19 crisis has been a stark reminder of the critical importance of having a robust electricity infrastructure capable to withstand and recover from major disruptions. Resilience will be at the core of the energy infrastructure of tomorrow. At the same time, the stimulus packages under development in different countries provide an excellent opportunity to place the development of a low-carbon resilient infrastructure at the centre of the economic recovery. After a period of unprecedented economic slowdown, maximising investment efficiency will be a priority. Policymakers will find in this study timely evidence on the most appropriate governing schemes to include nuclear in their recovery plans and build, in a cost-effective manner, a low-carbon, competitive and resilient electricity infrastructure for all.

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Director-General, Nuclear Energy Agency

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Acronyms and abbreviations

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ABWR	Advanced boiling water reactor
A/E	Architecture/engineering
ALARA/P	As low as reasonably achievable/practicable
BIM	Building information management
CB&I	Chicago Bridge and Iron
CCGT	Combined-cycle gas turbine
CfD	Contract for difference
CORDEL	Cooperation in Reactor Design Evaluation and Licensing
COTS	Commercial off-the-shelf
ECA	Export credit agency
EDF	Électricité de France
EP	Equator Principles
EPC	Engineering, procurement and construction
FOAK	First-of-a-kind
GDA	Generic Design Assessment
GIF	Generation IV International Forum
HPC	Hinkley Point C project
IAEA	International Atomic Energy Agency
IDC	Interest during construction
IEA	International Energy Agency
KEPCO	Korea Electric Power Corporation
KM	Knowledge management
LCOE	Levelised cost of electricity
LRL	Licensing readiness level
LW	Light water
MDEP	Multinational Design Evaluation Programme
MIT	Massachusetts Institute of Technology
NDE	Non-destructive examination
NEA	Nuclear Energy Acency
NETL	National Energy Technology Laboratory (United States)
NPP	Nuclear power plant
NRC	Nuclear Regulatory Commission (United States)

NSQA	Nuclear Quality Standard Association
NSSS	Nuclear steam supply system
O&M	Operations and maintenance
OCC	Overnight construction costs
OECD	Organisation for Economic Co-operation and Development
ONR	Office for Nuclear Regulation (United Kingdom)
PLM	Product lifecycle management
PPA	Power purchase agreement
PRR	Project risk register
PSA	Probabilistic safety assessment
PWR	Pressurised water reactor
R&D	Research and development
RAB	Regulated asset base
REDCOST	Ad Hoc Expert Group on Reducing the Cost of Nuclear Power Generation (NEA)
RIPBR	Risk-informed, performance-based regulation
ROW	Rest of world
S&W	Stone & Webster
SDS	Sustainable Development Scenario
SE	Systems engineering
SMR	Small modular reactor
SPC	Steel-plate composite
TMI	Three Mile Island
TRL	Technology readiness level
TVO	Teollisuuden Voima Oyj (Finland)
VRE	Variable renewable energy
WACC	Weighted average cost of capital

Units of measure

Bt	Billion tonnes
°C	Degrees Celsius
g	G-force (acceleration due to Earth's gravity)
gCO_2	Gramme of carbon dioxide
GW	Gigawatt
GW_e	Gigawatt electrical capacity
kW_e	Kilowatt electrical capacity
kWh	Kilowatt hour
mm	Millimetre
MW_e	Megawatt electrical capacity
MWh	Megawatt hour

Executive summary

Time for action if nuclear is to be a part of future electricity systems

Globally, the long-term contribution of nuclear power is needed if countries around the world are to meet their ambitious targets to dramatically reduce and eventually eliminate the net production of carbon dioxide. However, it is increasing clear that the world is not on track. According to the International Energy Agency (IEA) Sustainable Development Scenario (SDS), new nuclear capacity will be needed in addition to ambitious lifetime extension programmes for existing nuclear power plants. In 2019, nuclear power was not on path to reach the required output; in fact, the rate of annual capacity additions would need to at least double between 2020 and 2050 to meet the SDS target.[1]

There are many reasons for this shortfall, but the most impactful are related to the high cost of new nuclear projects, particularly in countries that have not built nuclear plants in recent decades. For those countries that have launched new projects, the experience has been difficult. These first-of-a-kind (FOAK) Generation III projects, particularly in most Organisation for Economic Co-operation and Development (OECD) member countries, have been affected by construction delays and cost escalations. Consequently, stakeholder and public confidence in the ability of the nuclear industry to build new projects has been eroded. Moreover, the perception that new nuclear plants carry high project risk dissuades investors and has further reduced the ability of countries to attract financing for future projects.

These issues are not present in countries that have been building plants continuously. In those countries, with their experienced project organisations and well-established supply chains, nuclear projects are being executed cost- and time-effectively. This suggests that the challenges experienced by many FOAK projects are not inherent to the nuclear technology itself but rather depend on the conditions in which projects are being delivered and on the interactions among the various project participants involved.

The use of nuclear power in many OECD countries is now at a critical juncture. After a long hiatus in plant construction, the completion of several FOAK projects has contributed to restoring industrial capabilities, resulting in a window of opportunity to capitalise on accumulated experience and improve the economic performance of future nuclear projects. While also applicable to small modular reactors (SMRs) and advanced reactor concepts for deployment in the longer term, this report focuses on potential cost and risk reduction opportunities for traditional Gen-III reactor designs that could be unlocked in the short term (i.e. for projects carried out by 2030). It also assesses the policy and governance frameworks needed to promote learning and continuous improvement in industrial performance.

Recent construction cost increases are due largely to indirect costs and reflect the nonrecurring costs of deploying a new generation of reactors

In some cases, capital costs account for more than 70% of total new nuclear plant production costs (similar to hydropower projects). Furthermore, the cashflow structure of nuclear projects requires large amounts of capital to be mobilised upfront. Construction lead times and costs, together with the cost of capital, determine a plant's economic performance. Once a plant is built its operational costs are low and predictable.

1. IEA (2019), *Tracking Power 2019*, IEA, Paris, www.iea.org/reports/tracking-power-2019/nuclear-power.

A breakdown of investment costs provides insight into cost reduction potential:

- A large portion of engineering, procurement and construction (EPC) costs are indirect and have expanded significantly in the past decade. This reflects the fact that recent cost escalations result mainly from design, planning, support service and installation expenses rather than from components and materials. These indirect costs can therefore be contained and reduced with proper project governance. Furthermore, most indirect costs are also nonrecurring (i.e. for design and licensing), especially with serial construction.
- As EPC costs are dominated by labour, measures to raise labour productivity could significantly reduce investment costs.
- Depending on the project and its country-specific conditions, financing costs often make up a significant share of total investment costs. The lack of stakeholder confidence in western OECD countries therefore raises financing costs, feeding into a vicious cycle.

Eight priorities to unlock nuclear construction costs reduction

This study focuses on both the reduction of construction costs through a selected number of well-defined cost drivers and on the reduction of the cost of capital through the improved allocation of construction and market-related risks faced by new nuclear projects.

To reduce nuclear construction costs, eight drivers have been identified to unlock positive learning and continually improve large Gen-III reactor projects (Figure 1). Implementing these cost reduction drivers should also attenuate the technology, organisational and regulatory risks associated with new nuclear power plant deployment.

Lessons learnt

Historical and recent evidence suggest that lessons learnt have been well understood and can be easily implemented in future projects. In fact, several non-OECD countries delivering competitive nuclear projects today are already taking advantage of them. As a result of entering this phase of more rapid learning, upcoming nuclear projects *should* be delivered at lower cost.

First, detailed designs must be complete and ready for construction. This implies engagement with the supply chain early in the design process to integrate all requirements necessary for construction. Ideally, when adequate design maturity has been achieved, the design configuration should be frozen and systematically replicated as many times as possible, capitalising on multi-unit and series effects to build up supply chain capabilities.

The design phase should also include a robust implementation strategy with clearly defined responsibilities and competences at all levels and stages of the project. A strong, experienced project management team is essential to ensure proper project execution and to deal effectively with all interfaces and unexpected situations. Regulatory regime predictability and stability are preconditions to implement these measures.

Second, the most effective way to reduce construction costs in the near term (early 2020s) is to develop a nuclear programme that takes advantage of serial construction with multi-unit projects on the same site and/or the same reactor design on several sites.

Cost reduction opportunities in the short term (up to 2030)

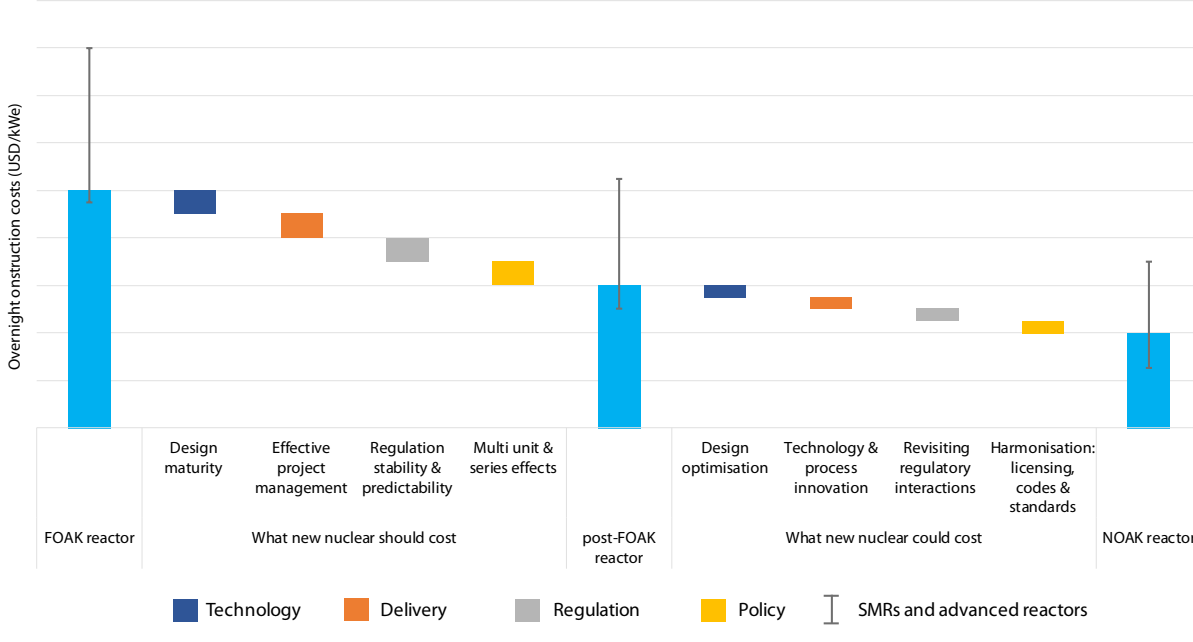
With these drivers and conditions in place, nuclear project costs could be further reduced in the short term. The interplay between plant design and delivery processes presents a range of cost reduction opportunities. These options are not necessarily sequential and can be mobilised even during the early planning stages to accelerate learning. There is evidence that countries in more advanced stages of learning are already benefitting from these opportunities and working on a continuous-improvement basis, similar to other industries. In addition, the right balance between improvement and replication needs to be found to preserve positive learning dynamics and maximise cost reduction potential. As learning develops, timely decision making is essential to optimise construction pace and limit the risk of over-engineering.

At the reactor design level, experience gained in early construction projects can lead to greater simplification, standardisation and modularisation, as well as to better integration of the latest technical advances. Organisational efficiency can also be unlocked through innovative techniques, and value-engineering (i.e. design-to-cost) can be incorporated into the design process to streamline and prioritise design optimisation according to cost targets while enabling greater supply chain involvement. Business processes and construction techniques can also benefit from digitalisation, new system engineering paradigms, and knowledge management approaches.

At the regulatory level, recent field experiences show that overall regulatory costs and risks can be reduced if regulators and licensees interact co-operatively and flexibly to ensure safety while avoiding misinterpretation.

Previous experience illustrates that the nuclear technology learning process involves a wide range of stakeholders – not just vendors and operators. As with other large-scale infrastructure that has a long-lasting impact on the economy and society, the context in which nuclear projects are delivered is of capital importance. Policymakers therefore have an active role in creating the most adequate conditions for the delivery of cost-competitive projects.

Figure 1: **Nuclear cost and risk reduction drivers**



Note: kW_e = kilowatt electrical capacity.

Additional opportunities in the longer term (beyond 2030)

There are indications that countries already in the more advanced learning stages are working towards longer-term cost reductions.

These further cost reductions can be unlocked by greater harmonisation of codes and standards and licensing regimes. Indeed, harmonisation efforts in highly regulated sectors such as aviation have already produced positive results. Without neglecting the political dimension and the need to protect the sovereignty of national regulators, international collaboration on regulatory harmonisation has demonstrated that it is possible to reach consensus in some areas. Joint actions by two or more national regulators can be highly beneficial as long as they do not lead to an accumulation of regulatory requirements based on the different approaches of the regulators involved.

SMRs are gaining recognition as potential disruptive options that could provoke a paradigm shift. Progress in concept design viability has been achieved in recent years, with the first potential sites identified and licensing milestones reached in the United States. Owing to their smaller size and modular construction, SMRs introduce a set of advances at the design and process level that could mean not only shorter construction lead times but extend nuclear power value proposition.

For SMRs to be a credible option by the early 2030s, successful prototypes must be developed in the 2020s to demonstrate the announced benefits. From a cost perspective, SMRs will follow the same learning curve as other nuclear technologies (illustrated in Figure 1), but the cost reduction factors will not carry the same weight. For instance, the series effect, simplification and standardisation will be relatively more important to balance diseconomies of scale. At the same time, several learning factors such as project management, construction advances and innovative organisational processes are not technology-specific, so SMRs should benefit from progress made with large nuclear power plants (NPPs) in the 2020s. This illustrates the complementarity of both technology families, with progress made in upcoming large Gen-III nuclear constructions supporting the future success of SMRs.

Concerted effort between government, industry and society are needed

Financial costs are central to cost reduction efforts, as they can represent more than 80% of capital expenditures. Having access to affordable financing therefore has a first-order impact on the levelised cost of nuclear power. The cost of capital is determined primarily by the risk premium expected by investors, which reflects the allocation of construction and market risks.

In countries that intend to rely on nuclear power, the cashflow structure of nuclear projects, the perceived associated risks (i.e. uncertainties founded largely on the poor recent construction record in western OECD countries) and current electricity market conditions provide a strong rationale for state commitment, regulation and, most likely, transitional financing in the early stages of the learning process. State financing can be provided in various forms: direct (i.e. equity, debt); indirect (market regulation, loan guarantees); or a combination of both. Financial support from foreign governments (e.g. through export credit agencies) could also have a positive impact.

In countries that successfully implement new-build projects, the government is highly involved in the nuclear construction programme. It absorbs the residual risks and provides the positive, long-standing policy signals and timely decision-making necessary for effective industrial planning and optimisation. The societal contributions of nuclear power have to be viewed as a social contract among policy makers, industry and society – the beneficiaries of successful project delivery.

The choice of strategy adopted may depend on various country-specific constraints and preferences. Not all countries can afford to pay for the entire nuclear learning curve and may instead prefer to take advantage of more developed supply chains. Other countries, however, would choose to restart a nuclear construction programme using in-house capabilities or just continue with long-term cost and risk optimisation. This report acknowledges all options to provide the evidence and measures necessary to make low-cost nuclear projects and long-term learning possible under various nuclear development scenarios.

Key policy recommendations

1. Capitalise on lessons learnt from recent Gen-III construction projects. With the construction of several FOAK Gen-III nuclear reactors completed, the nuclear industry and its supply chain have in large part redeveloped their capabilities in several OECD countries. By building on these reactor designs, governments have a window of opportunity to realise cost reductions in the early 2020s through timely new-build decisions. Delaying these decisions will prevent the sustainment of capabilities and therefore raise near-term project construction costs.
2. Prioritise design maturity and regulatory stability. Designing policies to support nuclear construction is critical to ensure that new-build projects start in the right conditions. Policy support mechanisms should include requirements for design maturity and, more specifically, construction readiness, and should ensure that the regulatory framework for nuclear safety remains stable and predictable throughout construction.
3. Consider committing to a standardised nuclear programme. For countries considering multiple new-build projects, commitment to a standardised nuclear programme to capitalise on the series effect, multi-unit construction and continuous design and process optimisation is the most promising avenue to effectuate cost reductions.
4. Enable and sustain supply chain development and industrial performance. Industrial and energy strategies for new nuclear plants need to be carefully articulated. For instance, investment in supply chain capabilities require assurance of long-term energy policy commitment to new nuclear construction to adopt the latest technical and organisational advances under the best conditions. New-build ambitions needs to be adjusted to integrate supply chain constraints and ensure continuous activity to enable and sustain development.
5. Foster innovation, talent development and collaboration at all levels. Governments can support cost reduction opportunities arising from innovative nuclear technologies (i.e. SMRs and Gen-IV reactors) by ensuring the timely development of demonstration projects and the licensing framework required to foster market deployment. Supporting talent development is also essential given the high level of technological expertise needed in nuclear power. National and international collaboration remains a key vector to achieve these objectives.
6. Support robust and predictable market and financing frameworks. Nuclear new-build projects require long-term government planning involving both specific commitments and market regulations. In addition, financial support is currently essential in western OECD countries – at least as a transitional measure – to deliver cost-competitive new nuclear construction.
7. Encourage concerted stakeholder efforts. Governments should create an environment that fosters a social contract with industry and society to reduce nuclear construction costs. Recent national initiatives such as the Nuclear Sector Deal in the United Kingdom provide clear evidence of how such frameworks can be developed and implemented.
8. Tailor government involvement to programme needs. The enabling role of governments will differ depending on the nature of the programme. Whereas government financial support in countries considering a fleet programme can be expected to decrease gradually as the industry reaches maturity and the perceived risk level falls, countries restarting a nuclear programme or considering only a single-plant project are likely to require further government support.

Part 1: Introduction and overview of nuclear power costs

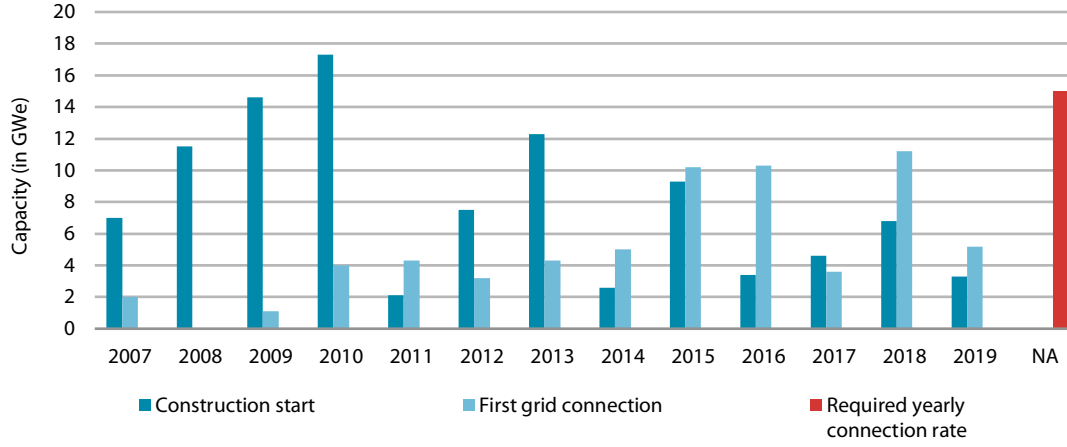
1. Introduction

1.1 The context: Time for action if nuclear is to be a part of future electricity systems

Since the Paris Agreement entered into force in November 2016, many OECD countries have been undertaking major efforts to decarbonise their economies to limit average global temperature rise to well below 2°C above the pre-industrial level. The electricity sector leads this transformation and is undergoing major restructuring. To meet the climate targets, the average carbon intensity of electricity generation in OECD countries has to be reduced from 430 grammes of carbon dioxide per kilowatt hour (gCO_2/kWh) in 2019 to less than 50 gCO_2/kWh by 2050 (NEA, 2019), requiring reductions of about 3% per year. After two years of growth, however, global emissions in 2019 were unchanged at 33 gigatonnes. Hence, global trends are far from being on track and further efforts are needed (IEA, 2020a).

According to the International Energy Agency (IEA), achieving sustainable development objectives will therefore require the mobilisation of all available low-carbon technologies, including nuclear power. In its yearly publication Tracking Clean Energy Progress, the IEA monitors the development of clean technologies to decarbonise the power sector in relation to the Sustainable Development Scenario (SDS) goals.[2] In 2018, 11.2 gigawatts of nuclear electrical capacity (GWe) were connected to the grid and construction of 6.8 GWe more was initiated. 2019 values are less encouraging, with 5.5 GWe connected to grid and little construction beginning (Figure 2). Regional trends confirmed that nuclear development is concentrated essentially in the Russian Federation and the People's Republic of China. According to 2019 values, nuclear power is not on track with SDS development targets (Figure 4).

Figure 2: **Nuclear power construction starts and first grid connections, 2007-2019**



Source: IEA, 2020b.

2. Under the SDS, temperature rise remains below 1.8°C with a 66% probability, without reliance on global net-negative CO_2 emissions; this is equivalent to limiting temperature rise to 1.65°C with a 50% probability. Under the SDS, global CO_2 emissions fall from 33 gigatonnes in 2018 to less than 10 gigatonnes by 2050 and are on track to net-zero emissions by 2070 (IEA, 2019).

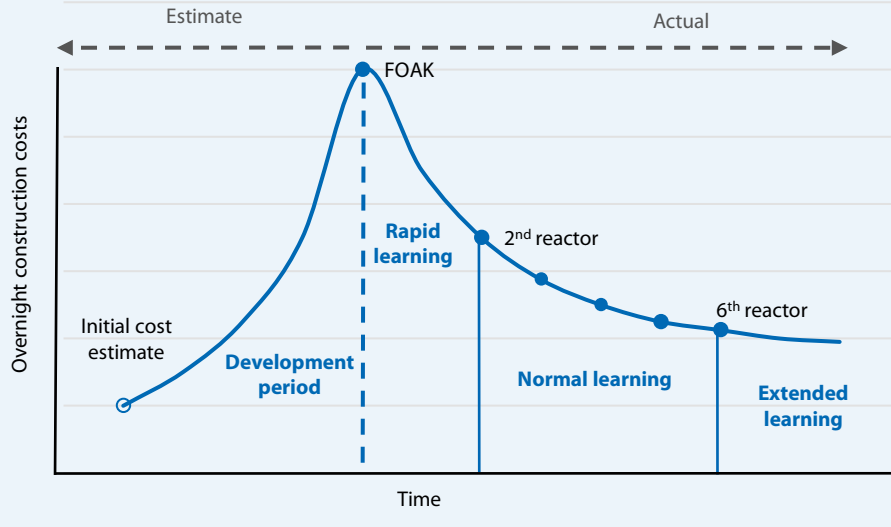
Assuming 60-year operation of most of the existing fleet, around 15 GWe of new nuclear is needed every year to keep pace with the SDS – at least double the current annual rate of capacity additions between 2020 and 2040. Such development is technically feasible, as proven during the first nuclear deployment era in the 1980s with yearly capacity additions of about 30 GWe (NEA/IEA, 2015).

The low level of new nuclear development results largely from the difficulties encountered with recent first-of-a-kind (FOAK) Gen-III projects, particularly in western OECD countries. These projects have had significant delays and cost overruns, exacerbated by initial estimates heavily influenced by low levels of design and execution planning maturity (Box 1) – as well as the increasingly uncertain political context – when construction began.

Box 1: **How project maturity affects cost estimates**

When evaluating the performance of a project by comparing actual costs and lead times with early estimates, a key factor to consider is the project's planning and design maturity. In fact, initial estimates and announced budgets tend to be calculated in a simplified way based on incomplete data that may not fully capture the complexity of large infrastructure projects, especially for projects in the early stages of development. The political context in which a project is launched also has a strong impact on the announced budget. As projects advance and more detailed data from suppliers and designers become available, cost estimates tend to increase to reflect greater technical detail and maturation. Finalisation of an initial project and execution of subsequent ones following a standardised design inaugurates a period of rapid learning (Figure 3).

Figure 3: **Nuclear new-build learning curve**

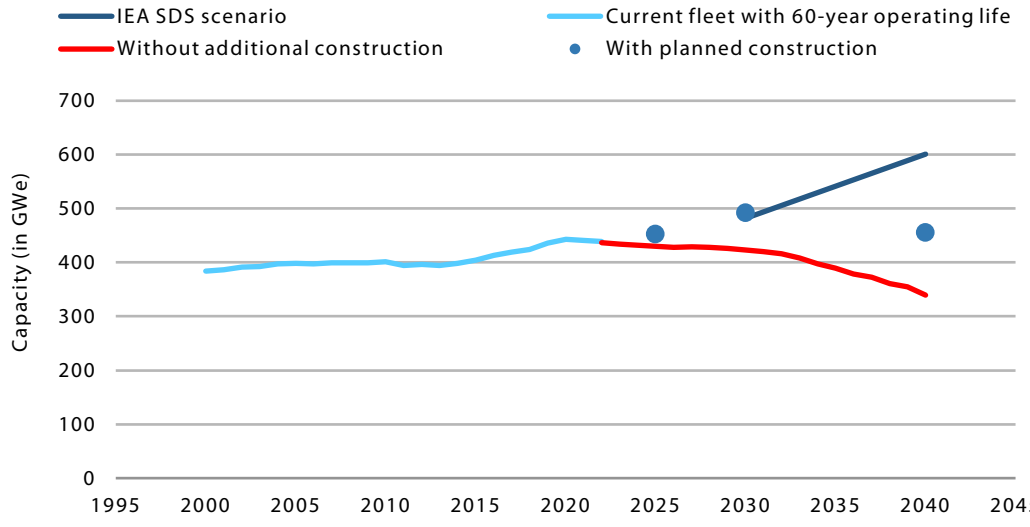


Source: Adapted from Yemm et al. (2012), "Pelamis: Experience from concept to connection."

The cost escalations and delays of recent nuclear construction projects are to a large extent the result of poor estimates due to the lack of design maturity in uncertain political contexts. With some projects nearing completion in western OECD countries, new estimates should be more accurate and cost reductions achievable for future projects.

These stages of learning apply not only to nuclear. For instance, Yemm et al. (2012) have shown that a similar learning pattern is apparent in the wind industry, with offshore wind power currently in a "rapid learning" phase and onshore wind power in "normal learning."

Figure 4: **Global nuclear capacity by scenario, 2010-2040**



Source: IEA, 2020b

Some of these recent projects are presented in Table 1. Differences between initial announced budgets and ex-post construction costs reflect the cost escalations that have affected these projects, but the gap should be analysed cautiously as the initial announced budgets are the result of very specific conditions in line with Box 1. Figure 6 illustrates a similar trend in projected overnight construction costs for OECD countries, showing a significant increase between 2010 and 2015. The same applies to construction delays, with schedules of typically five to six years announced, but actual construction times of around ten years. In fact, some of these projects are still under development and may be operational more than 15 years after their construction start.

Table 1: **Construction costs of recent FOAK Gen-III/III+I projects**

Type	Country	Unit	Construction start	Initial announced construction time	Ex-post construction time	Power (MW_e)	Initial announced budget (USD/kW_e)	Ex-post construction cost (USD/kW_e)
AP 1000	China	Sanmen 1, 2	2009	5	9	2 x 1 000	2 044	3 154
	United States	Vogtle 3, 4	2013	4	8/9*	2 x 1 117	4 300	8 600
APR 1400	Korea	Shin Kori 3, 4	2012	5	8/10	2 x 1 340	1 828	2 410
EPR	Finland	Olkiluoto 3	2005	5	16*	1 x 1 630	2 020	>5 723
	France	Flamanville 3	2007	5	15*	1 x 1 600	1 886	8 620
	China	Taishan 1, 2	2009	4.5	9	2 x 1 660	1 960	3 222
VVER 1200	Russia	Novovoronezh II-1 & 2	2008	4	8/10	2 x 1 114	2 244	**

* Estimate. ** No data available.

Notes: MW_e = megawatt electrical capacity. kW_e = kilowatt electrical capacity.

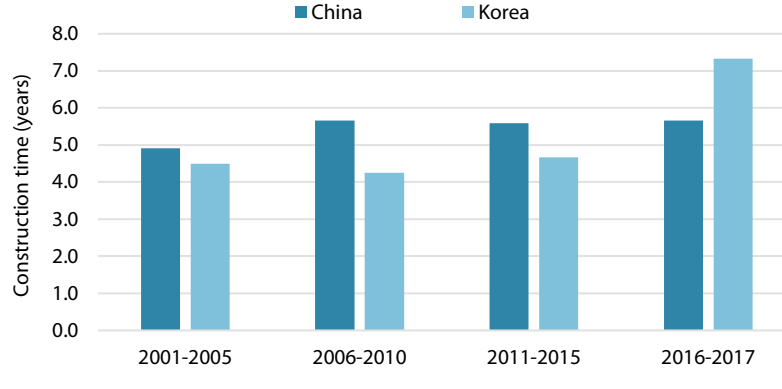
Source: NEA analysis based on publicly available information.

As a result, stakeholder and public confidence in the capability of the nuclear industry to deliver new build projects has been eroded. This situation has also raised the level of perceived investment risk, intimidating investors and further reducing the chances of attracting financing for future projects. In addition to cost and time escalations, nuclear projects are subject to risk premiums because it is difficult to deliver confidence on the final cost and scheduling of future nuclear projects. For instance, Portugal-Pereira et al. (2018) suggest that the standard deviation[3] of historical construction lead times[4] increased from 1.3 years in the 1960s to 7.5 years between 2011 and 2016, as did the number of maximum outliers. That is why this study repeatedly emphasises that improving the economic performance of nuclear power requires a holistic approach that includes both cost reductions and risk allocation and mitigation measures.

At the same time, the economic competitiveness of nuclear power in some OECD countries is also challenged on a levelised cost of electricity (LCOE) basis by adverse market conditions. The combination of low gas prices (especially in the United States) and the introduction of variable renewable energy (VRE) with specific support schemes are driving wholesale electricity prices down. Furthermore, there is growing recognition among energy policy experts that, due to the inherent intermittency of VRE and the absence of large-scale electricity storage solutions, high shares of VRE tend to raise electricity price volatility as well as overall system costs (NEA, 2019). In this context (bearing in mind country-specific conditions), using dispatchable low-carbon technologies such as nuclear power could increase the overall affordability and reliability of the electricity system. Current market designs fail to provide long-term price signals to properly value dispatchable generation attributes. Countries that support the construction of new nuclear power plants are considering the utilisation of specific support mechanisms – e.g. contracts for difference (CfDs) and power purchase agreements (PPAs) – similar to the schemes developed to promote VRE.

In other parts of the world, nuclear power is delivered essentially on time and on budget. In China and Korea, a significant number of projects have been executed in less than six years over the last decade (Figure 5). It could be argued that this better performance is the result of alternative design features (in terms of constructability, for example), but even for a same design there are notable country differences. This performance gap cannot be explained solely by site-specific conditions that induce slight design modifications. Thus, challenges to delivering new nuclear capacity in western OECD countries are not inherent to the technology itself but rather depend on the conditions under which the projects are developed and executed, and on the interactions among the various stakeholders involved.

Figure 5: **Median construction times for new nuclear in China and Korea**

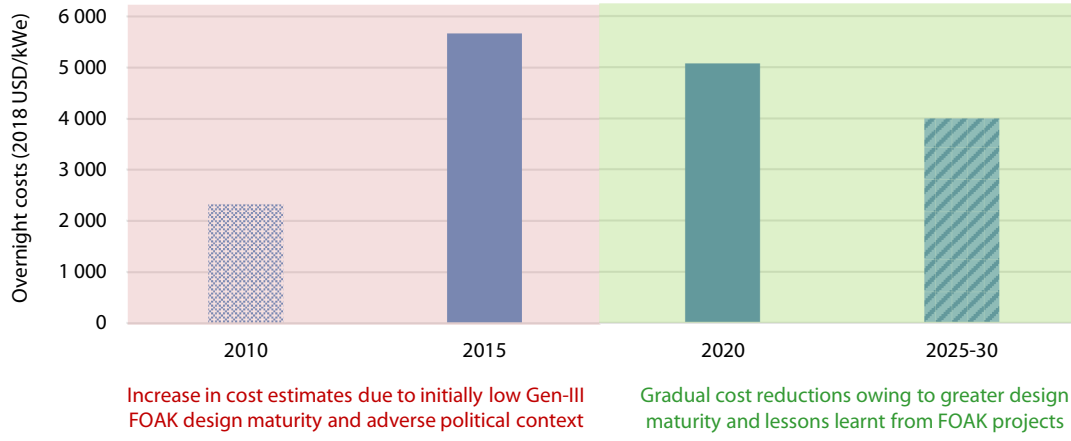


Source: IAEA (2019), Nuclear Power Reactors in the World.

3. Standard deviation can be used as a measure of risk because it reflects the volatility of a given parameter.
4. Portugal-Pereira et al. (2018) define lead time as the time difference between construction start (the beginning of licensing procedures) and commercial operations (when the reactor is connected to the grid after the initial test phase).

With several FOAK projects near completion, nuclear power in western OECD countries is now at a critical juncture. These projects were realised after a long hiatus in nuclear construction that had significantly eroded the nuclear supply chain and the industry's capabilities, reinforced by a deindustrialisation trend in some OECD regions (Western Europe and North America). The sums invested in these FOAK projects financed not only the construction of the reactors themselves, but rebuilt industry capabilities. If the nuclear industry takes advantage of the accumulated experience and lessons learnt from these recent projects, the costs estimates gathered during the course of this study indicate that nuclear plant construction can now enter a more rapid learning phase, allowing it to deliver future projects at lower cost (see Figure 6). These trends are also in line with the cost model illustrated in Figure 3.

Figure 6: **Projected new nuclear cost trends in OECD countries**



Notes: 2010, 2015 and 2020 OECD average overnight construction cost data based on 2005, 2010 and 2015 NEA/IEA projected cost reports, adjusted for USD inflation using OECD statistics.

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

These conditions have opened a window of opportunity to improve the economic performance of large Gen-III reactors in the short term (i.e. before 2030). The purpose of this study is therefore to serve as a practical guide for stakeholders to make cost reductions a reality. It not only details potential cost and risk reduction options, but assesses the policy and governance frameworks necessary to promote learning and continuous industrial performance improvement. Some analysis also addresses small modular reactors (SMRs) and advanced reactor concepts, as these technologies will surely rely on the same cost reduction drivers to reach commercial viability.

1.2 Structure of the report

This study is divided into three main parts (see Figure 7):

1. Introduction and overview of nuclear power costs (i.e. why and what).
2. Nuclear construction cost reduction drivers (i.e. how).
3. Policy frameworks to deliver competitive nuclear developments (i.e. who).

Part 1 contains an overview of the main trends in new nuclear development, highlighting the challenges as well as opportunities available for decision makers (aspects already covered in this chapter). Before assessing nuclear learning in more detail, Chapter 2 provides some notions and definitions of nuclear costs and their impact on the economic performance of this

technology. Several investment cost breakdowns offer further insight into the nature of these costs and potential areas for cost reductions.

In Part 2, several cost and risk reduction strategies that can enable learning in nuclear power are analysed in depth in different stages according to their implementation timeline. Activation of these measures should also help attenuate the technological, organisational and regulatory risks associated with the deployment of new nuclear capacity.

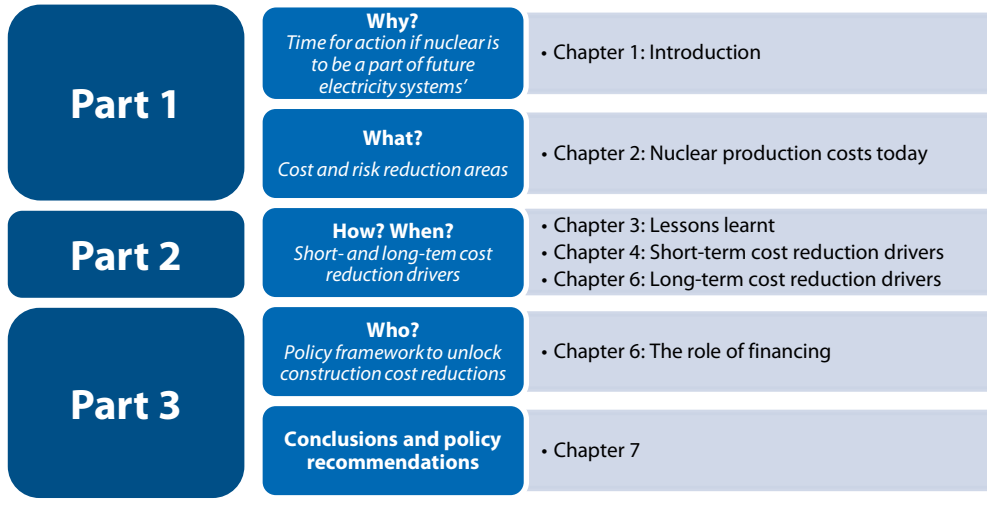
Chapter 3 assesses historical and recent construction projects to identify common core cost reduction drivers. Supported by robust evidence, these lessons learnt are the backbone of the nuclear learning curve. Chapter 4 explores additional cost-reducing measures to accelerate the learning process available in the short term (before 2030) for post-FOAK projects and complementary to those described in Chapter 3.

In the longer term (beyond 2030), more cost reduction opportunities may be possible thanks to the harmonisation of codes and standards and licensing regimes. Several countries in more advanced stages of nuclear learning are already moving in this direction. At the same time, more innovative concepts such as SMRs and Gen-IV reactors have made advances towards design viability. These concepts are expected to benefit from the same learning process described in Part 2. By design, they may take further advantage of specific cost-cutting strategies (i.e. the series effect, simplification, modularisation, etc.) to improve the economic performance of new nuclear installations. These possibilities are explored in Chapter 5.

Part 3 presents the policy frameworks necessary to mobilise cost and risk reduction drivers. The success of these measures will depend upon government commitment, market regulation and most likely transitional financing support during the early stages of the learning process. The impact of financing on the cost-competitiveness of nuclear power is analysed in detail in Chapter 6. After reviewing the rationale for government involvement to enable nuclear energy expansion, this chapter explains the forms state financing can take as a part of a systematic risk allocation and mitigation strategy in which all stakeholders, including society, have a key role.

Finally, Chapter 7 presents the conclusions and main policy recommendations elaborated from the findings of this report.

Figure 7: **Report structure**



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2. Nuclear production costs today

2.1 The impact of investment cost and risks on the economic performance of nuclear power

As highlighted in Chapter 1, nuclear energy is an essential part of future low-carbon energy systems. According to the International Energy Agency (IEA), however, its deployment rate is not on track largely due to the costs and risks associated with new nuclear construction projects. This chapter provides the concepts and insights necessary to understand the main cost drivers and identify potential key cost reduction areas.

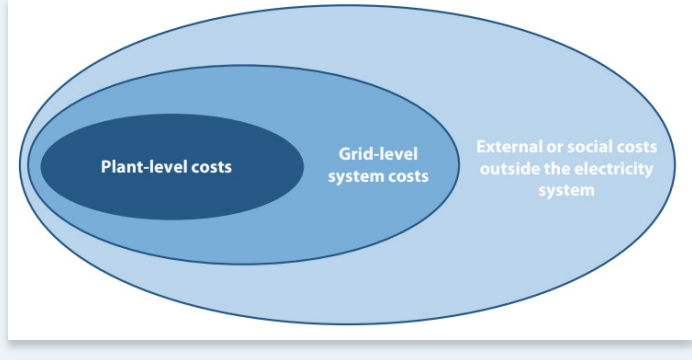
The cost of the electricity provision can be divided into several categories (Box 2), but reducing plant-level costs is the sole object of this report. Any cost reductions in this area will have a direct positive effect on the full cost of electricity provision.

Box 2: **The full cost of electricity provision**

Electricity provision costs fall into three different categories. The first category is plant-level costs, the reduction of which for the case of nuclear technology is the focus of this study (Figure 8).

The second category concerns electricity system costs, involving the transmission and distribution grid. It includes the costs that plants impose on the system to extend, reinforce and connect to the grid, as well as costs to maintain spinning reserves or additional dispatchable capacity when the output of some technologies (typically wind and solar photovoltaic) is uncertain or variable. The Nuclear Energy Agency (NEA, 2019) has formulated a comprehensive exercise to quantify the extent of system costs with high shares of nuclear and renewable resources.

Figure 8: **Electricity provision cost categories**



Source: NEA (2018), *The Full Costs of Electricity Provision*.

The third cost category quantifies the impact of a generation technology on individual and community wellbeing. This category covers a multitude of social and environmental costs (and benefits), among them impacts on local and regional air, water and soil pollution, climate change, the consequences of major accidents, land use and resource depletion. These costs also include the effects of different power technology choices on security of supply, employment and regional cohesion, and on innovation and economic development.

Box 2: **The full cost of electricity provision** *(cont'd)*

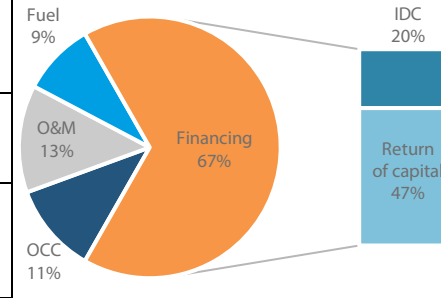
The full cost of energy provision is thus the sum total of all three categories.

It is important to point out that, in the absence of regulatory intervention, grid-level system costs and external costs are borne by society as a whole and not by the party that incurred them. A number of policy measures can internalise external costs, including standards and technical regulations, pollution taxes and new markets such as for emissions trading, as well as better information dissemination and research. Closing the knowledge gap is also part of transitioning to sustainable electricity systems; NEA (2018) covers all these aspects in more detail.

As with any other electricity generation technology, nuclear plant-level costs[5] represent all the expenses required to finance, build, operate and decommission a plant. The "build" dimension corresponds to *overnight construction costs*, and all the costs of operating the plant fall into *operations and maintenance costs*. Cost related to financing, contingencies and decommissioning are to be added to compute the levelised cost of electricity (LCOE)[6] (see Table 2).

Table 2: **Cost breakdown for nuclear power levelised cost of electricity**

Levelised cost of electricity (LCOE) of nuclear power	**Levelised capital costs**	**Capitalised investment costs**	**Overnight construction costs (OCC)**: includes the materials, components, manpower and cost of capital required to design, construct and commission the plant.
			Capitalised financial costs (CFC): includes interest during construction (IDC) and related fees.
		Return of capital: the cost of capital, which is a combination of the cost of debt (i.e. loan) and required return on equity (from the shareholders). IDC can also be added to this cost category to isolate the overall **financing costs**.	
	Operation and maintenance costs		**Operations and maintenance (O&M) costs**: all costs related to staffing, consumables and recurring maintenance activities necessary for safe operations once the plant has been built and commissioned.
			Fuel cycle cost: cost of the fuel used to produce electricity. In the case of nuclear power, includes costs related to mining, enrichment and the manufacture of fuel assemblies to be loaded in the core (i.e. front-end activities), as well as to managing the used nuclear fuel and waste (i.e. back-end activities).
	Decommissioning costs: Costs associated with dismantling the plant once it has reached the end of its lifetime and returning the site to greenfield state.		



Note: Calculations based on OCC of USD 4 500 per kilowatt of electrical capacity (/kW$_e$), a load factor of 85%, 60-year lifetime and 7-year construction time at a real discount rate of 9%.

5. In this report, this term is used indistinctly alongside other terms such as "generation cost" or "production cost", which refer to the same concept.
6. LCOE cost breakdown does not include taxes.

Every five years, the NEA and IEA jointly publish plant-level costs in Organisation for Economic Co-operation and Development (OECD) countries for all generating technologies in the *Projected Costs of Generating Electricity* series (IEA/NEA, 2010 and 2015).[7] To introduce the costs and basic economics of nuclear power, a comparison with combined-cycle gas turbine (CCGT) plants is proposed to highlight the contrasting economic patterns of these technologies.

The cost of new nuclear is essentially dominated by capital costs, which make up 72% of total production costs (see Figure 9). In addition, they are mostly fixed[8] and can, to a large extent, be considered a "sunk" cost.[9] O&M costs represent 16% of total generation costs, and they can also be considered fixed except for a small portion allotted to staff changes, materials and training needs. Fuel cycle costs make up 12%, and these expenses vary depending on the amount of electricity generated. The remaining 0.1% corresponds to decommissioning costs. This activity has very little effect on overall production costs given the long lifetimes (typically 60 years) of recent nuclear designs.

Figure 9 also illustrates that, under the same assumptions, most nuclear costs are fixed (up to 87%). Distinguishing between fixed and variable costs is particularly useful to indicate how much a technology is exposed to electricity market risks. Assets with high shares of fixed costs, such as nuclear power plants, have higher inertia, which impedes their capacity to react quickly to electricity price shifts and makes them more sensitive to market downturns.[10]

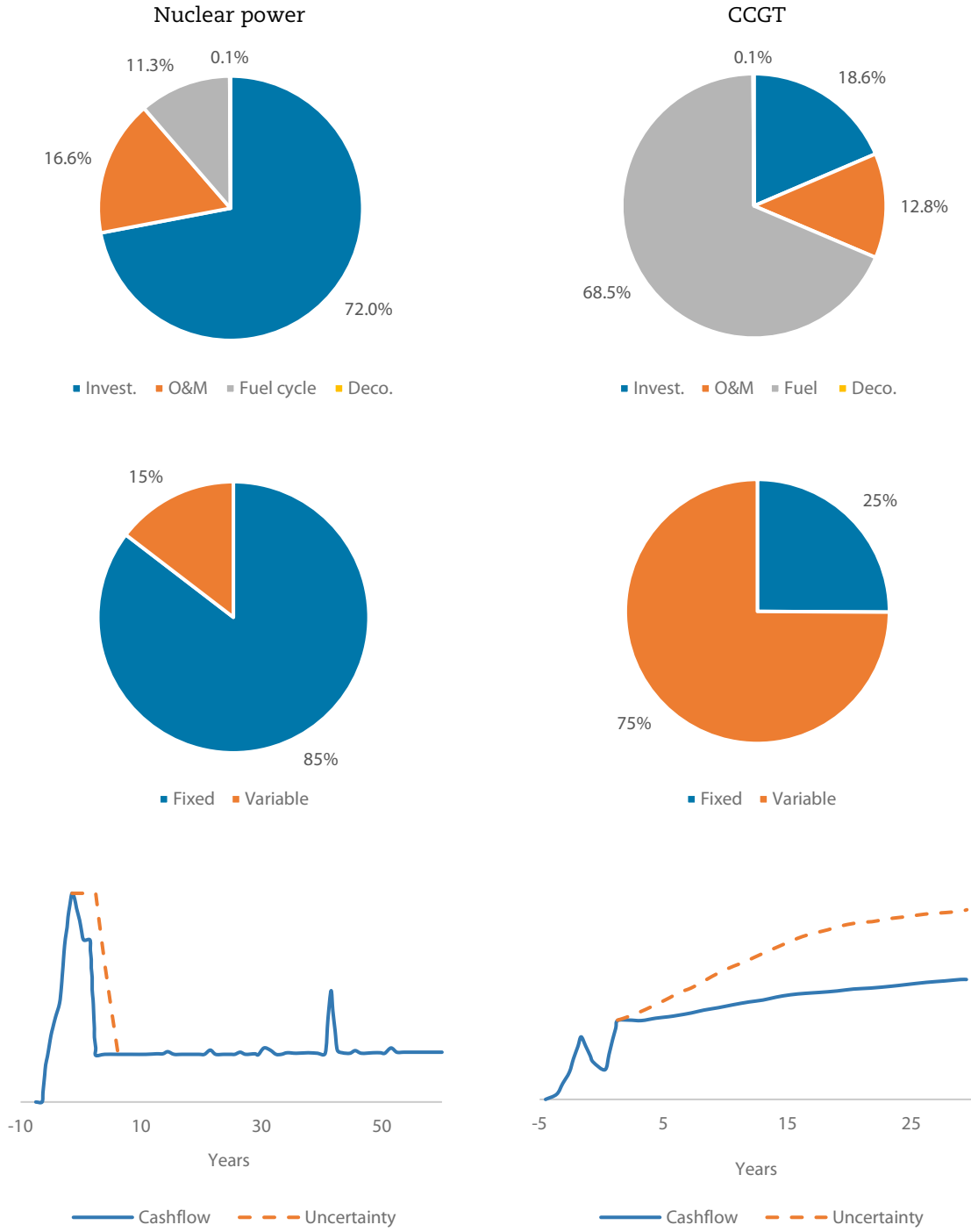
For instance, when wholesale electricity prices are low, both nuclear and CCGT face revenue losses. The difference is that even if nuclear power plants stop operating, they still have to recover a large portion of their fixed costs, whereas CCGT plants may choose to stop operating to avoid further losses, as most of their costs (>70%) are variable fuel costs.

Among other considerations, investors also take into account the *time value of money*, or the preference to receive a certain amount of money today rather than in the future, depending on the potential for that money's value to increase over a given period. At the same time, the potential risk of investment decisions must be remunerated. Therefore, when capital is being raised for a particular project, an interest rate is established according to whether financers judge the investment worth the risk compared with the expected return. This interest rate accounts for the cost of capital of a project, which is part of the capital costs (see Box 3).

What makes nuclear projects particularly sensitive to risk, as represented in the cashflow structures in Figure 9, are the high fixed upfront investment costs during the early development and construction phases, combined with long delivery times that tend to delay the first revenues, which are particularly important in deregulated electricity markets. Uncertainties that lead to higher-than-expected investment costs and delivery times (the trend for most recent nuclear projects western OECD countries) are perceived negatively by investors, who will ask for higher investment returns, thereby increasing the cost of capital. Nuclear generation costs will rise as a result, reducing the chances of attracting funding (see Figure 10). Nevertheless, once the plant is in operation, costs remain low and predictable for a long period of time.

7. Preliminary data from the 2020 edition of this publication, currently under development, has been used to compute most of the cost figures presented in this chapter.
8. Incurred independently of the amount of electricity produced.
9. Not all investments in fixed capacity are irreversible investments in the sense of being "sunk" costs. This depends on the possibility to transfer, at a reasonable cost, the initial investment from one market to another. However, investments in electricity generation capacity can be considered irreversible due to difficulties in physically moving the plants; electricity market competition based on marginal (and thus variable) costs; and limitations associated with interconnections (NEA, 2015).
10. This is in fact the case for all low-carbon investments (wind, solar power, nuclear, etc.).

Figure 9: **Generation costs and cashflow structures of nuclear power and CCGT plants, 2020**

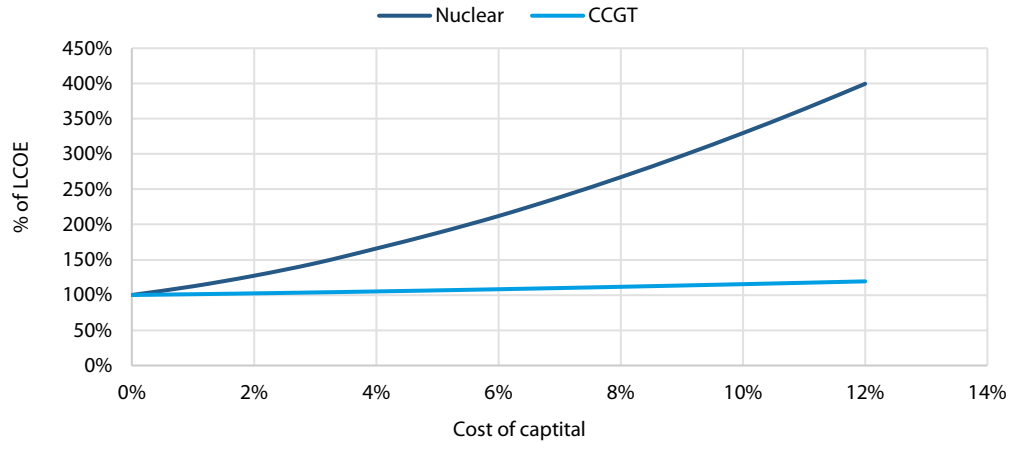


Notes:. Average cost share per megawatt hour (MWh) in OECD countries; real discount rate of 7%.

Sources: NEA (2015), *Nuclear New Build: Insights into Financing and Project Management,* (IEA/NEA, Forthcoming), *Projected Costs of Generating Electricity* 2020.

Conversely, CCGT plants have low and predictable investments costs but relatively high variable production costs due to considerable fuel-related expenditures. Uncertainties are essentially concentrated in the operations phase, as gas and CO_2 prices are subject to a certain amount of volatility. This cashflow structure may, however, create a more attractive risk profile for investors, as it anticipates a more rapid first revenue generation with a more affordable initial investment. In addition, as most budgeted expenses materialise in the long term, it is possible to exit the market with a smaller economic penalty. As illustrated in Figure 10, CCGT production costs are hardly impacted by the cost of capital.

Figure 10: **Generation costs as a function of the cost of capital, nuclear power vs. CCGT**



Nuclear production costs are therefore especially exposed to the cost of capital. Construction costs and delays are also key parameters, and the consequences of nuclear project delays are twofold:

- Impact on financing: The longer the construction period, the higher the interests accumulated and the greater the capital required. These additional costs increase the overall financial burden, raising perceived risk for investors. If new delays appear, investors may request even higher returns, triggering a snowball effect. Furthermore, construction delays also postpone revenue generation.
- Impact on construction costs: Most nuclear power plant construction activities take place on-site, requiring considerable manpower and heavy equipment that is, by nature, fixed (e.g. cranes) and cannot be quickly adapted to changes in the project environment. Consequently, lower productivity due to less-efficient use of personnel and idle equipment during delays raises overall construction costs (Locatelli, Bingham and Mancini, 2014).

These impacts may shift a nuclear project's break-even point[11] significantly. For instance, for a three-year delay, the break-even point is reached around ten years later, further reducing the attractiveness of nuclear investments (SFEN, 2018). On-time completion is therefore an effective lever to limit nuclear new-build cost and risk escalation.

Because capital costs figure so largely in the final generation costs of new nuclear, the next chapters of this report explain different ways of reducing capital costs to make nuclear technology more competitive (reducing O&M costs, which have a more limited impact, are

11. The production level at which total product revenues equal total expenses. When this point is achieved depends on the cost and revenue cashflow structure.

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

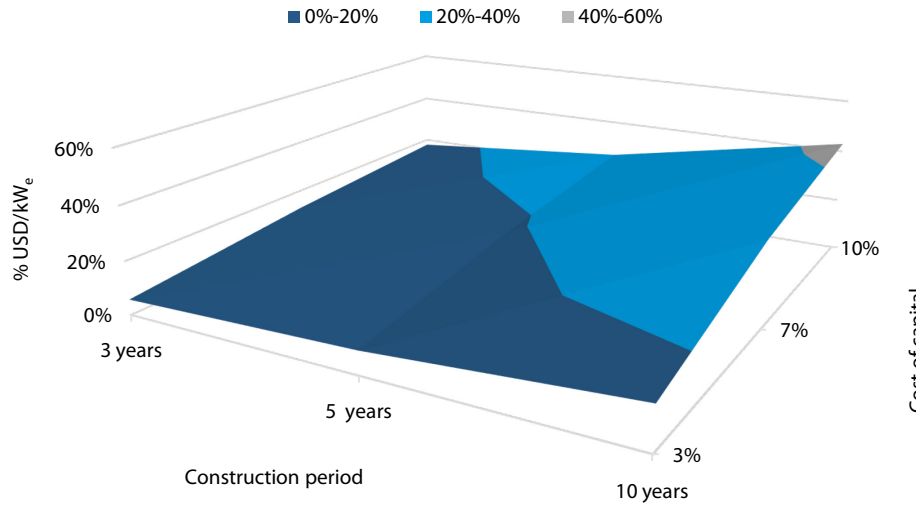
As indicated above, the investment costs of a nuclear power plant comprise all the elements required for its design, construction and commissioning. This covers expenditures for materials, components and equipment and their installation, as well as personnel wages and the cost of the capital involved – 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).

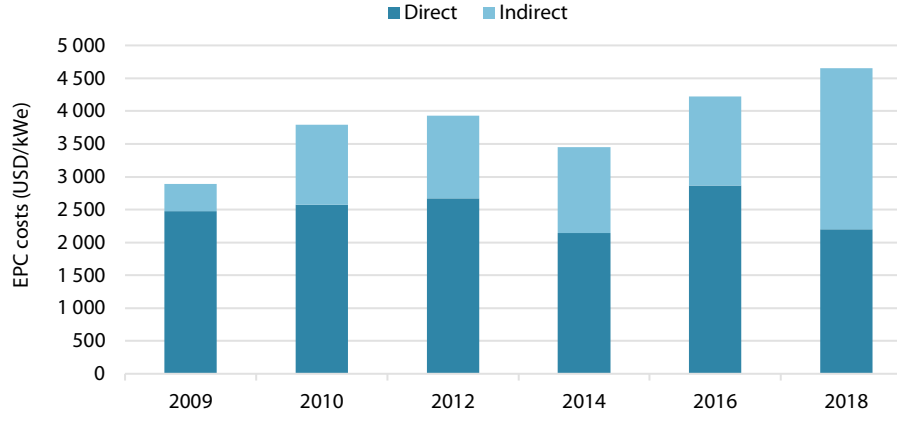
Table 3: **Generic EPC cost breakdown**

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).

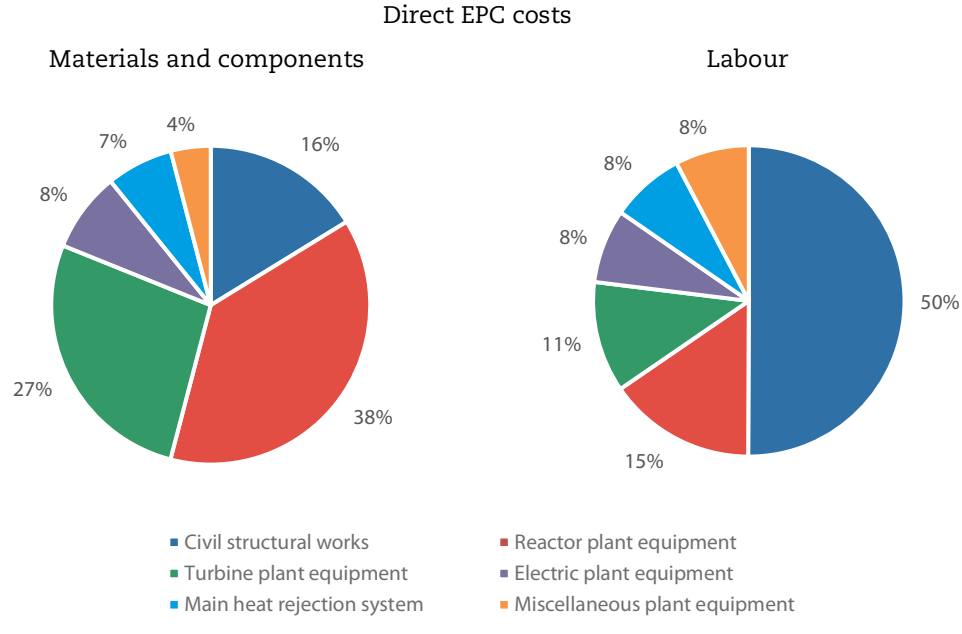
These results show that indirect costs should not be neglected. According to more recent estimates, they may account for an even greater share of total EPC costs than direct expenses do (approximately 53%, compared with 47% for direct costs) (ETI, 2018). This suggests that cost issues associated with 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).

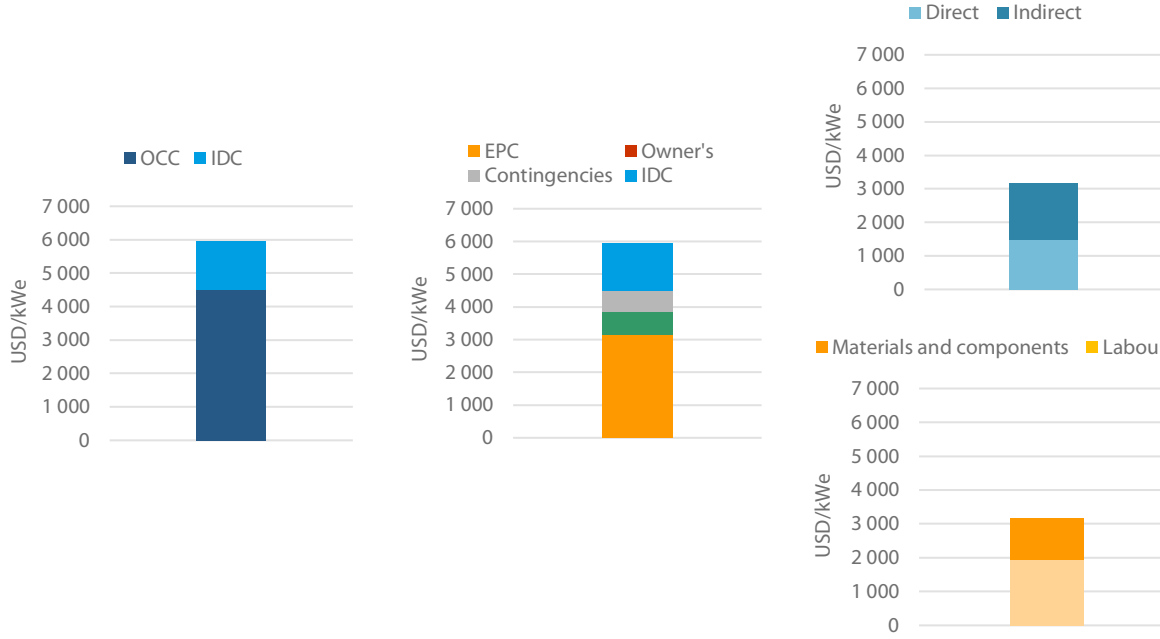
When assessing the impact of labour on nuclear investments, it is necessary to distinguish between salary and productivity. A recent Massachusetts Institute of Technology (MIT) study concluded that "while differences in labour rates play an important role[14] they do not account for all the variations 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)*

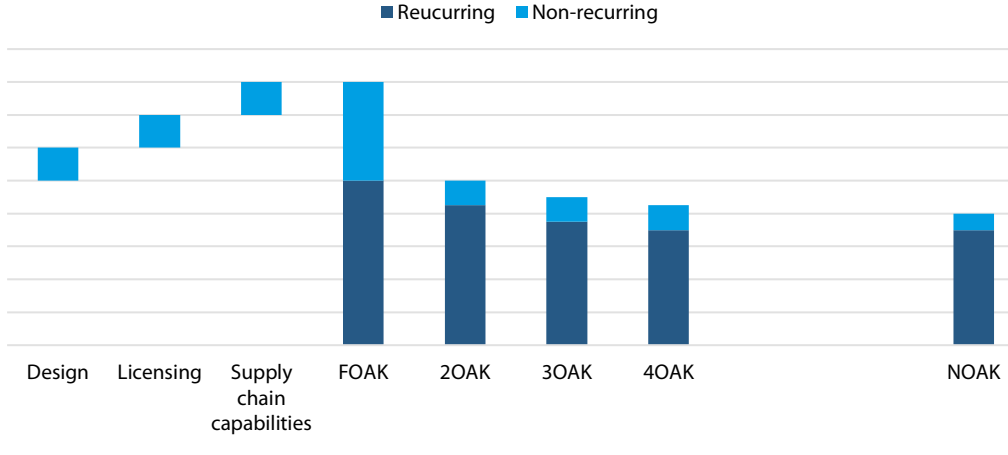
Although the different cost breakdowns presented in the previous section are useful to determine the categories that contribute the most to final nuclear investment costs, they fail to capture the positive effects of the learning-by-doing process that can be expected with the construction of several 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

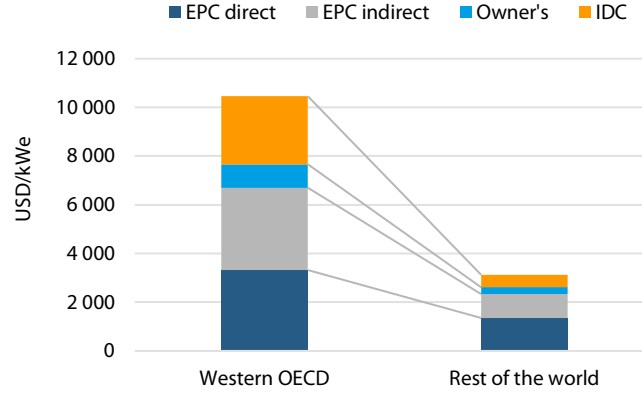
This chapter's analysis permits several areas for nuclear investment cost reductions to be identified:

- 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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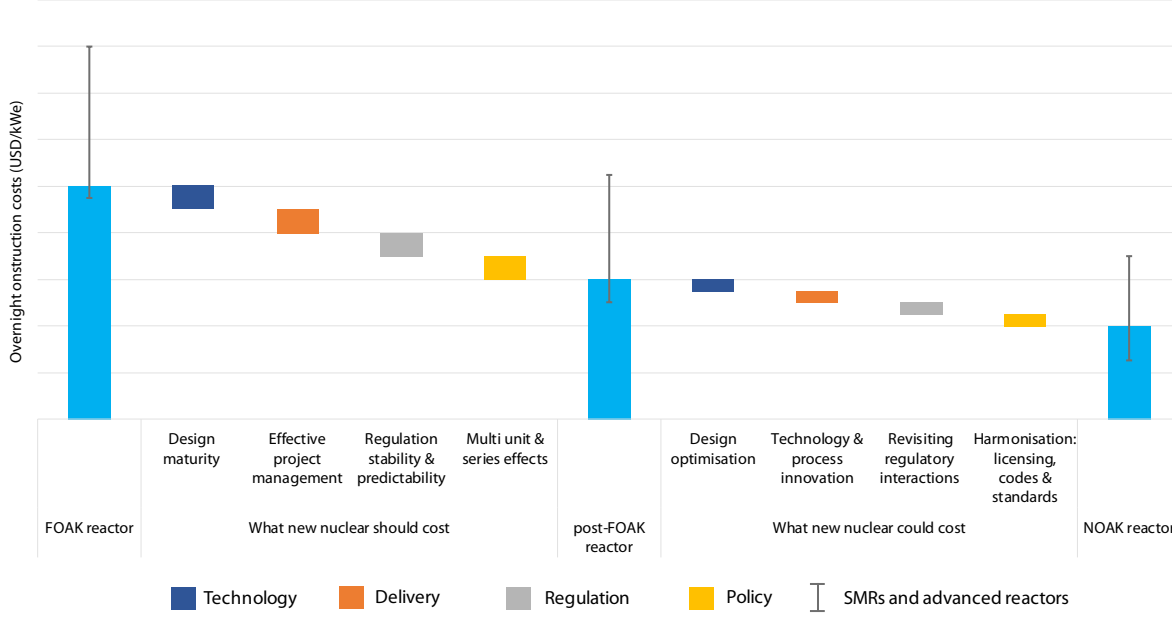
Part 2: **Nuclear construction cost reduction drivers**

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.

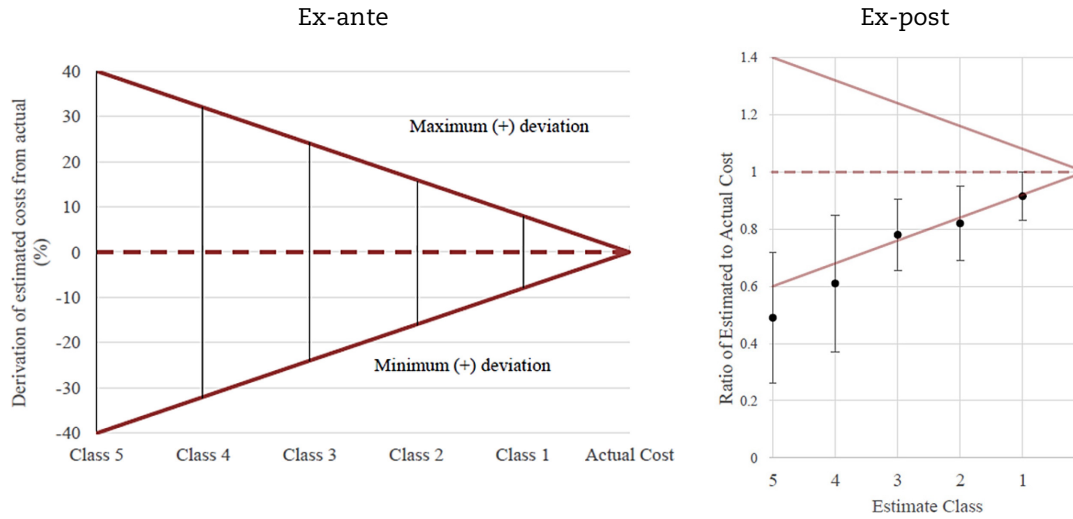
Several complementary factors help explain this trend:

- 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**

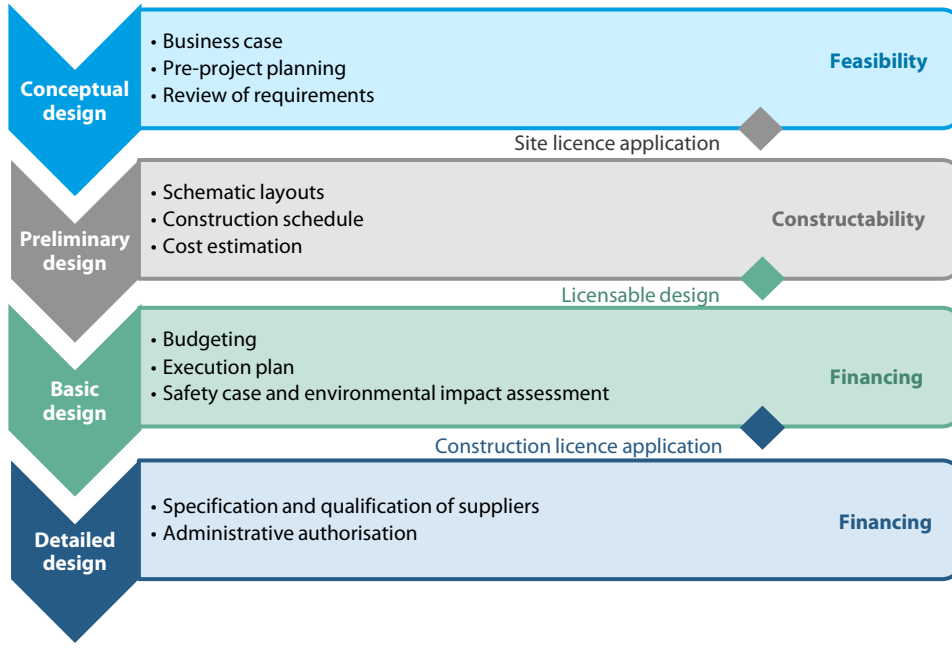


Source: Merrow, Phillips and Meyers (1981), *Understanding Cost Growth and Performance Shortfalls in Pioneer Process Plants.*

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).

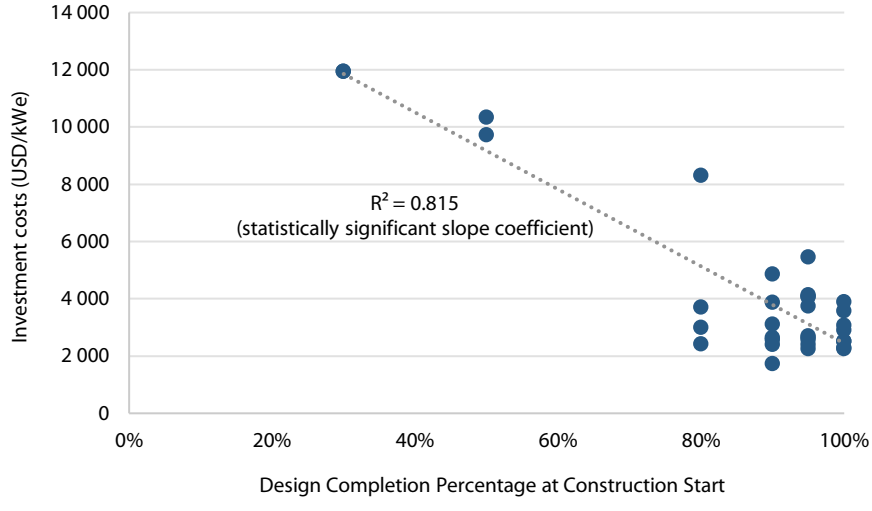
Figure 19: **Typical scope of design activities**



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

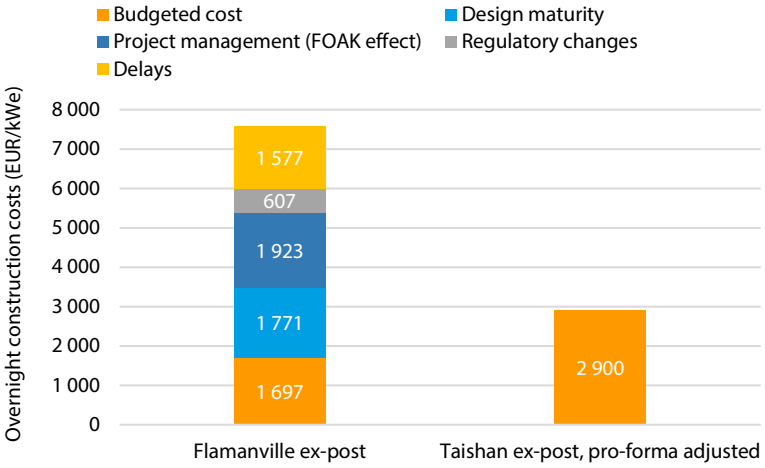
The EPR reactor was initially developed in the early 1990s as part of a French-German consortium led by Framatome (later Areva) and Siemens. In 1992, the beginning of the conceptual design phase aimed to combine technological features from the French N4 reactor and the German Konvoi reactor, with a core 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.

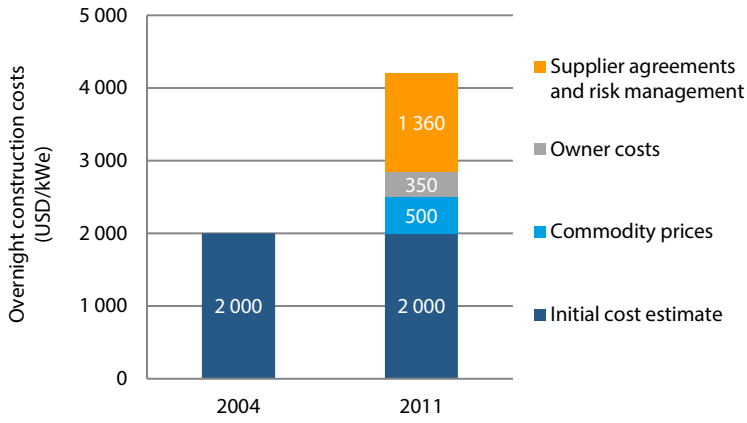
21. www.enr.com/articles/43325-witness-to-the-origens-of-a-huge-nuclear-construction-flop.html.

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.

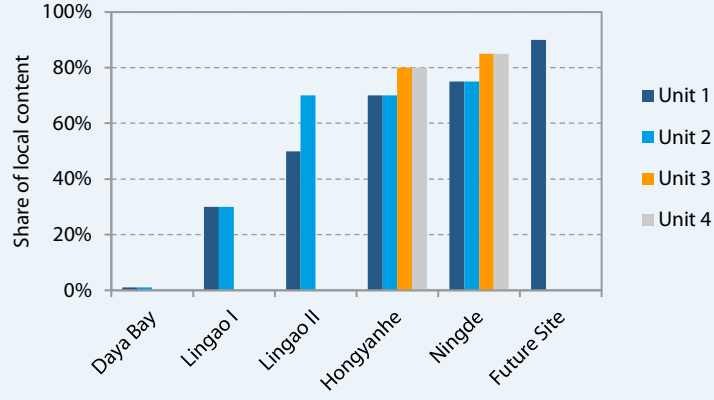
Box 8: **The opportunities and challenges of localisation strategies: Insights from the Akkuyu project**

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.

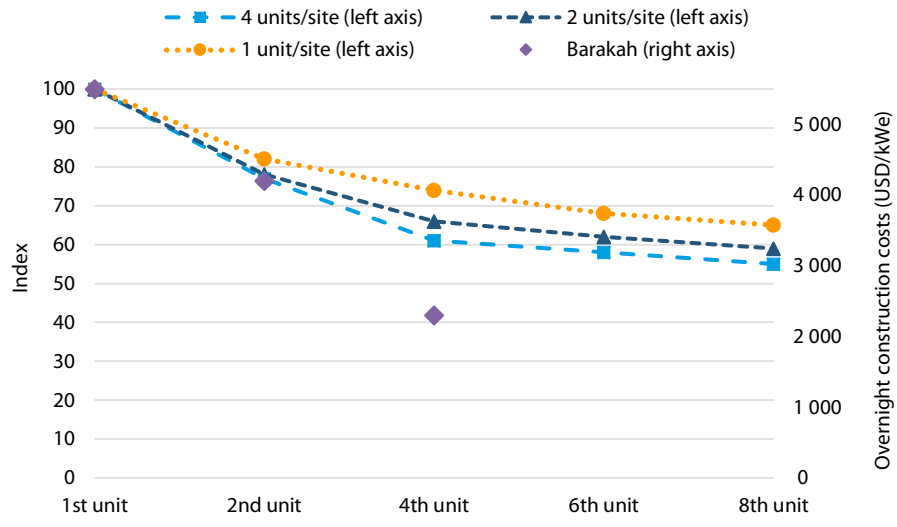
In addition, a twin project facilitates more efficient allocation of resources that can be optimised between the two units, reducing the risks and impacts of delays. For instance, in the case of delays on one unit, teams can be reallocated to the other. Similarly, considering that there will be a lag 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.

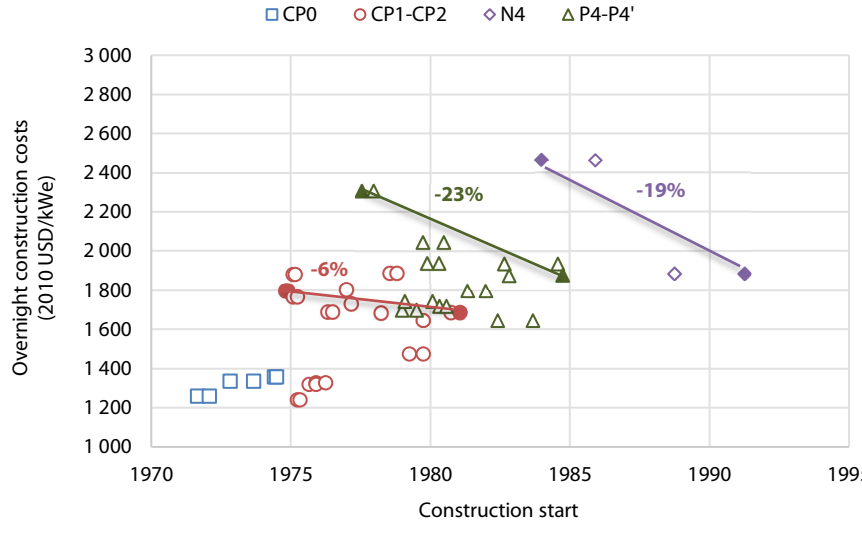
The impact of series construction of standardised reactors on OCC is quite substantial, with cost savings of 15-20% (NEA, 2000). The impact on time-related costs (IDC) is also significant (costs could decrease by more than 60%) because the construction period is substantially shorter. When time-related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

Empirical evidence indicates that more than six units need to be built to take full advantage of a standardised series effect. Korean nuclear programme experience shows that the construction lead time of 75 months for the first twin units can fall to 53 months for the second pair. France's 900-MW_e series deployment demonstrates similar findings, with the last units being delivered in less than 60 months.

- France's historical nuclear programme: Benefits of series construction

The French National Audit Office's report provides a sound statistical baseline for the construction costs of France's current fleet, expressed in nominal and real terms (using a gross domestic product deflator). The data show that the strategy of standardisation for the French fleet with a vertically integrated industrial organisation (with the operator, EDF, having architect-engineer responsibility) allowed EDF to realise significant cost reductions between the first and last pair of each reactor series (Figure 25).

Figure 25: **French nuclear programme construction costs, 2012**



Source: NEA based on data from Cour des Comptes (2012).

- The UK Sizewell B and C projects: Benefits of shifting from a single- to multi-unit project

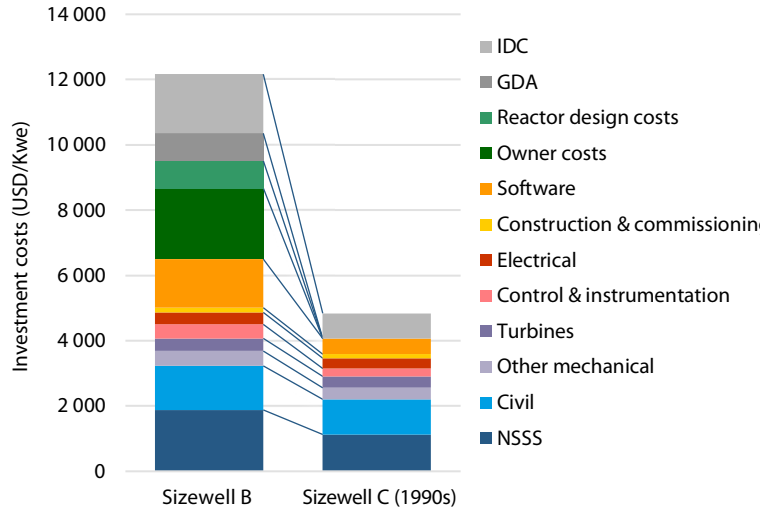
Sizewell B was the first pressurised water reactor (PWR) to be built in the United Kingdom, and it was finished on time and on budget. The single-unit reactor was commissioned in 1995, and for several years a detailed plan for a twin-unit project based on the same reactor design was considered for Sizewell C.[32]

It is estimated that the OCC would have fallen by 37% for the two projects, owing to both a reduction in indirect costs and sustained supply chain mobilisation. Sizewell C would have benefitted from the Sizewell B design phase's primary contractors and suppliers, which would have significantly reduced costs related to the reactor core (the NSSS), construction and instrumentation, and software development.

32. The current project for two EPRs at Sizewell C is based on the same site but is a different project in terms of reactor technology.

In addition, a number of nonrecurrent indirect costs related to reactor design, Generic Design Assessment (GDA) and site acquisition would have been avoided. Considering those nonrecurrent indirect costs, overall cost reductions could have reached 55% (Figure 26).

Figure 26: **Cost reductions expected between Sizewell B and proposed Sizewell C (1990s)**



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

Box 9: **Lessons learnt from industrial megaprojects**

Nuclear new-builds are major temporary undertakings, characterised by colossal budgets, considerable complexity and important socio-political and economic implications. Nevertheless, they are not the only projects with these features. Major transportation projects such as tunnels, bridges, ports and other massive facilities such as oil and gas platforms, liquefied natural gas platforms and power stations have similar characteristics, and they all fall into the category of industrial megaprojects.

The historical performance of megaprojects demonstrates that most of them have experienced cost and time overruns. For instance, transportation megaprojects are over budget all over the world (Locatelli, 2018). In the electricity sector, the costs of three-quarters of electricity megaprojects are higher than predicted, with an average budget overrun of 66% (Sovacool, Gilbert and Nugent, 2014). These trends suggest that nuclear projects are not unique and the poor performance of recent Gen-III FOAK projects can be explained, to some extent, by the fact that nuclear new-builds are among the most complex megaprojects.

The reasons for megaproject cost overruns have been studied extensively, and three key factors can be identified:

- Optimism bias: The combination of optimism bias and strategic misrepresentation is responsible for the underestimation of cost baselines and the deliberate overestimation of benefits to gain approval and funding. These factors are particularly important when political and social implications are significant.
- Design maturity: When the scope of work and potential risks of megaprojects are well identified in the pre-project phase, time and cost savings of roughly 20% can be realised. Detailed engineering and early validation and verification are at the core of practices that can make a difference (such as system engineering), as described in Chapter 4.

Box 9: **Lessons learnt from industrial megaprojects** *(cont'd)*

- Organisational complexity and inadequate governance: Recent studies suggest that megaproject costs escalate mainly because investments are so large and projects are very complex, particularly at the organisational level (Locatelli, 2018), involving numerous stakeholders with conflicting needs and a high number and variety of interfaces between the project and organisational entities. In these circumstances, a lack of strategic vision, ambiguity of scope and misalignment of stakeholder interests can be very damaging. It is therefore largely the governance of all these interactions that will determine the final performance of nuclear megaprojects.

Another challenge is low productivity. While the manufacturing sector has approximately doubled its productivity over the past two decades, construction productivity has remained flat or even declined. Wages, however, have continued to rise more quickly than inflation in many markets, resulting in higher costs for the same results (McKinsey, 2015).

These findings suggest that the organisational dimension may be key to the success of megaprojects. Organisational theory offers practical solutions to find the organisational optimum needed to cope with the complexity and changing conditions of megaprojects (i.e. hierarchies versus networks). As indicated in Box 6, practitioners also highlight the importance of leadership, organisational skills, mindsets, attitudes, behaviour and organisational culture. These "soft" issues, which are often overlooked but represent a non-negligible source of additional costs, are further explored in Section 4.2.1.

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4. Short-term opportunities to reduce nuclear construction costs

The previous chapter identified lessons learnt from recent and historical nuclear construction projects. Without these lessons, nuclear cost reductions could hardly be achieved. The concept itself is straightforward but fundamental: take a mature and frozen design with a capable supply chain and replicate it as many times as possible in a stable and predictable regulatory framework. Under these conditions, nuclear construction costs *should* decrease steadily, as in the past. Recent projects have contributed to design maturity and to the rebuilding of lost supply chain capabilities. By simply committing to a nuclear programme and taking advantage of the core lessons learnt, many countries will not only activate cost reductions but trigger a new range of cost-saving opportunities that can be exploited by the industry in the short term (i.e. before 2030) (see Figure 17).

These opportunities are the result of continuous design (or product) and associated process [33] improvements, similar to other industries, and are possible only with serial construction. The complementarity of this new set of cost reduction drivers with the lessons identified in Chapter 3 is illustrated in Table 4. In fact, these drivers are not sequential and could also be mobilised in the early stages of development to accelerate nuclear learning while mitigating technical, organisational and regulatory risks. The evidence gathered in this chapter shows that countries in more advanced stages of learning are already benefitting from these opportunities, suggesting that nuclear costs and risks *could* be further reduced. In the next sections, the cost reduction potential of each of these drivers is analysed in detail.

Table 4: **Complementarity of cost reduction drivers at different learning stages**

Risk dimension	Lessons learnt (core) (Chapter 3)	Short-term cost reduction opportunities (Chapter 4)
Technology	Design maturity	Design optimisation
Organisational	Effective project management	Innovative technologies and processes
Regulatory	Stability and predictability of the regulatory framework	Revised regulatory interactions

4.1 Design optimisation of Gen-III reactors

Learning by doing is not static. Learning rates differ among designs, depending on the efficiencies generated during their execution thanks to the optimisation that, for instance, takes requirements to improve delivery and constructability into account. Additional design optimisations may also maximise the power outputs of the existing design. This section covers four main design optimisation approaches: simplification; standardisation; reclassification of safety-related components; and power uprates.

33. The distinction between products and processes is at the core of the different cost reduction strategies analysed in this part of the report. In fact, some of the drivers apply directly to the design, another subset to the processes, and others influence both at the same time. This approach facilitates the adequate assessment of cost reductions, particularly those associated with indirect costs or "support processes", which have considerable potential. The interplay between a product and its delivery processes is further explored in Section 5.3.

It is important to remember that most of these design optimisation approaches can be considered when developing a new design from scratch; this section pays special attention to design optimisation opportunities that arise after the first-of-a-kind (FOAK) phase. In the post-FOAK phase, designers may prioritise marginal modifications and seek the best compromise between simplification and design replication to preserve learning from previous constructions as much as possible. The attractiveness of major design optimisations tends to increase with the number of units to be built, allowing for amortisation of the engineering investment.

4.1.1 *Simplification*

Design simplification is not a new issue for nuclear technology. Combining larger cores with higher regulatory stringency rapidly produced a complex technical and organisational layering still found in most contemporary designs. Vendors and designers have been pursuing greater design simplification since the early 1980s to limit the negative spillovers of complexity and nuclear costs.

Manno and Golay (1985) illustrate how design simplification is not a straightforward process, however. The main difficulty in developing a simplified design is to find a starting point, given the physical connections and interdependencies of plant systems. Vendors may adopt different methodologies, but all require sound engineering knowledge of the system and a comprehensive assessment of all possible impacts of design changes on the system's overall architecture and on plant reliability.

Some key lessons of past construction projects remain completely applicable today (NEA, 2000). The main simplification guidelines include:

- Streamlining overall plant architecture to reduce the number and volume of buildings while ensuring a compact, accessible layout.
- Exploring the potential of reactor systems sharing infrastructure when possible.
- Simplifying component, system and structure drawings, technical specifications and quality assurance requirements.
- Rationalising civil works, reducing the quantity and complexity of rebar, piping and cable by using new technologies when available.
- Reducing the number of system components when possible.

Some Gen-III designs are the result of significant simplification efforts (Box 10). Nevertheless, these efforts did not yield the expected benefits, as they were largely offset by the absence of the conditions and learning described in Chapter 3.

In addition, new opportunities arise from the adoption of product-oriented design processes commonly used in other industries. This is the case, for instance, with value engineering.

Value engineering aims to maximise the value of a product or service by meeting customer expectations at the lowest possible cost. When applied to nuclear designs, this approach assesses the functionalities of each component and systematically compares their costs with stakeholder expectations in terms of safety and performance requirements, which could result in major design simplifications.[34] At the same time, these principles help set priorities and refocus engineering efforts to reduce the risks of over-engineering[35] already reported for recent Gen-III FOAK projects. Box 11 presents an example of application, using design-to-cost methodology.

34. Simply put, if the functionality of component A is already provided by component B and the overall system complies with all requirements, component A can be discarded.

35. Engineering efforts that do not add value to the project.

Box 10: **Design simplification in large contemporary reactors**

AP1000 experience

The AP1000 design developed by Westinghouse received design approval from the US Nuclear Regulatory Commission (NRC) using approximately 60% fewer valves, 75% less piping, 80% less control cable, 35% fewer pumps and 50% less seismic building volume than usual reactor designs (Sutharshan et al., 2011). It also took advantage of the design simplification associated with passive safety systems, which rely on a gravity-driven mechanism and natural circulation. They have one-third of the remote valves needed in typical active systems and they contain no pumps. In most cases, these types of systems are also considered easier to inspect and maintain.[36] Equally important is the limited departure of passive systems from previous designs, which minimises the impact on neighbouring systems.

In addition, the implementation of passive safety systems enables the reclassification of some active safety support systems. This simplification applies, for instance, to the emergency diesel generators and their network support systems, which are no longer safety-class and can benefit from lower standards and higher competition in the supply chain. In some cases, the systems can be eliminated completely.

Another aspect reported by AP1000 designers is the higher degree of modularisation used in this design. The benefits and challenges of modularisation are explored in more detail in Section 4.2.2.

Advanced boiling water reactor (ABWR) and economic simplified boiling water reactor (ESBWR) experience

The ABWR developed by General Electric with Toshiba and Hitachi includes simplifications that have an impact on both the safety and overall economics of the plant. This design uses internal recirculation pumps that obviate the need for major piping found in earlier boiling water reactor designs. Build on ABWR experience, the ESBWR achieves greater simplicity by using natural circulation, leading to 25% fewer pumps and active drives than other designs relying on active safety systems.

The benefits of design simplification and value engineering are evident in both direct and indirect engineering, procurement and construction (EPC) costs as a result of the lower quantity and number of components as well as streamlined design processes. Furthermore, project management and productivity savings may arise from the reduced complexity of simplified designs and the lower risk of reworking.

It is important that any additional regulatory interactions required for design simplification not be neglected. As indicated in Chapter 2, licensing and certification are nonrecurring costs. If reproduced in subsequent constructions, they could hamper normal learning dynamics.

36. However, there may be challenges in periodic testing, as heat exchangers (HEs) tend to be larger. Furthermore, the cleaning of water-air HEs can also be problematic.

Box 11: Product-oriented approaches for post-FOAK design simplification: The EPR2 project and design-to-cost methodology

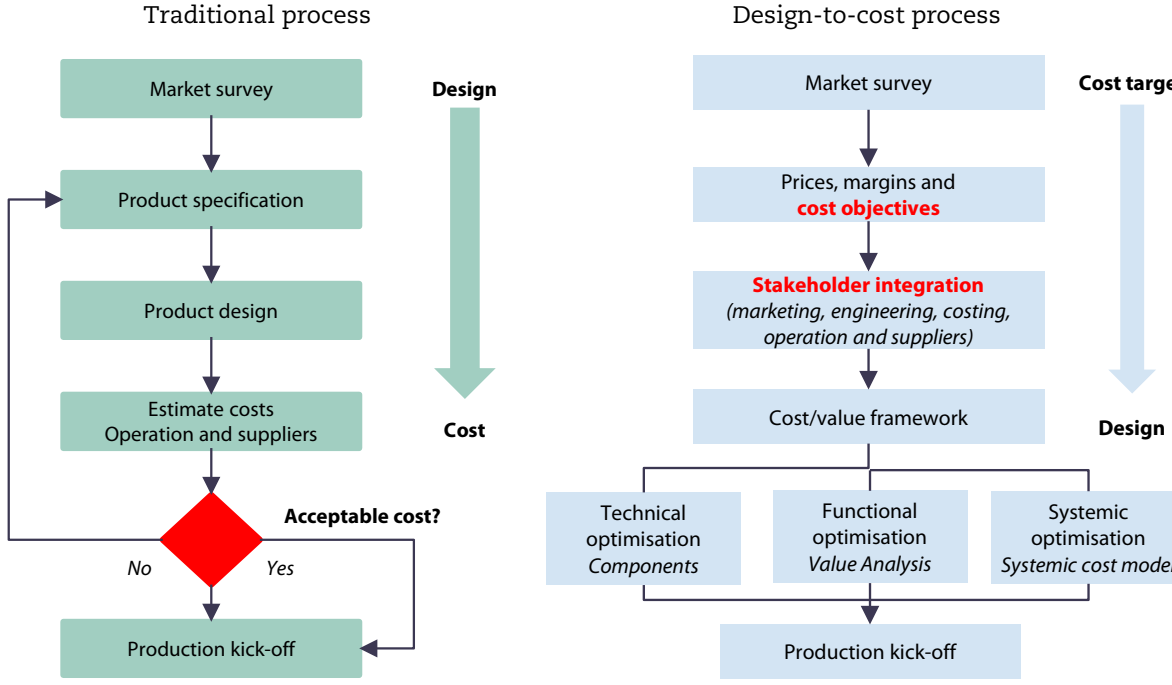
The EPR2 project is an evolutionary EPR design co-developed by the EDF and Framatome. It is a joint effort to optimise and simplify the previous design, taking lessons learnt from recent EPR projects into account.

Contrary to traditional processes that check cost acceptability once a design is completed, the design-to-cost approach sets a cost target at the early design stages (see Figure 27). The resulting design meets the cost objective while producing a final product of the highest value because value-engineering techniques are used to question the technical choices at each stage and identify the configurations that meet stakeholder expectations at the given cost target.

As a result, the new EPR2 has only three safety injection trains instead of four, a single containment with metallic liner, a reduced number of rooms, less rebar and materials, and fewer welds performed on-site. The French safety authority, following the recommendations from IRSN (2018), announced in July 2019 that the new design configuration meets current safety standards (ASN, 2019). This example illustrates how safety requirements can be met at a lower cost using the appropriate design techniques.

More importantly, this process also involves suppliers throughout all design phases to get immediate cost feedback and to verify that the solutions adopted are aligned with supply chain capabilities. Consequently, design-to-cost also provides an effective framework that enables collaboration as well as supply chain integration (Jorgensen, 2005). With the necessary adjustments, this methodology could also integrate some regulatory involvement in the future, which could lead to further cost savings (see Box 16).

Figure 27: **Traditional design vs. design-to-cost process**



4.1.2 *Standardisation*

Similar to other products and services in several industries, nuclear design could take advantage of standardisation to maintain design uniformity and homogenisation over several product iterations. Standardisation reduces the indirect costs associated with a new construction primarily by minimising recurring upfront design activities and enabling supply chain efficiency to foster series construction. Industrial code standardisation is addressed in more detail in Chapter 5.

In practice, the full uniformity sought by standardisation encounters some physical constraints. Due to the specific conditions of every site, some adjustments to the standardised design may need to be implemented. Experience shows that these design modifications are limited to:

- The foundations, as each site has specific conditions in terms of geology and seismicity.
- The heat sink, depending on the cooling capabilities, environmental rules and water chemistry, and whether the cooling circuit is open or closed.
- The power transmission network.
- The local industrial environment.

As indicated by the World Nuclear Association (WNA),

> the concept of standardised reactor designs does not require units to be completely identical. Rather all units that use the standardised design technology should at least share the same global architecture and the same specifications for the nuclear steam supply system design and components, and associated safety systems. (WNA, 2015)

France's case illustrates the economic benefits of defining a generic standard design that can be adapted to each site while keeping design modifications to a minimum (Roche, n.d.). Today, thanks to advances in seismic isolation, it could be possible to achieve higher levels of standardisation (see Section 4.2.2 for more information).

Standardisation also requires strong industrial organisation. Supply chain interactions must be homogenised to speeds up transactions and increase manufacturing process productivity with the production of a greater number of identical components. Volume production, and the associated allotment process, also improves overall quality (i.e. specialisation leads to the rapid detection of flaws in the manufacturing processes and a skilled workforce), increases supply chain competition and enables long-term contracting. The latter provides visibility to suppliers so that they can mobilise their resources in more optimal conditions.

Similarly, interactions with regulators (i.e. through the licensing process) are expedited and improved. Once a standard design has been licensed, it can be applied to all identical units (with adaptations to site-specific conditions), thus reducing time spent on regulatory activities compared with a diversified fleet (Ramana and Saikawa, 2011). In addition, design standardisation enables the accumulation of experience, which increases the probability that design flaws will be detected early, improving overall safety levels.

Consequently, standardisation must be thought of as an industrial strategy involving the whole supply chain and regulators working together to ensure that the overall design, functionalities and interactions are maintained as much as possible, and that potential factors that could prevent this are minimised. Standardisation also has noteworthy advantages in terms of plant operations, but they are outside the scope of this report.

Nevertheless, standardisation also has some drawbacks. The one most often cited is that a standardised fleet is more vulnerable to common problems (Ramana and Saikawa, 2011).[37] This risk can, however, be minimised with the adoption and standardisation of a proven and mature technology.

37. The French fleet already experienced this issue in 2016 when a carbon segregation problem was detected in the lower plates of the steam generators. Around 20 reactors were shut down to perform the necessary verifications, tests and maintenance work (Les Échos, 2016).

Another disadvantage of standardisation is its inability to foster nuclear design learning and experimentation, limiting the selection of superior design variants available that could, ultimately, also lead to lower costs.

Despite these limitations, most authors agree that at some point in a nuclear programme, extensive standardisation will be desirable to reduce nuclear construction costs, especially indirect costs associated with recurring design activities. This is supported by empirical evidence from the French and Korean nuclear programmes, which effectively relied on standardisation to enhance nuclear learning (see Chapter 3).

The key question is when standardisation should be undertaken (David and Rothwell, 1996). Timing will be determined by a country's ability to commit to several nuclear constructions, depending on national demand. Those that do not have enough electricity demand to deploy a standardised programme may find it more convenient to take advantage of more developed foreign supply chains. However, as Chapter 5 explores in detail, the lack of international harmonisation is still a major hurdle preventing countries from benefitting from international standardisation processes.

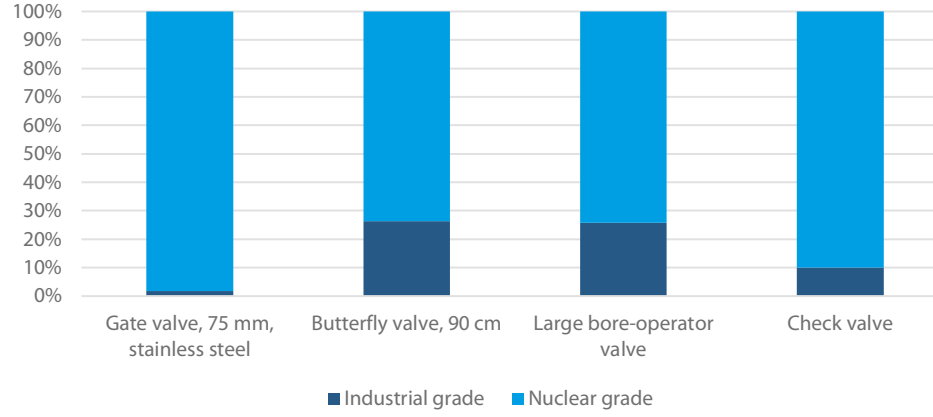
4.1.3 *Reclassification of safety components*

The high level of scrutiny to which nuclear design processes are subjected may have some undesirable spillover effects during the definition of technical specifications. Higher safety classes than required according to existing safety rules might be assigned to some components simply because they are going to be part of a nuclear facility.

The use of more refined risk-informed approaches during design stages may allow for better assessment of the boundary between nuclear and non-nuclear components. Reducing (or suppressing) the safety class in some systems enables the introduction of commercial off-the-shelf (COTS) components, especially for lower safety classes. As a result, substantial savings can be realised in the absence of nuclear-grade labels thanks to a greater supplier availability and keener competition.

Furthermore, using COTS components promotes higher levels of nuclear design simplification and standardisation, leading to additional cost cuts. Lastly, owing to manufacturers' extensive experience in a variety of industries, COTS components may be more reliable. As an example, a cost reduction of 98% could be obtained for valves, depending on the valve quality standards (Figure 28). The impact of quality assurance standards on the cost of nuclear components is further assessed in Chapter 5.

Figure 28: **Cost gap between nuclear- and industrial-grade valves**



Source: EPRI (2012), *Risk-Informed Strategies for the New Build Fleet: Risk-Informed Procurement and US NRC Rule 10CFR50.69.*

4.1.4 *Power uprates*

A power uprate is an increment of the net electrical power of a nuclear power plant (NPP). It takes advantage of economies of scale to reduce the overnight cost of a given design. The nuclear industry has accumulated extensive experience in performing power uprates in existing reactors, an approach that can be effective during the post-FOAK phase of nuclear design.

Higher power output can be achieved simply by employing enhanced techniques and sensors that reduce uncertainty in measurements of the flows necessary for calculating reactor power. More extensive power uprates may exploit the potential margins of current designs to accommodate higher outlet temperatures and steam flows, leading to higher power output. Achieving greater efficiency by minimising pressure drops on the secondary side and improved turbine blading could also be explored.

Power uprates must be performed with caution, however, as they may entail significant safety demonstrations (nonrecurring costs) that could be detrimental to learning, especially for reactors already operating at high power levels.[38] Developers also have to ensure that the size of the components and volumes remain unchanged so that established manufacturing processes are not altered, and they must keep commodity usage and civil work costs under control.

4.2 Innovative technologies and processes

Several innovations can be incorporated in the delivery processes of post-FOAK designs to accelerate their learning rates. Opportunities arise at several levels and include the introduction of new technologies as well as alternative organisational approaches and processes. The real value of these advances stems from their having already been proven in other industries, so that nuclear organisations could leverage this experience to reduce deployment time and potential risks.

It is important to highlight that these innovations represent incremental improvements rather than disruptive or revolutionary changes. The objective, similar to design optimisation, is to preserve the learning effect from previous constructions as much as possible.

Two domains deserve special attention when the adoption of innovative technologies and processes are being considered: organisation and management; and manufacturing and construction. (Opportunities and challenges associated with digital transformation are assessed separately in Box 12, as they are cross-cutting and have the potential to enhance multiple business processes at the same time.)

4.2.1 *Organisation and management*

As already highlighted several times in this report, the cost and risk issues affecting the nuclear industry today are not necessarily related to the technology itself, but rather to how the delivery infrastructure is being managed. NPPs remain one of the most complex capital projects, especially in organisational terms, as they involve numerous stakeholders, disciplines, systems and processes for which co-ordination and management can be difficult and time-consuming (Locatelli, 2018). Recent nuclear projects in western OECD countries provide evidence of these factors and how they have raised indirect costs in the last decade.

Nevertheless, the ways organisational and managerial issues contribute to nuclear construction costs are often overlooked. Box 6 explains the existence of significant *soft* costs resulting from organisational dysfunctions that are usually not properly accounted for in initial estimates. Inefficient project organisation, a lack of skills and competencies, and poor-quality control are the most common sources of soft costs in nuclear projects. All recent projects in Europe and the United States have suffered the consequences of problems in these areas, even though various organisational and management modes exist to overcome these issues during the design and construction of new nuclear projects. These techniques originate from (and have

38. High power levels tend to make safety demonstration more complex.

been successfully implemented in) the automotive and aviation manufacturing industries, which have levels of expertise and quality control similar to the nuclear industry.

However, in most cases these new management modes are a substantial shift from the more traditional approaches and mindsets that have classically governed the nuclear industry. To increase the chances of success, they must be accompanied by robust change-management practices, a dedicated budget and top management support.

Box 12: **Digital transformation in the nuclear industry: Opportunities and challenges**

Recent advances in computer power and information systems have introduced numerous digital applications that incite organisations to rethink the way they create value. Digital transformation is the organisational process of using digital solutions to enhance the performance of existing business processes,[39] and its adoption in the nuclear industry, particularly for design and construction,[40] could provide a range of benefits:

- Increased productivity: As labour represents approximately 60% of total EPC costs, the higher degrees of automation, simplification and streamlining that can be achieved with digital tools may offer significant cost savings.
- Detailed engineering: System engineering approaches can be digitally enabled to accommodate more simulations, analyses and verification in the early stages of design, thus reducing reworking risks.
- Supply chain integration: Digital platforms shared among suppliers based on extended enterprise frameworks enable greater alignment and co-ordination of the supply chain.
- Quick and well-informed decision-making: Digitalisation also allows for greater unification, synchronisation and traceability of information. Plus, information can be more easily retrieved, facilitating exchanges among stakeholders.
- New operational modes: Digital tools provide the opportunity to explore processes characterised by higher collaboration, reactivity, agility[41] and innovative thinking.

Based on experience gained in other industries, including the energy sector and aircraft manufacturing, several solutions are already available for the design, procurement and construction process of nuclear systems. These solutions are at a high level of maturity, and the nuclear industry is currently in the deployment phase while developing the standards and rules necessary to make them robust and their effects long-lasting.

Among the several digital tools being employed by nuclear vendors, product lifecycle management (PLM) systems are capturing most of the attention. A digital PLM platform enables the efficient management of data generated by a product (in this case an NPP) over its entire lifecycle. It provides a unified information system in which interaction with other applications and databases (i.e. document management systems, enterprise resource planning, etc.) is possible. With the appropriate access rights, the PLM platform can also be opened to external partners to increase supply chain integration. As a result, a PLM system acts as backbone, feeding all tools, activities and stakeholders involved in the lifecycle of an NPP with updated information. It codifies data exchanges and validation processes from systems to subsystems, and from design engineers to subcontractors throughout the entire lifecycle while assuring the accessibility and detailed traceability of all modifications and technical choices based on performance and regulatory requirements. The latter feature is particularly important in stringent and evolving regulatory frameworks.

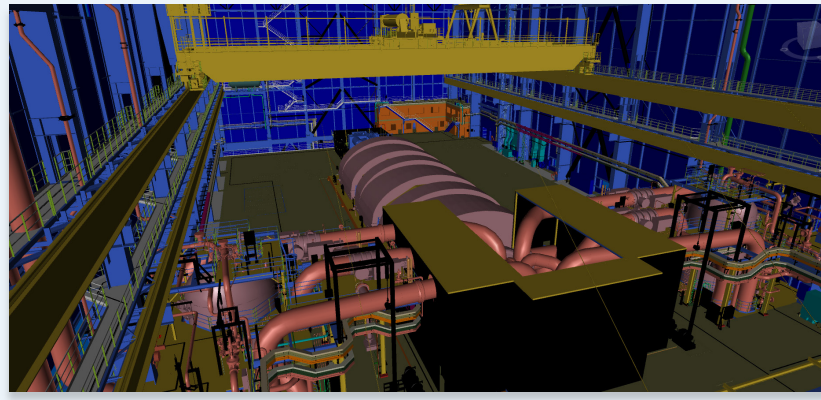
39. Generating new business and revenue streams is also possible with digital transformation.
40. Adopting digital tools would also positively impact plant operations and decommissioning, but these aspects fall outside the scope of this report.
41. Inherited from software companies, agile teams change protocols and silos by iterative and cross-functional interactions. In changing environments, this methodology has proven very effective in delivering high-quality products.

Box 12: **Digital transformation in the nuclear industry: Opportunities and challenges** *(cont'd)*

Other promising digital levers include building information management (BIM) systems, multi-dimensional (multi-D) tools and digital twins. A BIM tool is equivalent to a PLM system, but deals with the physical and functional characteristics of an NPP's various buildings and components. When used with a 3-D virtual environment, the digital mock-up provides a higher degree of integration and simulation capabilities (Figure 29). Most advanced versions couple the benefits of BIM with additional dimensions, such as a project's cost and schedule, to become multi-D tools.

Additional simulation capabilities can be used to optimise the installation sequences of critical components. Digital twins[42] make it possible to continuously update existing BIM and multi-D models, narrowing the gap between "as-planned" and "as-built" information, thus facilitating the detection and correction of deviations, and enabling quick and well-informed on-site decision-making. One interesting feature of digital twins is their potential to perform online resource planning, logistics and localisation. This facilitates the control of workforce densities[43] and avoids unnecessary movements and material handling, which is particularly relevant for nuclear projects in which the peak workforce can reach more than 4 000 people.[44]

Figure 29: **3-D virtual representation of the turbine hall with BIM tools**



Source: Courtesy of EDF.

Despite these opportunities, empirical evidence from other organisations shows that two-thirds of digital transformations fail. One of the reasons often cited by practitioners is the underestimation of organisational change. Like any other change management process, digital transformation may require strong leadership and a dedicated budget to absorb emergent risks and for employee training, communication and empowerment.

Most importantly, digital transformation should not be limited to one company only. Change management, IT infrastructure and harmonisation efforts have to extend to the whole industrial ecosystem, and this may take considerable time. All these aspects must be fully acknowledged and embedded in the digital strategy to overcome digital maturity differences among partners.

Finally, potential safety and security obstacles also need to be addressed in nuclear industry digitalisation. Regulator inertia and additional regulatory requirements (i.e. cybersecurity) are additional challenges the industry may face.

42. Digital twins are virtual and dynamic representations of physical assets and processes.
43. Number of workers within a unit working area.
44. A typical NPP construction project in Korea has 400 management staff and a workforce of 4 200 (Shin, 2018).

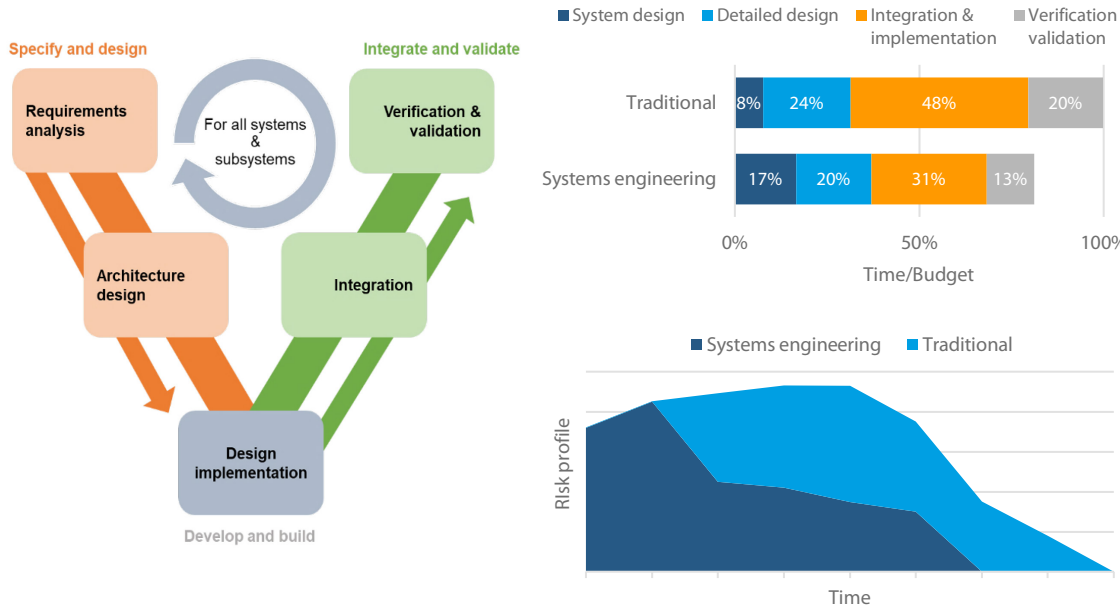
Systems engineering (project organisation)

The intricate architecture of nuclear designs, involving numerous systems and interfaces, makes managing projects particularly difficult. Systems engineering (SE) is a multidisciplinary approach to enable the successful delivery of systems and products in complex environments through comprehensive techniques and tools (Locatelli, Mancini and Romano, 2014).

One of the pillars of SE is the "V model" (Figure 30). Applied recursively to each system and subsystem, this tool enables detailed front-end engineering and early verification and validation of the different components of the system. This increases the chances of getting the design right the first time and avoiding very expensive construction delays (Figure 30 illustrates potential cost and time gains that can be achieved with SE design efforts).

One of the main outputs of the V model is an easily understandable reference system architecture that acts as a common language for all teams and stakeholders**.** If requirements evolve, this architecture also enables rapid impact analysis, smooth change management and rapid adaptation to complex environments. All these features and principles can be enhanced with digital tools and are currently at the core of most PLM systems (see Box 12).

Figure 30: **The SE "V model" and potential return on investment**



Knowledge management (skills and competences)

Nuclear energy is a knowledge-intensive domain that requires high technical skill, competence and excellence levels, which take a long time to be acquired and properly adopted across the entire supply chain. Of capital importance is knowledge acquired in a tacit[45] manner. Tacit knowledge is the result of experience, trial and error, human interactions and work practices. Most of the knowledge capital accumulated at the end of a project is tacit knowledge (Dudézert A. et al., 2012). The main issue with tacit knowledge is that it is "sticky" – i.e. inseparable from individuals and thus difficult to transfer. Consequently, once a project is finished, the learning tends to leak away as people move to other projects. Rising turnover rates of young professionals and uncertainty surrounding nuclear new-build orders in OECD countries aggravate this situation.

45. As compared with explicit knowledge, which is well documented and codified in books, archives, drawings, etc.

In this context, knowledge management (KM) is an emerging integrated, systematic approach to identify, manage and share an organisation's knowledge and enable people to create new knowledge collectively, and thereby help achieve the organisation's objectives (IAEA, 2012). The nuclear industry is already familiar with traditional KM approaches[46] but has been falling behind in embracing more bottom-up network-centric approaches that rely on communities of practice and digital platforms. These approaches consider knowledge as a resource that is built collectively and enriched through everyday interactions with peers, and they have proven to be an efficient way to sustain tacit knowledge, despite organisational turnover and activity downturns.

Digital transformation (see Box 12) therefore offers a prime opportunity to introduce these new KM techniques into business processes to raise the overall performance of nuclear organisations. For instance, bottom-up KM processes can be embedded within a PLM platform to incorporate new knowledge and valuable lessons learnt in the field, from recent and ongoing projects. As a result, the PLM system would become a virtual environment capable of ensuring the continuity of data, information and knowledge throughout the supply chain, accelerating learning effects in the nuclear industry. Lastly, as for other transformative processes, the introduction of new KM techniques may require corporate culture shifts and other organisational changes that have to be properly managed.

In spite of the potential of modern KM techniques, it must be underlined that the most effective way to create and sustain knowledge is to keep the same people doing the same activity for as long as possible (Mckinsey, 2018). Governments thus have a major responsibility to create favourable conditions by committing to a nuclear programme, which could be complemented by national-level strategic planning. To this end, government, industry and academics could work together to provide a functional framework for workforce development that includes attractive university programmes, rigorous professional training, research and development (R&D) investments, mobility, partnerships between utilities and universities, and international collaboration programmes.

Operational excellence (quality control)

If encountered once construction has begun, quality flaws could result in important delays and additional costs in terms of regulatory interactions, engineering efforts and reworking. As quality in execution is linked with skill and competence, it is important to underline that countries building several reactors will benefit from quality improvements and more effective quality management systems as supply chain capabilities develop.

At the same time, it is possible to mobilise a set of tools, techniques and principles to foster operational excellence and strengthen the quality control system continuously with every new construction. This is the aim of lean management (LM). Popularised by the Japanese car manufacturer Toyota in 1980, LM is a management philosophy that pursues the continuous improvement of processes by eliminating sources of waste and tasks that do not add value. It relies on workforce engagement as the best ally to identify operational flaws and propose potential improvements. Its application to the nuclear industry could help identify and remove redundant quality checks and engineering efforts while reducing the risk and number of non-quality issues at all levels: design, construction, component manufacturing and regulation.

4.2.2 *Construction and manufacturing*

In addition to organisational and managerial cost reduction opportunities, incremental innovations in construction and manufacturing could lead to additional cost savings in the short term. The most promising technologies and processes include advanced manufacturing; advanced concrete and rebar solutions; risk-informed inspection; improved seismic design; modularisation; and other advanced construction methods. These solutions essentially pursue greater labour productivity and more aggressive reductions in lead times and raw material

46. Including knowledge-mapping (the identification of knowledge-holders and flows), expert interviews and mentoring (IAEA, 2012). Practices are quite formal and adhere to top-down logic.

usage. As the following sections illustrate, the large size of components is the main technical barrier in implementing some of these solutions.

Advanced manufacturing

The manufacturing process can be particularly expensive, especially for large, heavy safety-related components such as the reactor pressure vessel (RPV). Particularly important is the thick section during the welding process. With traditional techniques based on tungsten inert gas (TIG) arc welding, around 100 runs are required for a 20-mm-thick section. Each run also requires heating, inter-pass temperature control and inter-stage non-destructive examination (NDE). As a result, the welding, inspection and completion of a RPV is an expensive and time-consuming process that can take several months, and accounts for a large proportion of fabrication costs and component lead time (Nuclear Engineering International, 2019).

Significant progress has been made in recent years in the development of manufacturing techniques and processes (joining, welding, machining, forming, etc.) in various industries, especially automotive and aerospace. Some of these techniques are electron beam welding, powder-metallurgy hot isostatic pressing, diode laser cladding and additive manufacturing (EY, 2016; Nuclear AMRC, n.d.). The cost and lead-time reductions these solutions may offer are also remarkable.

However, their large-scale application in the nuclear industry still needs additional development and the physical size of nuclear components does not facilitate their implementation. According to EY (2016), of 14 potential advanced manufacturing techniques, only 2 are applicable to large reactors and could be ready for production in 2022: rapid, large-body and in-process metrology; and automated welding and rebar assembly. The latter has been successfully used to weld the reactor coolant pumps of the Korean APR-1400 design and in the Japanese ABWR Kashiwazaki-Kariwa 6&7 project (IAEA, 2004).

Advanced concrete and rebar solutions

Activities involving concrete and rebar are labour-intensive. In some cases, steel congestion can be a serious problem as it stunts constructability by limiting access, increasing workforce densities and thus undermining the overall productivity of civil works. Considerable rebar congestion may also result in particular defects in concrete such as voids. Some advanced concrete and rebar solutions include high-strength reinforcing steel (EPRI, 2016), ultra-high-performance concrete and self-consolidating concrete (EPRI, 2019). The latter flows into place using gravity alone, reducing defects and labour requirements during placement. Its use in the nuclear industry has already been reported for AP1000 projects (MIT, 2018).

Another technique that is being increasingly adopted for nuclear civil works is the use of steel-plate composites (SPCs), which consist of two parallel steel plates connected by ties. The additional mechanical strength provided by the plates allows for the replacement of rebar and also facilities concrete-pouring without temporary supports during fabrication, resulting in a 50% reduction in installation time (MIT, 2018) (Figure 31). This technique has already been certified for nuclear applications in Japan, Korea (Lloyd, 2019) and the United States (MIT, 2018). For instance, it has been successfully implemented as a part of a global modularisation approach in the APR-1400 design (see Box 13).

These different techniques can all be combined as a part of a comprehensive advanced construction approach involving modularisation and more advanced construction methods, as described later in this chapter.

Risk-informed inspection

Risk-informed approaches used to redefine safety boundaries and enable the adoption of COTS components can also be extended to inspection, particularly to NDE. NDE is mandatory to comply with nuclear industry licensing requirements. It may involve significant resources during the manufacturing of critical components, especially those associated with reactor plant equipment subject to stringent safety standards. Requirements are usually generated using deterministic design analyses that quantify the necessary safety factors. This may produce

conservative inspection schemes that do not always take the probability of damage occurrence into account. Risk-informed methods rely on probabilistic techniques that lead to a more efficient inspection regimen by identifying appropriate inspection locations and frequencies.

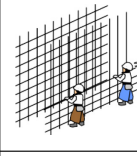
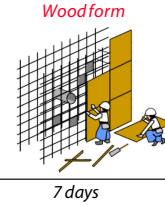
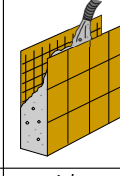
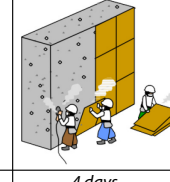
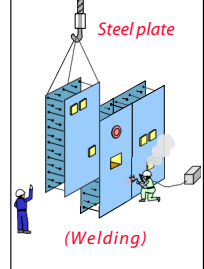
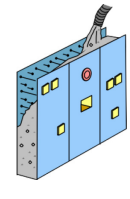
Modelling and simulation techniques are also an effective way to enhance risk-informed NDE processes. New configurations and sensors can be tested, and optimised accordingly, to increase the probability of success. The extension of existing risk-information NDE approaches to other components can be accelerated using simulations to generate the required scientific-based evidence for the regulatory bodies (EPRI, 2014).

Improved seismic design

Due to the lack of advanced models for dynamic load analysis during the 1970s-1980s, especially for seismic-related design activities, Gen-II reactor structural designs contained significantly conservative estimates. Current Gen-III designs, based on the legacy of the previous generation of reactors, may have inherited some of these conservative assumptions in their licensing approaches. More accurate estimates of the seismic response of current nuclear designs with more refined models may result in lower structural load requirements and thus major savings owing to downgrades in reinforcing-steel needs, concrete wall thickness, the number of structural steel connections, and anchorage between structural elements and components.

In addition to increasing the accuracy of ground-motion estimates, technologies such as seismic isolation systems can be implemented to reduce the overall effect of a seismic-related event.[47] As dependency on site-specific seismic conditions is significantly reduced, this type of technology enables greater design standardisation. Seismic isolation devices have already been successfully installed in the Cruas NPP, the ITER facility, the Jules Horowitz research reactor (France) and the Koeberg NPP (South Africa). In terms of cost, installing these devices is expensive. Investment attractiveness increases for ground acceleration peaks exceeding 0.2 g.

Figure 31: **Advantages of SPC vs. rebar-based structures, ABWR study**

Work / Structure	Rebar arrangement	Formwork (assembling)	Placing concrete	Formwork (removal)
RC				
Total 28 days	13 days	7 days	4 days	4 days
SC	———			———
Total 14 days		10 days	4 days	

Source: IAEA (2004), *Construction and Commissioning Experience of Evolutionary Water Cooled Nuclear Power Plants.*

47. Seismic isolation systems consist of devices (elastomeric [rubber] bearings or low-friction sliders) that "isolate" a structure from the ground by absorbing shock for the buildings. Compared with a fixed-based structure, seismic isolation effectively dampens horizontal acceleration from an earthquake, although vertical displacements must still be considered.

Modularisation and other advanced construction methods

Modularisation is the process of breaking a large and complicated product down into smaller building blocks, or modules, according to a set of limited constraints. The objective is to maximise the amount of work that can be transferred to a shop or factory, as this type of environment offers greater predictability and control, greatly improving overall productivity (and often quality) while making parallel construction possible. Constructability is also enhanced as the number of components, interfaces and workers (i.e. site congestion) is reduced.

A more controlled environment could be also more convenient for critical processes such as concrete-pouring, welding, steel-cutting and testing. Modularisation has already provided benefits in other industries such as shipbuilding, aviation, chemical processing, and oil and gas. General observations of modularisation in the power sector indicate lead-time reductions of 40% and 20% lower costs (Lloyd, 2019).

Large stick-built Gen-III reactors already accommodate a certain amount of factory construction, approximately 30% of construction costs[48] (EY, 2016). According to recent results from the University of Cambridge, for reactors with a power output greater than 750 megawatts of electrical capacity (MW_e), this number could be increased up to 40% through modularisation (Lloyd, 2019). The nuclear industry has already accumulated some experience in implementing modularisation techniques for large reactors (Box 13), but evidence indicates that larger projects could be delivered faster with more extensive modularisation. However, if the supply chain's ability to deal with the modules is limited, this could rapidly offset expected benefits.[49] Also, additional upfront engineering efforts and funds are required to assess the feasibility of the different modules and secure their procurement before construction begins.

As with advanced manufacturing techniques, component size, weight and geometry are the main physical constraints on modularisation. These parameters directly dictate how easily the various components can be transported, lifted and installed. The infrastructure to access the site and national transportation standards may present additional restrictions.

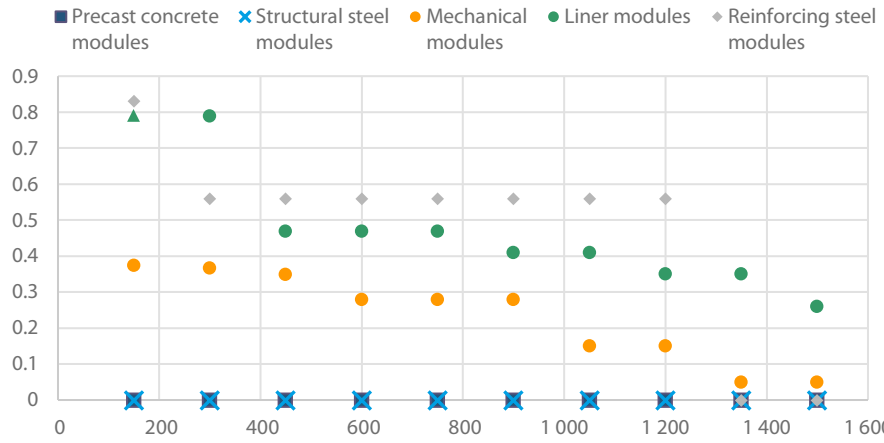
Figure 32 illustrates a more granular analysis of the degree of modularisation of different types of components: as the size of the component tends to increase with power output, the degree of modularisation falls. While concrete and structural steel components cannot be easily modularised for all ranges of power, reinforcing steel, liner and, to some extent, mechanical components offer higher potential for modularisation. To counteract these constraints, designers may adopt more aggressive modularisation strategies, further subdividing modules to make them transportable.[50] Furthermore, a net improvement in the degree of modularisation for reduced power outputs presents opportunities for factory-based construction for smaller reactor concepts. This is one of the main factors that makes small modular reactors (SMRs) and micro-reactors attractive, as Chapter 5 will discuss in more detail.

Other advanced construction techniques include open-top construction; parallel construction; layout and crane optimisation; and all-weather conditions. These construction approaches and their associated benefits have been well documented in past in publications (NEA, 2000; IAEA, 2004 and 2011; EY, 2016), but they are still applicable and could produce additional savings for post-FOAK nuclear projects.

The design phase is critical, because it is in this stage that all the construction techniques must be assessed and combined into an overarching construction plan to reduce construction risks and improve constructability. Digital solutions such as BIM and multi-D tools (see Box 12) enable higher degrees of testing and experimentation, and therefore a more optimal construction plan. Modularisation is a clear example of how construction techniques have to be incorporated into the design as soon as possible, with the early involvement of the supply chain.

48. This essentially involves fabrication of the reactor and turbine plant components and control systems.
49. This issue has been observed in the delivery of first AP1000 units.
50. Lloyd et al. (2018) explore the relationship between the module division factor and the number of modules possible in an NPP design. While the S&W scheme results in 1 417 modules, when the dimension of the modules is halved the total rises to 6 324, potentially increasing the degree of modularisation.

Figure 32: **Maximum degree of modularisation for different components attainable with S&W scheme**



Source: Lloyd, Roulstone and Middleton (2018), "The impact of modularisation strategies on Small Modular Reactors."

Box 13: **Modularisation schemes for large reactors**

Modularisation efforts are not recent in the history of nuclear power. The Stone & Webster (S&W) modularisation scheme developed for a generic 950-MW_e Westinghouse PWR in 1977 was supposed to be used in the Sundesert NPP in California. The project was halted and the S&W scheme was never implemented, but it certainly inspired subsequent modularisation efforts for the AP1000 design.

The S&W scheme uses time and cost savings to determine final modules selection. Feasible modules must create cost savings of at least 5% (either on materials, labour or both). The strategy involves the use of on-site shops for the fabrication of modules, limiting the remaining constraints to heavy lifting only. Nevertheless, transportation is cited as one of the primary limitations. The S&W report identifies roughly 1 400 modules, most of them structural (approximately 1 300) and the remainder mechanical.

More aggressive modularisation approaches show that is possible to design combined modules, incorporating structural elements with other components such as piping, cable trays or ducting. These types of modules are typically selected if the equipment layout in the given area is very compact. The density of bulk commodities inside combined modules is therefore a key parameter for its selection and design. Consequently, procurement may become an issue in combined modules as the build sequence is altered from that of conventional construction (Lloyd, 2019).

AP1000 experience

The AP1000 modularisation approach is the materialisation of efforts initiated with the S&W scheme. It consists of 160 structural and 56 mechanical modules that target essentially three areas: the containment building, the auxiliary building and the turbine building (Niemer, 2011).

One of the main structural modules (known as CA-01) is a multi-compartment structure comprising the central walls of the containment's internal structure. The vertical walls of the module house the refuelling cavity, the reactor vessel compartment, and the two steam generator compartments. The CA-01 consists of 40 prefabricated walls, or steel plates, call submodules. These submodules can be transported by rail to the site, and they weigh between 10 tonnes and 73 tonnes; if barge access is available at the site, larger subassemblies can be envisaged. The various modules are assembled in an on-site shop, and the completed CA-01 is then lifted to its final location within the containment vessel with a very-heavy-lift crane (Sutharshan et al., 2011). After erection, concrete is finally poured between the steel plates. The level of standardisation of the modules or super-modules of the AP1000 is reportedly low (Lloyd, 2019).

Box 13: **Modularisation schemes for large reactors** *(cont'd)*

ABWR experience

Unit 7 of the ABWR Kashiwazaki-Kariwa project used the "large modularising construction method." The seven floors of the ABWR building were divided into three levels and constructed in three steps in a preassembly yard before the pieces were successfully lifted and installed. The heaviest and most complicated module was the "upper drywell super large-scale module". It was a combined module consisting of walls and support structures, pipes, valves, cable trays and air ducts weighting around 650 tonnes[51] (IAEA, 2004).

Hitachi-GE Nuclear Energy has made significant improvements in its modularisation strategy since the Kashiwazaki-Kariwa 6&7 project in the late 1990s. In 2009, 193 modules were used, compared with only 18 in 1985. These modules involve piping, platform equipment, cable trays and civil modules. Module weights vary between 5 tonnes and 650 tonnes and they are shipped using trucks, trailers or barges, depending on their weight, size and site location (Lloyd, 2019). The Hitachi-GE design and modularisation approach is 90% complete before construction starts, reducing the chance that reworking will be needed by about 20 times (Choi and Song, 2014)

OPR-1000 and APR-1400 experience

OPR-1000 Unit 2 at the Shin-Wolsong project provides insights into the modularisation of containment liner plates. The limiting factors of the liner modules are dimensions and constructability, not weight. The strategy that was retained combined smaller ring modules into a larger super-module before lifting it into place. As a result, the number of construction steps was reduced from 11 to 8 and the building schedule was shortened by 30 days. Furthermore, the total number of lifts was also reduced, allowing 54% of the welding jobs to be performed at ground level instead, improving both worker safety and weld quality (Lloyd, 2019). The APR-1400 design includes SPC structural modules and several combined modules.

4.3 Revisiting regulatory interactions

Regulation, alongside safety culture, is at the core of all nuclear activities. Its objective is not only to ensure that nuclear installations are safely operated and meet all standards, but also to create stakeholder and public confidence. An efficient, independent and transparent nuclear regulatory body is paramount to establish the social licence[52] needed for nuclear power to have a stable and durable foundation in any society.

The regulation of nuclear power involves several dimensions and stakeholders. First, given the complexity of nuclear systems, regulation is dominated by high levels of expertise. Second, to build and maintain a social licence, regulators must be able to interpret what society expects in terms of requirements imposed on licensees. How this interpretation is accomplished may vary from one country to another, depending on, among other elements, public attitude and regulatory practices. Conversely, the economic dimension of regulation is rarely discussed.

The first economic impact of regulation, as indicated in Chapter 3, is on nuclear project costs in the absence of regulatory predictability and stability. While regulatory decisions may delay the initial design and construction schedule, delays are more detrimental once construction has begun. Longer lead times may trigger not only an IDC increase but productivity

51. For comparison, the largest crane in the world (the SGC-250, also called "Big Carl"), developed by Sarens especially for the EPR Hinkley Point C project, has a maximum lifting capacity of 3 000 tonnes.

52. The concept of social licence to operate (SLO) covers three key ideas: i) a SLO is granted by the local community hosting a project; ii) it entails processes of acceptance and approval of industry activities; and iii) it is constructed through dynamic interactions among the community, stakeholders and companies (Lehtonen et al., 2020).

downturns. Regulatory decisions may impose changes on the design that, again, would be particularly damaging in the construction phase. US experience provides empirical evidence of this type of impact: during the 1970s, especially after the Three Mile Island (TMI) accident, many regulatory-driven design changes affected both existing plants and those under construction. As suggested by Lovering, Yip and Nordhaus (2016), the NPPs that were under construction during the TMI accident and were eventually completed afterwards had higher median costs and durations compared with pre-TMI trends.

Regulatory requirements may also impose base design changes, particularly for reactor designs that have already been licensed under the regulations of the country of origin but require design modifications to comply with the import country's regulatory framework.[53] The case study presented in Box 14 suggests that adaptation of a base design to a foreign regulatory regime might induce an EPC cost increase of around 30%. As will be explored in Chapter 5, the harmonisation of regulatory regimes may help limit the impact of adaptation costs.

Box 14: **Case study: Estimating the costs of adapting to national regulatory frameworks**

The lack of nuclear regulatory regime harmonisation implies that for nuclear designs to be exported, some modifications may be required for them to comply with the other county's safety requirements. This case study offers a macro-level estimate of potential costs incurred to adapt a base design to a country-specific regulatory framework. The results were recognised by the REDCOST expert group.

The four main potential sources of adaptation costs are:

- An increase in the bill of quantities (BoQ) due to anticipated increases in the volumes of buildings.
- An increase in the number of systems and equipment.
- An increase in the number of work hours based on these modifications.
- An increase in the number of work hours for licensing-related tasks.

In line with the cost structure presented in Chapter 2, EPC expenses were assumed to be made up of 39% material costs and 61% labour costs. Another important assumption is that most of the adaptation costs induced by various regulatory requirements are captured by safety-related systems, components and structures such as the reactor plant and instrumentation and control (I&C) equipment, and construction works. The turbine and main heat rejection systems, however, were assumed to be outside the scope of adaptation costs.

Using expert and engineering judgement, sets of multipliers were determined for the material and labour costs of each component; it was considered fair to assume a 30% increase in the BoQ and in the number of systems and equipment needed to meet more stringent safety requirements. This resulted in a general multiplier of 1.3 for the BoQ for construction works and concerned equipment.

The correlation between the BoQ and construction work hours is almost linear, so a similar multiplier was used for work hours related to the various modifications. However, depending on the national licensing process, significant additional work might be needed for the licensing activities associated with safety-related components (i.e. reactor and electric plant equipment). This explains why different labour multipliers were used depending on component type, as well as the rise in indirect costs. The table below presents the cost breakdown and estimated multipliers of the selected safety-related components.

53. Safety requirements may vary from one country to another in areas such as defence-in-depth concept; diversity and redundancy; and physical separation. These aspects are further investigated in Chapter 5.

Box 14: **Case study: Estimating the costs of adapting to national regulatory frameworks** *(cont'd)*

	Materials and components	Labour	Materials and components	Labour	Materials and components	Labour
Civil structural works	5%	9%	**1.3**	**1.4**	6%	13%
Reactor plant equipment	11%	3%	**1.3**	**2.2**	14%	6%
Turbine plant equipment	8%	2%			8%	2%
Electric plant equipment	2%	2%	**1.3**	**2.0**	3%	3%
Main heat rejection system	2%	2%			2%	2%
Miscellaneous plant equipment	1%	2%			1%	2%
Indirect costs	11%	42%		**1.4**	11%	58%
Total	39%	61%			44%	86%
		100%				**130%**

Material costs rise from 39% to 44%, and labour costs from 61% to 86%, leading to an indicative cumulated cost increase of 30%. Based on this analysis and underlying assumptions, adapting a design to a different regulatory regime may raise EPC costs by around 30%.

It is important to note that these estimates are subject to significant uncertainties. Adaptation costs may also vary depending on the design and the extent of the regulatory gap between countries. Nevertheless, this exercise confirms that adaptation costs are not negligible and potential cost savings could be obtained by strengthening regulatory harmonisation.

From an economic perspective, the additional costs induced by regulatory activities are the price that must be paid to reduce the externalities associated with nuclear power, to ultimately maximise social benefits. Economic theory postulates that optimum nuclear power safety efforts are reached when the marginal social cost of protection equates the marginal social benefit in terms of potential harm avoided. Beyond this optimum, any additional regulatory effort is more costly than the potential benefits to the society. In practice, however, finding this optimal level is not a simple task. One of the main hurdles is the incompleteness of information. In fact, the marginal costs of regulatory efforts are not well known and uncertainties surrounding the marginal costs of risks avoided are high.

Since establishment of the first regulatory bodies, rules and approaches for safety demonstration have not ceased to evolve. Various adjustments have been made to integrate increasing knowledge of the physical phenomena involved, as well as to improve regulatory efficiency and find a better balance between the costs and benefits of safety regulation. Traditional regulatory processes were characterised by high levels of prescription. This type of approach makes sense only when knowledge of nuclear safety is limited in order to reduce levels of uncertainty, ambiguity and misinterpretation (Sainati, Locatelli and Brookes, 2015). At the same time, safety demonstration relied heavily on deterministic approaches.[54]

54. Build upon defence-in-depth principles (prevent, protect and mitigate), deterministic safety assessment postulates a series of incidents and accidents that may occur for a given design, and evaluates, by means of codes and analytical methods, the capability of the design to withstand these transient conditions. If the safety requirements are not satisfied, design modifications (e.g. the introduction of additional safety systems) are implemented. It is the ability of defence-in-depth principles to meet safety criteria – and not necessarily their effectiveness to reduce overall risks – that prompt design modifications.

With the emergence of probabilistic safety assessment (PSA),[55] the introduction risk-informed, performance-based regulation (RIPBR) was facilitated. Instead of defining technical rules and then verifying their proper application, under RIPBR the regulator establishes basic requirements and sets overall performance goals, and the plant's management then decides how to best meet the stated goals. Using risk metrics obtained through PSAs allows resources to be allocated to plant equipment and systems according to their safety relevancy. As a result, regulatory processes can be streamlined to remove unnecessary rules (as their contribution to safety is judged negligible) and focus efforts on critical stages and components.

To reduce costs related to regulation, economic analysis suggests that RIPBR is more convenient for several reasons. As the choice of how to meet performance criteria is left to licensees, they have an economic incentive to select the least-costly solutions (Lévêque, 2014). Freedom of choice also implies greater innovation opportunities to further reduce costs and improve overall industry performance, and regulators also save the costs associated with gathering expert knowledge.

However, the weakness of RIPBR is that it is difficult to measure performance itself, as performance can normally be observed only indirectly or during the operating period. Plus, PSA metrics are also subject to uncertainties, particularly those related to human factors and behaviours. Lastly, deterministic safety assessment is the only way to identify factors that may still be unknown and, under accident conditions, it provides the right tools to mitigate the most severe consequences.

All these circumstances mean that, in practice, regulatory bodies adopt a more dual approach that combines the right level of prescription with goal-setting initiatives. Deterministic approaches are usually used for design-basis transient analysis, while probabilistic methods are more suited to beyond-design-basis assessment of accidents (i.e. external hazards, such as for the Fukushima Daiichi accident). The guiding principle of ALARA/P – as low as reasonably achievable/practicable – is widely accepted by all countries to ensure the proportionality and effectiveness of regulatory efforts in the interests of society.

The ALARA/P principle is essentially based on the philosophy that operators and regulators should constantly be asking themselves, "How safe is safe enough?". In the end, it is up to society to decide, on the basis that all the technical information is available. Regulators must therefore frame technical safety requirements in a way that reflects the expectations of society as a whole, considering the overall risks of nuclear activities. Consequently, in addition to potential interpretations of the ALARA/P concept, it is also important to understand the different strategies envisioned by regulators to translate the social perception of nuclear power into technical requirements and how this process may impact the cost of the technology.

In practice, it is extremely difficult for a regulatory body to accurately assess the level of risk deemed acceptable by the society it represents. The public inquiries, parliamentary questions and media coverage that follow any untoward nuclear event may provide the most reliable indication (NEA, 2000). Regardless, regulators have to ensure that the ALARA/P principles are clearly understood and properly applied at all stages of the safety assessment. Some studies suggest that ALARA/P guidelines are often misinterpreted in regulatory interactions, which may result in nuclear safety standards being applied uniformly to the entire plant rather than being adjusted, at the component level, according to its safety relevance (NIRAB, 2019). The adoption of risk-informed frameworks may provide a set of rules adequate to avoid this type of situation (Box 15).

55. PSAs seek to quantify the probability of cascading failure occurrence that, combined with potential consequences, yields the associated risks.

Box 15: ONR's risk-informed decision-making process

The United Kingdom's Office for Nuclear Regulation (ONR) deserves attention for its significant efforts to ensure proportionate and adequate application of the ALARA/P principle, using risk-based approaches to inform regulatory decision-making.

In *Risk Informed Regulatory Decision Making* (ONR, 2017), the ONR details the main principles and criteria guiding its regulatory decision-making process. Its philosophy is based on "tolerability of risks", which does not mean acceptance of risk but rather the willingness to live with it to secure certain benefits for society, in the confidence that risks are being technically and properly controlled. Risks are not therefore ignored, but kept under review and reduced as much as is reasonably practicable. For a risk to be acceptable, however, the society must be prepared to accept it. Consequently, the ONR's regulatory framework includes a set of criteria to decide whether risks are unacceptable, tolerable or broadly acceptable. ALARA/P guidelines are used to proceed though the risk tolerability continuum, underpinned by risk-informed approaches and metrics.

When it is considering whether licensees need to implement further measures, the ONR compares the degree of risk reduction with "the sacrifice, whether in money, time or trouble involved in the measures necessary to avert the risks." Unless the licensee can demonstrate a gross disproportion between these two factors and prove that the averted risk would be insignificant, additional measures to reduce risks have to be considered.

The ONR also indicates that "there is no precise legal factor or algorithm able to define gross disproportion between the costs associated with the measures to reduce risk and the benefits in terms of risk reduction." Numerical calculations are also rare, so in its decision-making the ONR recognises a disproportion factor (the cost-benefit ratio of a given solution) of up to approximately ten (this value is based on evidence from the Sizewell B public inquiry). Also, when the disproportionality of regulatory decisions is being assessed, the initial position of the risk on the tolerability continuum must be considered. Applying a costly solution to move risk from the "unacceptable" to the "tolerable" zone is not the same as using expensive means to shift it from "tolerable" to "broadly acceptable."

Consequently, in addition to the stability and predictability conditions highlighted in Chapter 3, regulatory frameworks can support cost reductions by revisiting regulatory interactions and approaches through:

- Increasing awareness among regulators that their activities increase the cost of the technology (by an amount that is necessary for the benefit of society but that should be proportionate to the risk avoided), and engendering among regulators a willingness to understand how their decisions may impact the final performance of the technology. For instance, in its 2019-2020 corporate plan the ONR expressed its commitment to develop greater understanding of the costs imposed by regulatory decisions, to use economic advice in framing and assessing its regulatory decisions, and to refine its current guidance on ALARA/P and gross disproportion (ONR, 2019).
- Identifying mutually beneficial situations, in which regulators and licensees can co-operate while maintaining regulatory independence and the highest level of safety. For instance, Box 16 presents success story of revisited regulatory interactions for cost optimisation on the Horizon project, and the design simplifications approved for the EPR2 design are also a good illustration (see Box 11). These examples show that stringent regulation does not necessarily imply higher costs when safety efforts are more focused and regulatory interactions permit some flexibility while satisfying the interests of both parties. Early engagement with regulators is essential.
- Avoiding misinterpretation and fostering the clear and transparent communication of requirements. Poorly interpreted requirements may lead to a lack of focus and additional efforts with limited added safety. This is even more important if the requirements are new and are imposed once construction has begun.

- Aligning regulator and licensee objectives and outcomes. Gaining design acceptability is an important objective, but so is the construction of a safe, secure, environmentally acceptable and affordable reactor. Regulators can establish these conditions, but licensees should also be proactive and work closely with regulators in developing clear safety cases and fixing potential shortfalls.

Governments also have a key role in establishing such a regulatory framework. They are responsible for setting regulator missions and objectives, while at the same time providing the means necessary to guarantee the independence and transparency of regulatory decisions (NEA, 2011). In the United Kingdom, the ONR's quest to better understand the economic costs of regulation is framed by the national Better Regulation initiative (ONR, 2019). This initiative requires the evaluation of business impact targets (BITs) to determine the financial impact that qualifying regulatory provisions have on business (in this case, the nuclear industry). National missions may also seek to limit potential distortions of the ALARA/P principle towards "zero-risk" approaches that may not maximise benefits for the whole society.

Finally, the innovative organisational modes described in this chapter (digital transformation, knowledge management, lean management, etc.) could also be adopted by regulatory bodies. The quality and efficiency of regulatory activities could thus be improved, resulting in lower costs as well as greater safety. An interesting example is the NRC's transformation plan (see NRC, 2019).

Box 16: **Cost optimisation with regulator involvement: The Horizon project**

This case study illustrates the value of securing a design that is ready for construction and has undergone design optimisation prior to the beginning of construction.

From 2012 until January 2019, Hitachi invested in potential UK nuclear new-build projects to deploy twin Advanced Boiling Water Reactor projects at Wylfa in North Wales and at Oldbury on the Severn river. In January 2019, Hitachi decided to "pause" these projects due to the suspension of further investment. The lead project at Wylfa was in an advanced stage of development, with the reactor design having passed the UK Generic Design Assessment (GDA). Ongoing activities at the time of suspension were focused on informing a final investment decision, with the anticipated subsequent construction expected to support commercial operations of the first reactor in the mid-2020s. (The decision to pause this investment is a separate matter outside the scope of this report.)

The 2016 estimate of construction costs for the Wylfa NPP deploying the UK GDA design was evaluated as unaffordable within the project's business case (project economics were determined by revenue from a contract for difference with an expected strike price of around GBP 75 per megawatt hour [/MWh]). The project challenge addressed in this case study reflects the need to reduce construction costs through design optimisation to achieve acceptable construction and operational risks while delivering a viable project business case.

A wide range of potential cost reduction opportunities was identified, including:

- Avoiding unnecessary system and building duplication by deploying an integrated twin unit rather than two single units, as per the GDA evaluation.
- Optimising the plot plan to reduce costs, including by reducing the number and size of support buildings and associated service galleries.
- Modifying engineering solutions to accommodate the hazards and constraints of the specific proposed UK site rather than the generic UK site.
- Employing alternative engineering solutions to mitigate selected natural hazards identified as significant cost drivers by extreme value analysis (e.g. peak maximum ambient temperature).
- Using an alternative approach to characterise the seismic hazard and associated ground motion spectrum.
- Optimising the redundancy and diversity of significant safety systems as necessary to meet the requirements of the safety case.

Box 16: **Cost optimisation with regulator involvement: The Horizon project** *(cont'd)*

The approach for reviewing over 100 potential optimisation opportunities was designed to:

- Provide an understanding of the potential impact on the safety case.
- Describe a set of principles for how to explore these opportunities.
- Maintain the integrity of the GDA as much as possible.
- Minimise deviations from the GDA as much as possible.

This review was implemented from October 2016 in parallel with completion of the GDA, with constructive results:

- A set of "papers of principle" was developed describing how the design optimisation phase would be delivered and how the safety case would be achieved. These papers were to ensure the UK regulators' understanding of the process and approach.
- From the individual opportunities, associated individual engineering propositions to implement the papers of principle were developed and finalised by May 2017.
- A regulatory review of Horizon's proposals was completed by the end of 2017.

Horizon's design optimisation process produced numerous outcomes:

- Regulators were engaged and motivated to support this process at the executive level.
- Regulatory knowledge and experience in general were enhanced by the GDA evaluation of two reactor designs already evaluated for potential UK deployment.
- The process benefitted from the capabilities and experience of both the project team and the regulators.
- Benefits were realised from challenging the initial design assumptions associated with co-locating units on the same site.
- It was discovered that design and regulatory efforts can be reduced by focusing on a specific rather than generic deployment site earlier in the project development process.
- The approach of designing a project to mitigate the impact of natural hazards may often use data from extreme value analysis, but using other approaches may be beneficial when they can be justified.
- Significant savings were successfully realised in the estimated construction cost of a twin-unit ABWR at Wylfa.
- There were indications that further significant cost reductions could be realised if there were a commitment at the outset to four units at the same site – greater savings than for an initial commitment to a twin unit with potential for a second twin unit at the same location.

The design optimisation phase pursued by Horizon realised expected overnight capital cost reductions exceeding 20% for twin-unit ABWR deployment at Wylfa, compared with deploying two units as per the GDA design of the UK ABWR. Horizon's design optimisation phase benefitted from a regulatory engagement process that gave Horizon and its stakeholders confidence that the optimised design for construction was acceptable to safety and environmental regulators. This case study confirms that a period of design optimisation focused on constructability and cost reduction is an important step in the project development process prior to construction commitment. With appropriate regulatory engagement, significant cost savings can be demonstrated through improved engineering without compromising safety and environmental standards.

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5. Long-term opportunities to reduce nuclear construction costs

As described in Chapter 4, countries adopting serial construction in the decade ahead could benefit from lower costs and risks thanks to implementation of a set of incremental improvements such as design optimisation, the adoption of new technologies and better organisational and construction approaches, as well as revisited regulatory interactions. These cost-saving strategies would also help mitigate nuclear risks in several dimensions as will be further detailed in Chapter 6.

In the longer term (beyond 2030), further cost reductions could be unlocked through greater harmonisation and materialisation of the economic case for more disruptive technologies such as small modular reactors (SMRs).[56]

These new opportunities are part of a long-term industrial performance strategy that envisions sustained efforts to activate the various cost reductions drivers and continuously raise the sophistication of products and processes by capitalising on learning acquired in each successive construction. The interplay between the product and the processes enables complementarities and synergies among different technology families. Evidence gathered for this study suggests that long-term cost reductions are achievable and that countries in the most advanced stages of learning are moving towards this direction.

5.1 The role of harmonisation at the industrial and regulatory levels

The concept of harmonisation is intimately related to the standardisation process detailed in Section 4.1.2. In fact, the uniformity sought by standardisation practices is not only limited to design but can be extended to the governance of nuclear activities. Current governing frameworks are essentially country-specific, creating a regulatory heterogeneity that may impact the overall cost of nuclear technology.

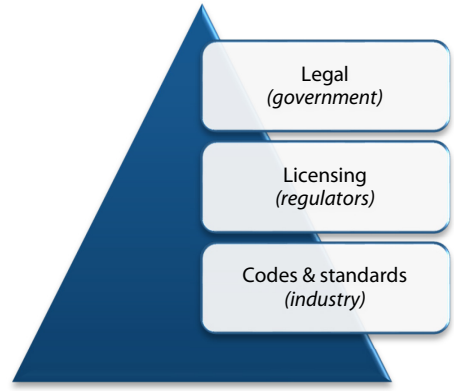
This report considers that harmonisation encompasses all activities and processes that seek to increase the homogenisation and convergence of nuclear rules among countries at three different levels (Figure 33):

- legal (governments);
- licensing and regulatory guidelines (nuclear regulators);
- codes and standards of practices (industry).

Each level is characterised by its own specific challenges and developmental pace, and even though complete harmonisation is unlikely, experience has shown that is possible to achieve consensus in some specific areas, particularly at the regulatory and industrial levels.

56. SMR progress has been significant in recent years, with some developers announcing the first prototypes for before the end of the decade. Nevertheless, recent work suggests that for SMRs to fully yield their expected benefits, several challenges in terms of licensing, harmonisation, technology risks and supply chain development must first be overcome (NEA, 2019). The extent of these challenges could vary depending on the maturity of different concepts (i.e. light water-cooled versus alternative coolants). REDCOST experts recognise that these issues are not likely to be resolved until after 2030.

Figure 33: **Harmonisation levels**



5.1.1 *Licensing regimes*

Licensing regimes set the requirements, guidelines and processes that regulators use to assess safety and certify nuclear designs. At the international level, the International Atomic Energy Agency (IAEA) provides high-level safety standards and recommendations; although they are broadly accepted by most countries, they are not binding (WNA, 2013). Furthermore, their level of detail is low and they are often subjected to interpretation. More comprehensive design, engineering and licensing requirements are therefore needed, resulting in regulatory regimes that tend to vary from country to country.

Areas in which harmonisation is still lacking include the defence-in-depth concept, the principles of diversity and redundancy, physical separation, external hazards (e.g. air-crush protection) and severe accident management. Consequently, vendors must perform design modifications and undergo certification processes for every host country. This situation turns nonrecurring design and licensing efforts into recurring activities and thus hampers nuclear learning in reactor construction abroad. Extra costs incurred by the lack of harmonisation (i.e. adaptation costs) are estimated at approximately 30% of the engineering, procurement and construction (EPC) costs of a generic nuclear power plant (NPP) (see Box 14). This value may vary depending on the extent of the regulatory gap between countries.

Nevertheless, harmonisation at the regulatory level may encounter some obstacles:

- The protection of national sovereignty: While respecting the internationally shared fundamental principles of nuclear safety, some countries may be reluctant to accept certain requirements, as they may not be aligned with their national interests and regulatory practices. Protecting the sovereignty of national regulators is also important to preserve the nuclear industry's social licence to operate in a country and the public's acceptance of regulatory decisions. This aspect inevitably has a strong political dimension and explains why regulatory harmonisation may face greater inertia than similar initiatives at the industrial level.
- Increased stringency: There is also a risk that harmonised regulations, being the sum of the highest expectations in all fields for all countries, may become too stringent and thus more expensive and less practical.

International collaboration therefore remains essential to identify areas of regulatory convergence. Two initiatives lead harmonisation efforts internationally: the Multinational Design Evaluation Programme (MDEP) and Cooperation in Reactor Design Evaluation and Licensing (CORDEL). (The latter is actively building on aircraft industry experience.) As is further detailed in Section 5.2, harmonisation is central to the development of SMRs.

5.1.2 *Codes and standards*

Similar to licensing regimes, nuclear codes and standards may vary from one country to another. Typical national quality standards include the American ASME NQA-1 code,[57] the French RCC-M and RCC-E codes and German KTA standards. Even if a certain level of convergence has been achieved among codes, some differences persist, and different total quality management systems still prevail at the national level.

More importantly, the cost of adopting nuclear standards is quite significant: for instance, it can almost double the cost of an industrial-grade valve (see Figure 28). Most of the cost burden is associated with the establishment of a quality management system (i.e. qualification process). As a result, some companies may be reluctant to qualify their processes, especially if the number of orders is limited, reducing the pool of qualified suppliers available.

In 2010, Bureau Veritas and Framatome (formerly AREVA NP) founded a global initiative, the Nuclear Quality Standard Association (NSQA), to lead harmonisation efforts while strengthening the quality management processes of the nuclear industry. Their efforts resulted in publication of the ISO 19443 in 2018 (ISO, 2018). This standard internationally harmonises the minimum level of requirements, creating a common language that can accelerate the qualification of a global supply chain. To guarantee the success of the ISO 19443 standard, further efforts in the accreditation process and in overseeing implementation may be needed in the near future. It is essential that the nuclear industry manage this process, with the endorsement of the regulatory bodies.

Given the nuclear sector's long time frames, it is difficult to describe with certainty the equilibrium that could be achieved through the combination of modularisation, harmonisation and potential externalisation strategies covered in this report. While modularisation has some limits, improved standardisation and flexible co-operation among different vendors, regulators and suppliers are likely to play significant roles in the future. In some cases, this will require changes to leadership practices and the type of cultural shift that is only possible in the long term. Additionally, the digital transformation is advancing quickly and will certainly reshape the final situation thanks to greater information traceability.

5.2 Construction costs of small modular reactors

The difficulties encountered in large Gen-III nuclear projects in western OECD countries have undermined investor and decision-maker confidence in nuclear energy, particularly in Gen-III designs. Although this report explains how the costs and risks of large contemporary nuclear designs can be reduced, large Gen-III reactors will to some extent continue to be complex, capital-intensive projects with significant labour costs and on-site work. Interest is therefore growing in more evolutionary concepts – "beyond" large Gen-III designs – that incorporate all the learning and techniques of previous projects (largely covered in this study) to yield greater productivity and predictability per unit. This could be the case for the SMR delivery model, for instance.[58]

SMRs have unique key design features that allow them to capitalise more extensively on some of the cost reduction strategies described in this report (Box 17). However, the smaller size of SMRs has a major economic drawback: the inability to benefit from economies of scale. Instead, their economic performance can be improved through series production and higher learning rates thanks to (also see Figure 34):

- Simplification: Passive mechanism improvements and greater design integration would reduce the number of components and result in containment building savings.

57. This standard has been widely adopted as part of the technology transfer agreements signed by American companies with several countries.

58. In this report, the term SMR refers to both light water-cooled and advanced concepts (see Box 17).

- Standardisation: The lower power output of SMRs reduces the need to adapt to local site conditions, raising the level of design standardisation compared with large reactors.
- Modularisation: Smaller SMR size means that transporting their modules would be easier than for large reactors. As illustrated in Figure 32, the degree of modularisation increases considerably for power outputs of less than 500 megawatts of electrical capacity (MW_e). This trend could be improved with more aggressive modularisation techniques tailored to the logistical constrains and transport standards of each country. It is estimated that 60-80% factory fabrication levels are possible for SMRs (with power outputs below 300 MWe) (Lloyd, 2019). This would also facilitate the implementation of advanced manufacturing techniques such as electron beam welding and diode laser cladding by 2025 (EY, 2016). Others, such as powder-metallurgy hot isostatic pressing and additive manufacturing, are at lower technology readiness levels but significant progress is being made (EPRI, 2018).
- Harmonisation: Having access to a global market is necessary to foster series-production economies, but this is possible only with regulatory and industrial harmonisation.

Box 17: **SMR definition, classification and key design features**

SMRs are generally defined as reactors with power outputs of between 10 MW_e and 300 MW_e that integrate higher simplification, modularisation, standardisation and factory-based construction in their design to maximise the economic advantages of series production. The various modules can be transported and assembled on-site, with the shorter lead times enhancing construction predictability and savings.

SMR designs can be classified in a number of ways (NEA, 2011), as they involve a variety of coolants and fuel arrangements at different technology readiness levels (TRLs) and licensing readiness levels (LRLs):

- Light-water (LW)-cooled SMRs: Some vendors are using the well-stablished LW-cooled technology to propose Gen-III designs with unique features thanks to the lower power output.
- Generation-IV or advanced SMRs: Some SMRs integrate alternative coolants (other than light or heavy water) and fuel arrangements into their designs, producing more revolutionary concepts. They are essentially based on the six systems selected by the Generation IV International Forum (GIF) in 2000[59] and could also offer additional economic advantages thanks to higher outlet temperatures, among other qualities. Advanced materials and their qualification are key research and collaboration areas.
- Micro Modular Reactors (MMRs): More recently, smaller concepts of less than 10 MW_e have been proposed. They are capable of semi-autonomous operation and have improved transportability compared to other SMR concepts. They involve a wide range of technological approaches including Gen-IV systems and even heat pipes.[60]

Around 50 SMR concepts were under development in 2018: 50% LW SMRs and the other 50% Gen-IV (IAEA, 2018). The LW SMRs are at a higher TRL, as they take advantage of experience accumulated with the existing fleet of water-cooled reactors and therefore encounter fewer regulatory uncertainties. It is important to mention that while the term SMR has been adopted around the world to refer to all small reactor designs, there are significant differences among the major types, particularly in their degree of modularity.

59. Sodium-cooled fast reactor (SFR); very-high-temperature reactor (VHTR); supercritical water-cooled reactor (SCWR); molten salt reactor (MSR); lead-cooled fast reactor (LFR); and gas-cooled fast reactor (GFR).
60. Heat-transfer devices that combine the principles of both thermal conductivity and phase transition to effectively transfer heat between two solid interfaces. They are extremely simple, as the coolant flows by means of capillary action, centrifugal force or gravity within the tube. They are also being tested in experimental nuclear-propulsion aerospace applications (NASA, 2018).

Box 17: **SMR definition, classification and key design features** *(cont'd)*

Although simplification, modularisation and standardisation were described in Chapter 4 as potential strategies to reduce the costs of large projects, the size of Gen-III reactors, and the layering of their auxiliary systems impose several design constraints that may limit the applicability of these approaches. The impact of size is particularly acute for simplification and modularisation, but small nuclear cores have advantageous features that counteract these technical limitations (Ingersoll, 2009):

- Enhanced passive or gravity-driven mechanisms: The lower power output and higher surface-to-volume ratio offered by smaller cores increases the efficiency of passive safety systems for both normal and off-normal operating conditions. Many LW SMR designs have a very large water capacity to cool reactor systems even under extreme circumstances.
- Integral designs: An integral system incorporates all the components of the nuclear steam supply system (NSSS) into a single vessel. This is viable with small cores, as otherwise the size of the vessel would be prohibitively large.
- Reduced inventories: The total quantity of radionuclides that could be potentially dispersed in accidental conditions – referred to as the source term – is roughly proportional to the power level. Smaller inventories may enable reduced shielding in various systems and components, thus simplifying the design. Smaller inventories may also permit emergency planning zones (EPZs) to be smaller, which would increase siting flexibility.

SMR features also allow for below-grade siting, providing more protection from natural (e.g. seismic or tsunami, depending on the location) or man-made (e.g. aircraft-impact) hazards.

Nevertheless, regulator experience with some of these new design features may be limited. These innovations may also introduce new safety issues that will have to be assessed in more detail. Regulatory uncertainty is even higher with Gen-IV designs, as current licensing regimes may require some adjustments.

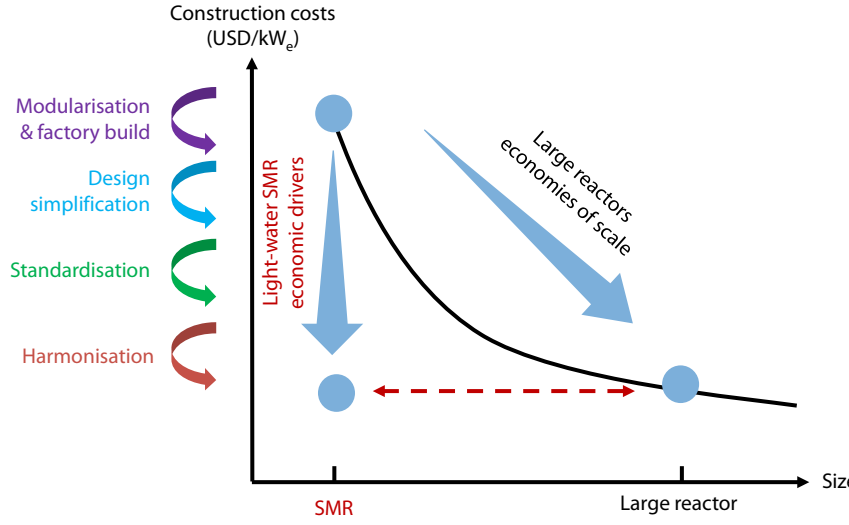
The cost reduction potential of these drivers for large reactors has already been covered in this report. In fact, SMRs (like any new nuclear product) can follow the same learning curve as the one illustrated in Figure 17 and may exploit the same cost reduction approaches. However, the series effect, simplification, standardisation, modularisation and harmonisation will carry more relative importance in order to counterbalance the lack of economies of scale compared to contemporary large reactors. The potential of these strategies to reduce costs has been well documented in other industries, such as shipbuilding and the aircraft industry, in which serial manufacturing has produced learning rates of 10-20% (NNL, 2014). Nevertheless, these practices still need to be proven for SMRs.

Furthermore, the timely deployment of this technology will also require new licensing regimes. Current licensing frameworks typically rely on an extensive experience base with large single-unit LW reactors and proposed LW-based SMRs have similar operating conditions and fuel arrangements, which should facilitate licensing. However, limited experience with these novel designs poses challenges in demonstrating and approving their safety case. Moreover, the introduction of alternative fuels and/or coolants (i.e. Gen-IV SMRs) will translate into greater deviations from previous regulatory paradigms and may require more flexible licensing approaches (Sainati, Locatelli and Brookes, 2015).

Consequently, attaining economic benefits for SMRs will require a co-ordinated effort by the various stakeholders, a dedicated policy and regulatory framework and, most importantly, a global market. Regulators will therefore need to determine how they can work together to devise more streamlined and harmonised regulatory frameworks to create a true global SMR market; experience gained through initiatives such as the MDEP, CORDEL and NSQA could prove useful in this process. It is also imperative to appropriately estimate the size of this market to establish a robust supply chain (i.e. key partnerships) and sustainable construction know-how that results in competitive capital costs (Lyons, 2020).

Finally, it is important to note that, beyond the potential cost savings described above, SMRs also offer a different value proposition in terms of financing, ancillary services, and off-grid and non-electric applications that could also improve their economic performance (NEA, 2019). Unfortunately, these prospects are outside the scope of this study.

Figure 34: **SMR economic drivers that help compensate for diseconomies of scale**



5.3 Long-term industrial performance and design development

Previous sections of this report address numerous construction cost reduction opportunities for nuclear systems in several areas (i.e. technology, organisation, regulatory) that allow for the main underlying risks to be contained and even mitigated. They tackle both direct and – more importantly – indirect costs, the latter being determined by governance, including project management.

Specific recognition has been given to the dichotomy between product (i.e. design) and process, in light of strong evidence that rising nuclear construction costs have consisted largely of indirect costs in the past ten years (see Figure 12). Delivery processes therefore warrant special attention.

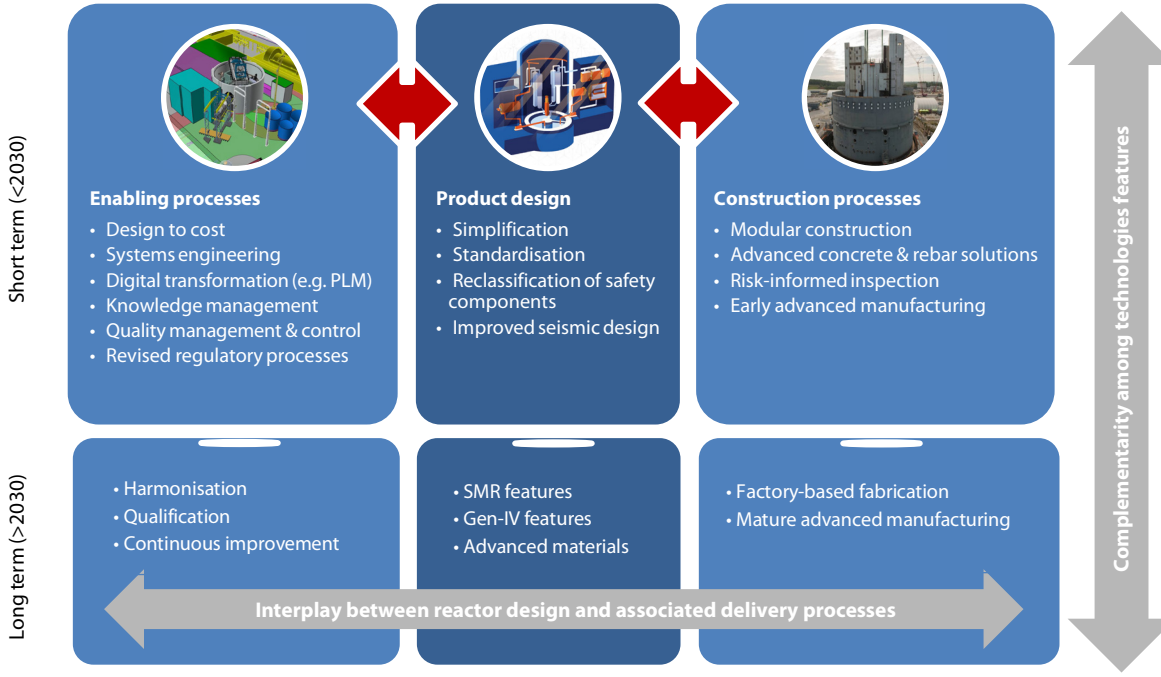
Projects are one-off temporary endeavours that aim to complete a number of tasks on time and on budget, to meet the expected requirements. Once they are completed, the project teams simply leave, taking their valuable experience with them most of the time. Conversely, *products* do not have an end date but a lifecycle and they are designed to create value and satisfy customer needs which may evolve over time. Consequently, products are more *permanent* compared to projects and require multidisciplinary teams to continuously integrate improvements and adaptations to customer specifications. They incorporate product-oriented "enabling" processes that foster the sophistication of the product, as well as of the associated fabrication/construction processes for their successful delivery. The various nuclear construction cost reduction drivers, with their potential timelines, can be categorised according to this framework (Figure 40).

The nuclear industry's long-term economic performance can be achieved through constant mobilisation of the various cost reduction enablers presented in Chapter 3, continuously improving designs by capitalising on learning gained from replications and new projects. However, the number of project orders must be large enough to drive continuous learning. Furthermore, the elements driving cost savings result from the interplay between design optimisation approaches and the enabling construction processes. This interplay is key, as the boundaries between product and process are sometimes blurred. For instance, modularisation is a construction process that also requires significant work in the design phase. Similarly,

standardisation is not limited to the design phase but can be also interpreted as an enabling process, accelerating transactions with the supply chain.

At the same time, the product-oriented framework presented in Figure 35 is compatible with the development of different families of products (i.e. a product portfolio) at various maturity, growth and market share levels. It is therefore possible to create an optimised product portfolio wherein complementarities and synergies among products and processes can be explored. For instance, a mature product with well-established market shares could support other products that are at earlier stages of development and facing more risks.

Figure 35: **Cost reduction as interplay between product and process**



This approach is particularly interesting for SMR technology, as it involves numerous concepts at different TRLs and LRLs. Due to their innovative nature, SMRs may introduce additional technology and supply chain risks that do not necessarily exist with current large LW reactor designs.[61] To be credible options by the early 2030s, prototypes and demonstration units will be needed to prove the announced benefits of SMRs. From a cost perspective, these technologies should follow the same learning curve illustrated in Chapter 3, but the various cost reduction drivers will not carry the same weight (see Section 5.2).

Moreover, several learning factors, such as project management, construction advances and innovative organisational processes, are not technology-specific, meaning that SMRs should also benefit from progress made with large NPPs in the 2020s. This illustrates the complementarity between both technology families, with the next large Gen-III nuclear constructions playing an important role in the future success of SMRs.

61. LW rector-based SMRs incorporate non-traditional components such as helical coil steam generators, internal control rod drive mechanisms or new in-vessel instrumentation for which operational experience is limited. Plus, Generation-IV SMRs will include features that have never been tested before. Pilot facilities could help demonstrate these features and introduce the new technologies to the market, which is consistent with historical experience (NEA, 2019).

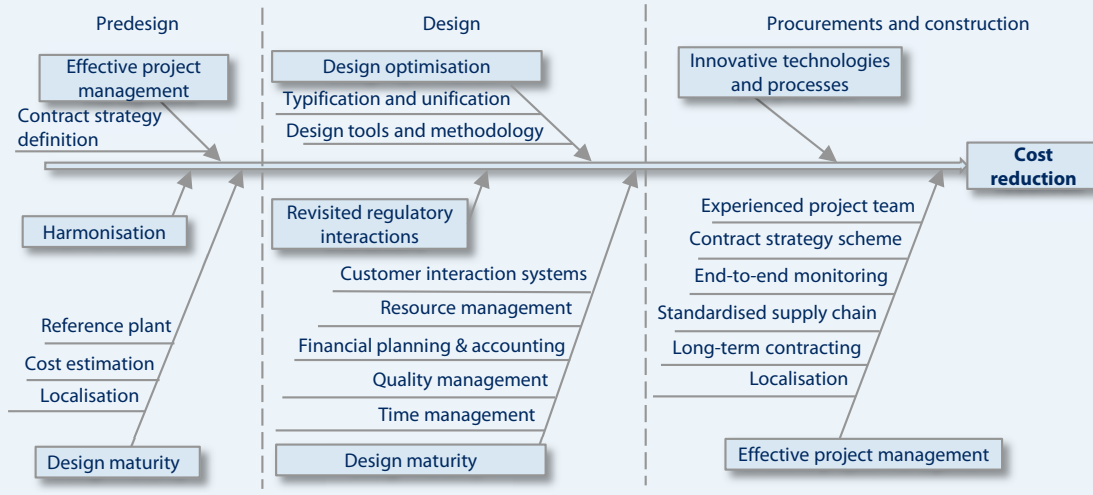
Countries at more advanced stages of nuclear construction learning are already working at continuously improving and optimising their product portfolios similarly to other sectors, Russia being a prime example (Box 18).

Box 18: Russia's long-term industrial performance and product design development

According to preliminary data from the forthcoming IEA/NEA *Projected Costs of Generating Electricity* 2020 report, the overnight costs of new nuclear construction in Russia are 54% below the OECD average. In fact, having accumulated more than 30 projects at home and abroad, Russia is already benefitting from a long-term industrial strategy. Stimulated by a constant inflow of projects, Rosatom, the state-owned company in charge of designing and constructing nuclear reactors, is leveraging experience from previous and ongoing projects to continuously refine its products and processes and drive down nuclear costs. Its long-term industrial strategy (Figure 36) provides insight into how, with a sufficient level of experience, the cost reduction opportunities explored in this report can be adopted at the various project stages:

- Pre-design: During this phase the first cost estimates are performed and the contract strategy is defined. The availability of a reference plant facilitates this process and increases the accuracy of the estimates. Localisation opportunities could be exploited, especially for commodities and non-safety-related equipment. Any progress in regulatory or industrial harmonisation should already be identified in this phase to minimise qualification and engineering work.
- Design: Based on the maturity of the design, sound quality control systems for design documentation as well as real-time time and resource management systems can be developed and supported by more advanced digital solutions. At the same time, design optimisations can be performed, in accordance with the desired cost target and by means of new design tools and methodologies, to streamline engineering efforts while increasing standardisation and reducing the risk that reworks will be required.
- Procurement and construction: Execution of the contract strategy could benefit from effective project management with experienced teams, and a standardised supply chain built on long-term contracting schemes while exploring localisation opportunities when possible. In this phase, several technical construction advances and innovative processes can be implemented to increase productivity, facilitate quick decision-making and ensure end-to-end monitoring and analysis of the execution of supply contracts and construction/installation works.

Figure 36: **Long-term industrial performance fishbone diagram**



Box 18: **Russia's long-term industrial performance and product design development** *(cont'd)*

Rosatom is using the experience it has gained with Gen-III large reactors and civil marine nuclear propulsion to develop other products. In December 2019, the floating Akademik Lomonosov SMR was connected to the grid. It is based on the LW-cooled KLT-40S concept, from the RITM reactors series (i.e. Russian civil marine nuclear propulsion reactors).[62] Six units of a new evolutionary concept, the RITM-200, have already been manufactured and installed in several icebreakers (Moskvin, 2019), and Rosatom is planning to extend this technology to land-based industrial applications. Two sites are being considered, with works to start by 2024 (NucNet, 2020b). This reflects Rosatom's strong product-oriented and long-term industrial vision in developing nuclear technology.

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62. Other concepts from the RITM reactor series are being operated in a lighter-aboard ship (KLT-40) and two icebreakers (KLT-40M).

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Part 3: Policy frameworks to deliver competitive nuclear projects, and policy recommendations

The overall nuclear policy framework is central to implementation of the construction cost reduction strategies identified in Part 2. Part 3 therefore addresses the key areas in which governments can support the delivery of future nuclear new-build projects, with Chapter 6 devoted to the financing framework and Chapter 7 offering key policy recommendations.

As already emphasised, financial costs are a central area for cost reductions, as they can make up more than 80% of capital costs. Having access to affordable financing therefore has a first-order impact on the levelised cost of electricity (LCOE) from nuclear power. The cost of capital is primarily driven by the risk premium expected by investors, which reflects the allocation of construction and market risks.

Today, the cashflow structure of nuclear projects, the associated perceived risks (founded largely on the recent poor construction performance record) and current electricity market conditions provide clear rationale for state commitment, regulation and, most likely, transitional financing in the early stages of the learning process. State financing can be provided in various forms: direct (i.e. equity, debt); indirect (market regulation, guarantees); or a combination of both. Financial support from foreign governments (e.g. through export credit agencies) could also have a positive impact.

While this government role in financing is particularly important for restarting nuclear programmes, it should be viewed as transitional, as industry maturity will reduce both risks and costs.

In best-performing countries, governments lead the nuclear construction programmes. They absorb the residual risks and provide positive and long-standing policy signals as well as the timely decision-making necessary for adequate industrial planning and optimisation. A nuclear power programme must be seen as a social contract among policymakers, industry and society, the primary beneficiaries of successful project delivery.

6. The role of financing frameworks to deliver cost-competitive nuclear new-build

As discussed in Chapter 2, the high fixed costs, low variable costs and 60-year operating lifetime of Gen-III nuclear reactors mean that the cost of capital has a first-order impact on the levelised cost of nuclear energy.

The cost of capital is determined primarily by the risk premium expected by investors, which reflects the allocation of construction and market risks. Today, the track record of delays and costs overruns for recent first-of-a-kind (FOAK) projects has heightened investors' risk perception and further policy interventions may be warranted to effectively allocate and mitigate these risks. This chapter outlines how to assess and allocate risks, particularly for post-FOAK projects, and discusses the support policies governments can implement.

The scale of these challenges means that cost and revenue risks may be considered more important for investment decisions than the cost estimates. Consequently, the core issue of "financing challenges" is not the financing *per se*, but rather the effective allocation and mitigation of risks, which will be reflected to a large extent in the financing conditions of the project.

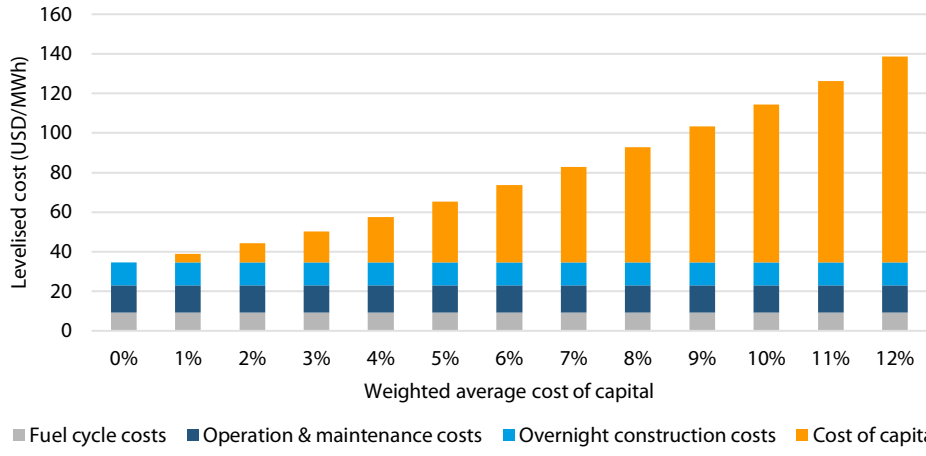
6.1 Financing conditions and nuclear power cost-competitiveness

Financing conditions directly affect the levelised cost of electricity (LCOE) and therefore the competitiveness of new nuclear construction. These conditions are strongly influenced by both the nature of the risks (with higher risks leading to a higher expected rate of return on investment, and therefore a higher cost of capital) and the organisational and ownership arrangements that allocate risks among stakeholders. Policy intervention plays a central role, as governments may decide to directly or indirectly carry a certain share of the risk. As discussed in Section 6.3.3., this can be arranged as part of policies to establish the conditions for developing low-carbon technologies, to ensure security of supply, or to correct for market failures. Strategies can also be introduced to transfer some of the risk to the final consumer.

Figure 37 illustrates the impact of the cost of capital on the LCOE of nuclear power: a 6 to 9% increase in the nominal weighted average cost of capital (WACC) raises the levelised cost by 50% in a reference scenario with an overnight cost of USD 4 500 per kW_e and a lead time of seven years. Reducing the nominal WACC to 5-6% would be in line with the social discount rates typically used to assess public investments, such as infrastructure projects (NAO, 2017). Assuming a 2.5% inflation rate, this equates to a 3.5% real WACC – in line with normative estimates of the social discount rate (see footnote 68).

At a holistic level, however, it is important not to consider financing conditions per se as a lever to reduce the cost of nuclear power, as they simply reflect the underlying industrial organisation and government/public participation choices that designate risk allocation and mitigation. The financing framework is therefore defined by the organisational and ownership structures at the project level, as well as by the national and international contexts that determine the available sources of financing. For this reason, the overall policy framework should especially be considered, as government intervention can play a significant part in carrying and mitigating some of the risks associated with nuclear construction, as well as in addressing the higher risk perception associated with recent FOAK projects.

Figure 37: **LCOE of a new nuclear power plant project according to the cost of capital**



Note: MWh = megawatt hour. Calculations based on OCC of USD 4 500 per kilowatt of electrical capacity (/kWe), a load factor of 85%, 60-year lifetime and 7-year construction time

Box 19: **Addressing risk perception for nuclear new-build projects**

The recent delays and cost overruns of nuclear new-build projects have raised risk perception for potential investors, but also for society as a whole. This directly affects risk premiums and, therefore, the cost of financing.

Furthermore, the higher cost of financing resulting from greater risk perception can further reinforce the perception of nuclear construction risks for future projects, creating a cycle in which nuclear technology competitiveness is hindered well into the future.

Addressing risk perception requires, first and foremost, effective mitigation of construction risks by delivering upcoming new-build post-FOAK projects without significant delays or cost increases. At the same time, government commitment, regulation and financial support (at least transitional) are essential to attract private investment in long-lived assets such as nuclear power plants (NPPs).

Lastly, greater engagement between nuclear new-build developers and the financial sector can further mitigate the misperception of risk. This is especially important in the early developmental stage to put the project on the right track, especially for reputational risks, which are hard to quantify.

6.2 Construction risks: Allocation and mitigation priorities

Identifying and addressing risks during construction is standard procedure in the process of financing infrastructure projects.

A variety of risks from project planning through execution can impact new nuclear plants and directly or indirectly lead to construction costs overruns. Indeed, understanding and appraising these risks is often a key factor in investment decisions, more important than cost estimates. Today, the track record of recent FOAK projects and the broader specificities of nuclear projects are making this assessment particularly sensitive.

The sensitivity of nuclear projects arises from a combination of factors: the scale of investments; the long lead times; and the complexity of the decision-making process involving multiple interested stakeholders. It is therefore critical to address risks – particularly construction risks – early in the development phase, with all the relevant stakeholders, to support a robust and sound decision-making process as well as address potential risk perception issues.

6.2.1 *Nuclear construction risks and key mitigation priorities*

Construction risks can be divided into three broad categories:

- Technology risks are associated with reactor design, particularly design maturity, but also with the integration of new technologies.
- Organisational risks relate largely to project management but also the capabilities of the supply chain to meet quality assurance standards and to manufacture key components.
- Policy framework risks include policy issues related to safety regulation, the financing framework and political support. These risks need to be considered as early as possible, but some will persist after commissioning.

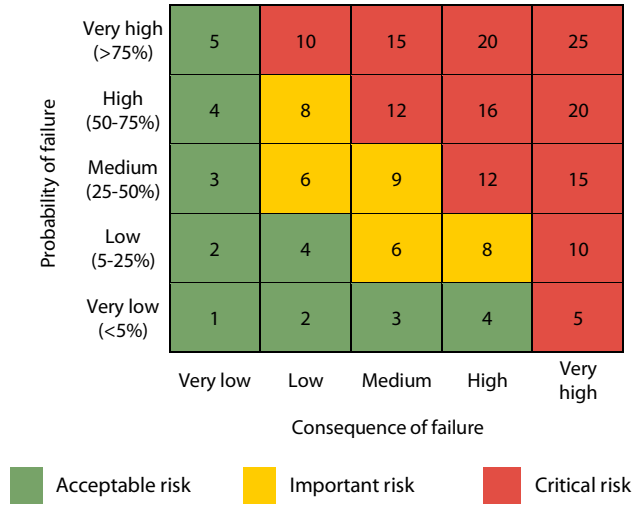
In addition, post-construction risks across the project lifetime will also need to be assessed using the same approach (IAEA, 2017; NEA, 2008). These risks can impact costs and, just as importantly, future revenues:

- Market risks: lack of long-term revenue certainty (prices and quantities), including CO_2 price trajectory (e.g. functioning of carbon markets).
- Operational risks: plant performance, reactor availability, fuel supply.
- Liability risks: insurance and insurability, nuclear liabilities, natural disasters and force-majeure circumstances.
- Waste management and decommissioning risks.

Once identified, the appraisal of these risks typically relies on a well-formalised process wherein each risk is defined in terms of origins, probability of occurrence, and potential consequences. Consequences of construction risks fall primarily into two categories – delays and costs overruns – but non-completion is also possible, particularly if there is a change in political support. Sub-optimal performance once the plant is operating may also be an issue.

The risk assessment process is therefore project-specific and can be summarised in a risk criticality matrix (Figure 38), then integrated into a dedicated document – a project risk register (PRR) – by the developer. This document is central to discussions with key stakeholders, within the industry and at the government level to establish the contractual framework. It is also vital for discussions with the various institutions involved in financing: current/future equity shareholders, debt-provider financial institutions, and guaranteed providers such as export credit agencies (ECAs).

Figure 38: **Illustrative risk criticality matrix**



Risk mitigation priorities will need to be assessed based on the PRR. Affecting this process are the short-term costs reduction opportunities explored in Chapter 3, which are intrinsically linked with risk mitigation priorities for future post-FOAK projects (Table 5). For example, risks related to design could be mitigated largely by starting construction only when a high level of design maturity has been achieved, especially once a reference plant has already been built and licensed by the same regulatory authority. Similarly, project management challenges could be further addressed by using new digital tools such as product lifecycle management (PLM) and systems engineering.

Table 5: **Key risk categories and mitigation priorities**

Risk category		Principal risks	Risk mitigation priorities
Technology risks	**Design**	- Implications of design misspecification: • redesign during construction • licensing amendments • equipment replacement and rework	- Design maturity before start of construction - Early supply chain involvement to integrate requirements - Systems engineering and new digital tools - Reduce rework: better anticipate the impact of design modifications on the rest of the plant - Get it right the first time
	Integration of new technologies	- Impacts on the construction schedule and/or plan due to regulatory approval or constructability issues	- Integrate constructability requirements when considering new technologies - Use proven technologies unless a case can be made for the risks vs. benefits of a new technology - Early supply chain involvement
	Nuclear quality assurance standards	- Challenges for the supply chain to meet nuclear quality assurance standards (including verification/validation) leading to extensive rework	- Near term: oversight during construction and consolidation of the nuclear supply chain - Long term: innovative reactors with simpler nuclear heat supply systems to simplify the safety case and associated quality assurance processes
Organisational risks	**Project management**	- Poor planning/scope definition and division - Inefficient resource allocation - Inefficient oversight and low reactivity to change during construction - Costs overruns and results non-consistent with specifications	- Proactive early supply chain engagement - Delegate authority to project manager for faster on-site decision-making - Procurement strategy incentives - Incentives to increase workforce productivity and encourage on-time completion - Develop a process to encourage adaptability to specification changes - New digital tools: use PLM to improve traceability and knowledge management of requirements and modifications
	Supply chain capabilities	- Lack of manufacturing expertise/knowledge in critical areas - Lack of manufacturing capabilities for large components, leading to bottlenecks	- Long-term nuclear new-build perspective to support supply chain mobilisation - Supply chain co-ordination with vendors at the international level to prevent bottlenecks - Comprehensive knowledge management strategy
Policy framework risks	**Political support**	- Uncertainties regarding the government's position on nuclear: • politicisation of the nuclear agenda • change of government policy	- Establish and maintain broad national and local political consensus on the role of nuclear power - Political leadership to absorb residual risks - Legal and contractual cover for political risks
	Licensing framework	- Unpredictable licensing/regulatory framework - Unstable licensing/regulatory framework	- Outcome-focused dialogue between vendor and regulator to ensure proper interpretation of requirements - Regulator awareness of cost implications for industry and regulator to find best approaches to meet required safety objectives
	Financing	- Unexpected changes in financial conditions (interest rates, taxes, exchange rates) - Insurability of nuclear liabilities according to regime - Unavailability of funding	- Allocation of technological, organisational and governance risks to those best equipped to mitigate them - Legal framework for liabilities - Contract strategy aligned with financier requirements

Reviewing risk mitigation priorities emphasises that near-term technical and organisational construction risks decrease significantly when standardised reactors are built in standardised series using a proven design and supply chain; policy framework risks are also likely to be reduced. However – as the next section highlights – these risks are only partially owned by the industry, with the government playing a central role in their mitigation, especially through providing political support and long-term energy policy and financing frameworks.

6.2.2 *Allocating construction risks among stakeholders*

The general principle for efficiently allocating project risks is to allocate them as much as possible to the stakeholders best placed to mitigate them. The various construction risks are typically allocated to two types of stakeholders: i) the risk owners that have primary risk mitigation responsibility; and ii) other stakeholders of key importance for effective mitigation (Table 6).

Table 6: **Typical stakeholder allocation of key construction risks**

Risk categories		Risk stakeholders							
		Industry				Other stakeholders			
		Plant owner	Vendor	Project team	Supply chain	Government	Society	Safety authority	Financiers
Technological	Design	x	**x**	x					
	Integration of new technologies		x	**x**	x				
	Nuclear quality assurance standards	x	x	**x**	x			x	
Organisational	Project management	x	x	**x**					
	Supply chain capabilities		x	**x**	x	x			
Policy framework	Political support	x				**x**	x		
	Licensing framework	x				**x**	x	x	
	Financing	x				**x**			x

Notes: **x** = primary risk owner; x = other key risk mitigation stakeholders.

For most of the categories, risk allocation is reflected in several complementary contractual arrangements (IAEA, 2017):

- Ownership arrangements: The ownership structure of the future NPP is of critical importance, as it determines the commercial and contractual arrangements of the investment decision. For example, under a state-owned model the government directly finances the project, meaning that it will explicitly or implicitly carry a large share of the project's construction risks.
- Procurement arrangements: Under fixed-cost contracting, risks related to supply chain capabilities tend to be allocated at the level of the supply chain. As highlighted in the discussion on recent FOAK projects in Chapter 3, issues may also arise when contracts are incomplete and can trigger a lack of risk allocation certainty. This can lead to litigations, resulting in additional costs and delays.

- Financial arrangements: Certain "pure" financial risks, such as exchange-rate variation, can be addressed through financial instruments applied at the level of international financial markets. These includes financial products to mitigate changes in commodity prices or the foreign exchange rates.

In addition, it is noteworthy that technological and organisational risks tend to be owned by different stakeholders than policy framework-related risks.

Technology and organisational risks should generally be allocated within the nuclear industry, which includes the plant owner, the vendor, the project team and the supply chain as a whole. However, outcomes may often not be determined by a single company but by a concerted effort across the industry. For example, project management-related risks may primarily be the responsibility of the project team, but the interconnectedness of these activities means that the actions of the rest of the industry also affect the project. In addition, allocating part of these risks to the rest of the industry through incentive contracting can further support the concerted mitigation efforts needed. As highlighted in Chapter 3, incentives must be designed such that each contractor, and potentially each subcontractor, does not assume large risk margins, as this would raise overall costs.

Risks related to the policy framework will tend to be owned by the plant owner but will often be shared with the government. Again, this may vary from project to project: for instance, in the Hinkley Point C (HPC), specific contractual clauses were introduced in case policy changes affected the contract-for-difference mechanism. More generally, governments can support nuclear project financing through direct equity stakes, loans or loan guarantees. Similarly, licensing framework-related risks remain primarily with the industry (the plant owner or vendor), but – as highlighted in Chapter 4 – also benefit from co-ordinated efforts with the regulatory authority as well as the government to set up a framework that provides sufficient predictability and stability.

In parallel, governments should also be involved in market risk mitigation, particularly in liberalised electricity markets, to support long-term price signals.

Hence, beyond the specificities of each nuclear project, the efficient allocation and mitigation of policy-related risks generally requires close co-ordination between industry and the state.

6.3 Nuclear new-build financing frameworks

6.3.1 The specifics of financing nuclear projects

As highlighted in the previous section, risk identification and assessment underpins the financing framework. This mainly involves construction risks, but must also include risks once the plant is in operation as well as long-term liabilities.

Nuclear new-build projects are similar to other large infrastructure projects in that the scale, complexity and importance of political factors and social acceptance can significantly impact financing decisions. Nevertheless, nuclear projects also have a number of specific features that can reinforce these challenges (Pehuet Lucet, 2015).

First, private financial institutions such as equity funds have a limited credit time horizon (Offer, 2018), as they remain reluctant to invest in long-lived assets because policy uncertainty increases significantly beyond 10-15 years, rapidly raising risk premiums. In addition, new banking regulations were introduced following the 2008 financial crisis, requiring that banks improve their solvency ratios to comply with Basel-III regulations. These rules indirectly affect bank funding availability for long-lived assets such as nuclear projects, particularly because they are now required to put aside a percentage of equity as soon as they commit to lend money. Because these commitments prevent them from entering into other engagements during the tendering period, banks are less inclined today to finance long-term capital-intensive projects such as new NPPs.

Second, nuclear projects must comply with specific regulatory frameworks for safety and non-proliferation across the project lifecycle. This includes several layers of national and international norms and rules, such as IAEA guidelines, international treaties and conventions, and industry standards.

Third, in addition to general risk reviews, specific requirements have been added in the past two decades regarding environmental and social issues. Managing environmental and social risks has become a stringent obligation. The International Finance Corporation (IFC) Sustainability Framework and the Equator Principles (EPs) framework set the standards and references for addressing environmental and social risks in infrastructure projects.

All nuclear projects financed through international financial institutions are now governed by the EPs. This requires that they perform environmental and social-specific risk assessments, formulate action plans and report according to the EPs guidelines, through their lead bank.

6.3.2 *Ownership structures*

As explained above, the ownership structure of a nuclear new-build project is central to the series of contractual arrangements that underpin risk allocation and drive financing decisions. Three broad models are traditionally considered:

- Sovereign model: The state funds the project, either directly through the state budget or via public borrowing. This model implies that taxpayers carry the project risks unless they are explicitly transferred to consumers. Countries with low sovereign risk will be able to provide advantageous financial conditions, including for international projects, as projects can benefit from the state's credit rating.
- (Private) corporate model: Utilities with strong balance sheets can finance large projects by raising equity and borrowing money (debt); creditors may claim the loan against the company's overall assets. While the advantage of this financing model is its simplicity, it is also expensive and is accessible only to a handful of large corporations.
- Project-finance model: Project investment is financed through a combination of debt and equity as in the corporate-based model, but a project company is created to establish a legal separation from the sponsors' other assets. Hence, lenders have limited recourse beyond the revenues and/or assets of the project. As the debt remains in the project company, it does not appear on the investor's balance sheet.

In practice, these approaches are neither definitive nor exclusive. Ownership structures include hybrid formats that combine the attributes of the different approaches and/or complement them with specific support mechanisms that further shift risk to a specific stakeholder. The choice of structure is based largely on the project's economic environment, with the degree of electricity market unbundling and liberalisation particularly affecting interest in developing project finance. Similarly, competition rules may hamper the ability of the state to directly own and finance a nuclear project under a sovereign structure, at least without counterparties. Finally, interest in shifting risk from the investors to other parties can also be a strong determinant of project financing.

Table 7 summarises the financing models as well as market and construction risk allocation for selected Gen-III nuclear projects, revealing a number of important findings.

First, in recent years corporate finance has been implemented only for large (monopolistic) nuclear utilities in countries such as France and Korea.[63] In the rest of the world, project finance is the dominant approach. A notable exception is Finland, where the Olkiluoto 3 project was financed through a hybrid co-operative model (the Mankala model) with a pool of energy-intensive industries.

63. This also applies to Russia, which is not represented in Table 7.

Second, almost all nuclear new-build projects require some mechanisms – either contractual or regulatory – to allocate market risks to the final consumers. For instance, recent projects in the United States are eligible for a nuclear production tax credit from the federal government as part of the 2005 Energy Policy Act, effectively transferring market risks to taxpayers. Flamanville 3 is the only project financed without the explicit transfer of risks to consumers or taxpayers.

Third, there is more variability in the allocation of construction risks. Utilities, developers and vendors have accepted to carry part – and sometimes all – of the construction risks for a number of projects. Only projects located in countries or states with regulated electricity markets have allocated construction risks to final consumers[64]. In addition, when construction risks have been allocated to the industry, this has been driven by a range of considerations beyond the scope of the project. Eagerness to benefit from first-mover advantages in the nuclear new-build market was a particularly important stimulus for several projects prior to the Fukushima Daiichi nuclear accident.

Table 7: **Financing structures and market and construction risk allocation for recent nuclear new-build projects**

	Status	FOAK	Structure of financing			Allocation of market risks			Allocation of construction risks			Debt guarantee
			Corporate finance	Project finance	Hybrid model	Consumers	Taxpayers	Utility	Consumers	Utility/developer	Vendor	
Olkiluoto 3	Under construction	Yes			x	O				O	C	French ECA
Flamanville 3	Under construction	Yes	x					O		O	C	None
Taishan 1&2	In operation	Yes		x		R			R*			None
Vogtle 3&4	Under construction	Yes		x		R	R		R		C	US federal guarantee
VC Summer 2&3	Cancelled during construction	Yes		x		R	R		R		C	US federal guarantee
South Texas 3&4	Cancelled before construction start	Yes		x		C				O	C	None
Hinkley Point C	Under construction	Yes		x		C				O		UK government
Wylfa Newydd	Suspended before construction start	Yes		x		C				O		Japanese ECA
Akkuyu 1&2	Under construction	No		x		C				C**		None
Shin Kori 3&4	In operation	Yes	x			R			R			None
Barakah 1-4	Under construction	No		x		C					C	Korean ECA

* Set after commissioning. ** Build-own-operate (BOO) model.

Notes: O = Ownership; C = Contract; R = Regulation; ECA = Export credit agency.

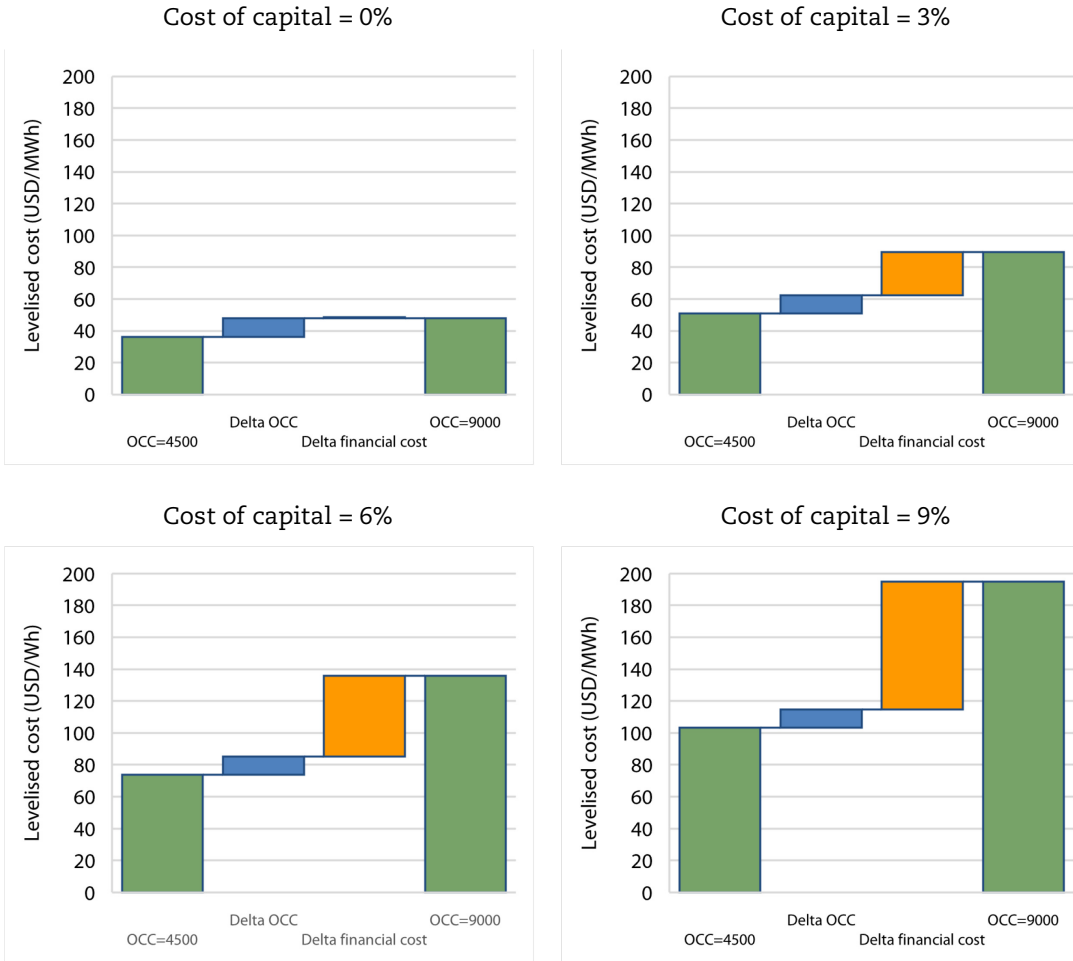
64. In practice, national or state power sector regulators may decide that some costs are not deemed reasonable and prevent the utility from passing these costs on to the final consumer. This is typically the case for US states with regulated power sectors. In addition, some residual construction risks – typically in case of bankruptcy – can also be explicitly borne by taxpayers through loan guarantee schemes. This has applied to projects in regulated markets but also in the United Kingdom.

Today, the allocation of construction risks to industry participants is at the root of the high risk premium expected by private investors, and therefore of the cost of capital. This is best illustrated by the HPC project, for which the WACC was estimated at around 9% – well above the 6% return required by the UK government for public infrastructure projects (NAO, 2018).

More generally, Figure 39 illustrates LCOE sensitivity to a doubling of overnight construction costs (OCC) for different costs of capital, from a reference point of USD 4 500/kW$_e$ to USD 9 000/kW$_e$.[65] Similar to the direct impact of the cost of capital on the LCOE (presented in detailed in Figure 37), most of the cost increase originates from the indirect rise in financial cost that – even at a relatively low 3% cost of capital – represents USD 15.6/MWh, or 57% of the cost increase. For a cost of capital of 9%, the additional financial cost rises sharply to USD 104/MWh, which represents 90% of the cost increase.

In other words, the effect of a construction cost overrun on the LCOE is dominated by an indirect impact on financial costs, especially for relatively high costs of capital. From a public policy perspective, it would be of considerable social benefit for the government to allocate part of the construction risk to other parties, in particular consumers and/or taxpayers.

Figure 39: **LCOE sensitivity to the cost of capital and overnight construction costs**



65. An OCC of USD 9 000/kW$_e$ is in line with the highest ex-post OCC for recent FOAK projects in OECD countries (see Table 1).

6.3.3 *Government financial support*

From the outset, government commitment and political consensus to incorporate nuclear in a long-term energy strategy is a prerequisite for any nuclear new-build project. Government involvement will also be central to establish an effective regulatory framework for licensing of the reactor, and to secure social licence to operate from the society.

A core goal of government support is therefore to create conditions conducive to successful industry performance. This builds on the standard principles of sound public governance for public-private partnerships to establish a framework that continues to incentivise cost reductions and limits the risk of cost overruns.[66]

In addition, considering the various ownership structures, a government can support financing directly or indirectly. Government support is primarily motivated by positive nuclear power externalities and electricity market failures, as well as broader macroeconomic considerations.

First, the positive externalities of nuclear energy require that government intervention be adequately valued[67]. For the energy sector, this includes the contribution of nuclear power to energy security (NEA, 2011), energy diversification, and climate change mitigation (IEA, 2016). Furthermore, nuclear programmes can create macroeconomic benefits for the economy as a whole (NEA, 2018), particularly in terms of industrial development, research and development (R&D) spillovers, and the high level of training and expertise of its workforce. Given the nature and diversity of these positive externalities, the government is often best placed to properly value and internalise these benefits.

Second, the willingness of OECD countries to liberalise electricity markets during the 1990s represented a shift from the normal regulated environment, in which tariffs are calculated such that investors and utilities recover their costs, including financing. Nuclear energy, along with other low-carbon energies such as hydropower, wind and solar photovoltaic, is a technology whose cost structure is dominated by investments during construction. In the absence of specific incentive policies, these energy production methods are especially exposed to market risks, which raises the cost of financing because private investors require higher risk premiums (Rothwell, 2006). The strong correlation among electricity, gas and CO_2 prices further implies that, compared with combined-cycle gas turbines (CCGTs), NPPs may retain limited option value in private investors' portfolio strategies (Roques et al., 2006).

Third, electricity markets can be subject to specific market failures that hinder investments in long-lived assets such as NPPs. Current electricity market structures in OECD countries in particular have often been initially designed to organise competition among existing assets, rather than to support long-term investments in new capacities (IEA, 2016). Markets may therefore fail to deliver the long-term price signals needed to match the lifetime of nuclear reactors.

Fourth, the current macroeconomic environment, with interest rates persistently low in many OECD countries, is dramatically changing the impact government support schemes can have on the cost of capital. The volume of global private equity has been increasing rapidly in the past decade, exceeding private investment and resulting in a lower cost of equity. However, despite the overall excess of private equity, investors continue to require relatively high risk premiums for investments in infrastructure with time horizons beyond 10-15 years (Newbery

66. See the OECD's *Principles for Public Governance of Public-Private Partnerships*: www.oecd.org/gov/budgeting/oecd-principles-for-public-governance-of-public-private-partnerships.htm.

67. From a more theoretical perspective, the environmental cost-benefit literature examines the normative social discount rate (also referred to as social time preference rate) to assign value to climate change mitigation action. While estimates of the social discount rate continue to be debated, the typical range is 1.4% (Stern Review) to 3/3.5% (W. Nordhaus). For instance, the UK *Green Book* recommends a social discount rate of 1.5-3.5% in real terms (for risk-to-life values) when appraising infrastructure projects. This is consistent with the 6% nominal discount rate used in the UK National Audit Office (NAO, 2018 review of Hinkley Point C, assuming 2.5% inflation: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/685903/The_Green_Book.pdf.

et al., 2019). As part of post-COVID-19 economic recovery policies, there is therefore strong macroeconomic rationale for government policy intervention to steer private capital towards infrastructure assets that would contribute to long-term economic growth.

In this evolving context, governments can encourage better financing conditions through a number of policy support schemes:

- direct government financial support;
- indirect government support through long-term power purchase agreements (PPAs);
- indirect government support through regulated models (e.g. regulated asset base [RAB]).

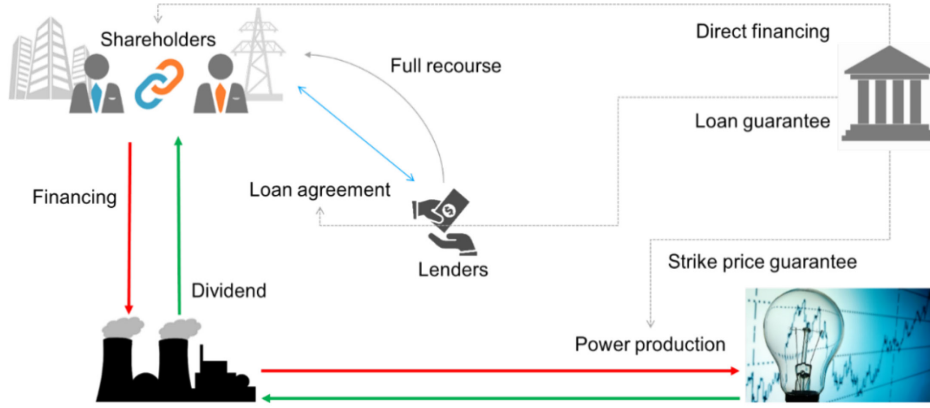
Direct and indirect financial support

Government support for financing can first be provided as part of the ownership structure through an equity stake in the project or public loans. Considering new NPPs as strategic infrastructure projects means that governments will expect a lower rate of return than the private sector, resulting in a lower cost of capital. This is especially the case in today's international financial environment, with macroeconomic shifts having led to historically low – and sometimes negative – borrowing rates for governments.

Additional support from public entities, particularly from ECAs in the vendor's country in the case of an international projects, has proven successful for several projects, including the Angra 3 plant in Brazil, Qinshan I & II in China, and Paks II in Hungary.

ECAs are traditionally national financial organisations set up to promote national exports through trade financing for domestic companies. Their core activity is therefore to provide loan guarantees and insurance, as well as direct loans for overseas projects. In effect, ECAs play a central role in covering political risks, but also contractual risks. In OECD countries, export credits follow specific guidelines (OECD, 2018) that allow ECAs to support up to 85% of the export's contract value, including third-country supply but excluding local costs, with additional specific guidelines for repayment terms and minimal applicable interest rates.

Figure 40: **Direct and indirect government support approaches**



Finally, other indirect financial support can also be envisaged to improve project profitability or reduce investors' risk exposure, such as production tax credits, risk insurance and loan guarantees. Such schemes have typically been used in recent projects such as Vogtle in the United States and HPC in the United Kingdom.

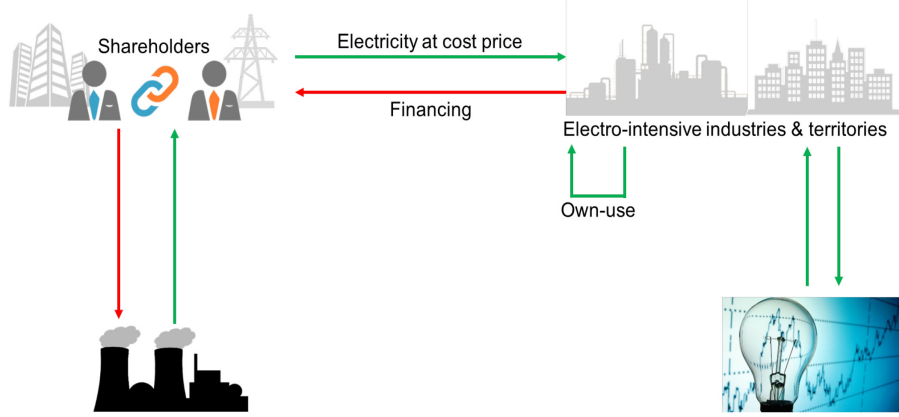
Indirect government support through long-term power purchase agreements

To mitigate market-related risks for investors and provide long-term price signals, PPAs can be established to support the revenue stream. PPAs are often part of corporate and project finance ownership structures and can be contracted with a range of public and private parties.

For instance, the Mankala model has been used for the Olkiluoto 3 project. In Finland, a Mankala company is a limited liability company that sells the produced electricity and heat to shareholders at cost, proportionate to their holdings in the company. Mankala shareholders are usually energy-intensive users (industries and municipal utilities) seeking long-term energy cost stability, and they reduce their individual risk exposure by investing in projects together.

Other corporate PPA models could also be considered, although none have been applied to recent nuclear new-build projects. For example, in France a consortium of energy-intensive users and banks formed a limited liability company (Exeltium) in the early 2000s to finance upfront investments for the long-term operation of the nuclear fleet (Pehuet Lucet, 2015).

Figure 41: **PPA under the Mankala model**



When investment opportunities for energy-intensive users are limited, the government can take action by establishing specific contracts. One option widely used now for renewable energy projects is the contract for difference (CfD). A CfD is as a swap between an agreed fixed price and the wholesale market: the difference between the agreed price in the CfD and the market reference price is paid to the project developer (if positive) or paid by the project developer back into the system (if negative). This approach has been successfully used to address market risks for the HPC project in the United Kingdom.

It is important to stress, however, that the CfD model addresses electricity market risks only, while project developers retain the construction risks. To lower this hurdle, governments can complement the CfD model with state guarantees, as has been done for HPC. Consequently, HPC's WACC is estimated at 9% – higher than the 6% return required by the UK government for public infrastructure projects (NAO, 2018). With a 9% WACC, HPC's strike price is 50% higher than it would be in a scenario with direct or indirect government financing, which would reduce the WACC to 6%.

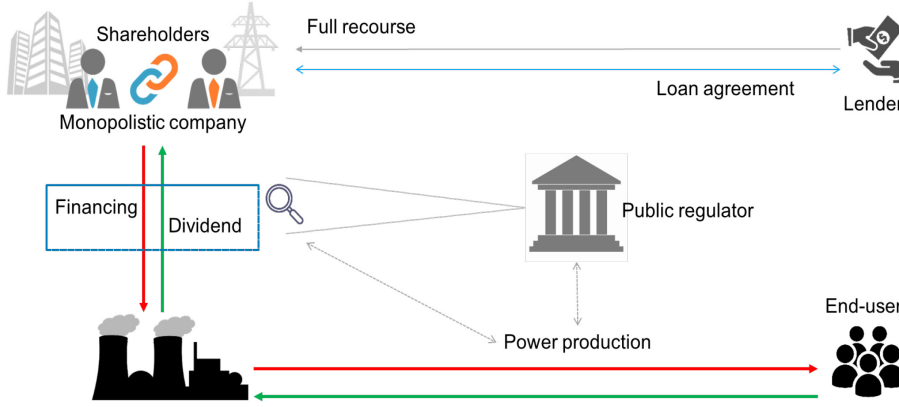
In addition, the role of electricity market reforms to support long-term price signals should not be neglected. Long-term CO_2 price trajectories can especially complement CfDs and PPAs to reduce the expected gap with the wholesale electricity price and strengthen the market framework.

Regulated asset base

The government can also mitigate both construction and market-related risks by considering a nuclear project as a regulated asset. In the United States, several states have maintained vertically integrated utilities in which the regulator can decide whether to integrate nuclear projects as part of the utility's rate base.

Among several rate-of-return regulatory approaches, the RAB model is receiving renewed scrutiny for nuclear new-build projects.[68] It has been widely used in several OECD countries – the United Kingdom in particular – to support and regulate long-lived capital-intensive investments in infrastructure assets. Under the RAB model, an economic regulator sets the end-user price. In some cases the project owner (often a utility) is allowed to adjust the end-user bill during construction to secure a reasonable rate of return. Payments can also be received upfront, reducing interest during construction (IDC).

Figure 42: **Regulated asset base model**



The RAB model can be effective in mitigating construction and market risks by ensuring a return regardless of market conditions. This approach can also designed to avoid some of the drawbacks of standard rate-of-return regulation. Periodical price reviews create an incentive for costs savings and avoid over-investments. Hence, the RAB model aims to optimise risk allocation by balancing the benefits of passing some of the risk of the cost of capital on to consumers with the need for sufficient incentives for the industry to manage and reduce these risks.

The success of this approach will depend on a strong regulatory framework and consistent political leadership to overcome challenges during construction. In particular, the (economic) regulator will need to develop sufficient understanding of the nuclear project to review allowable and disallowable costs. This will be especially important to give the stakeholders involved in project financing confidence in the regulator's decision-making process. Some historical projects in the United States, including the recently cancelled VC Summer project in South Carolina, demonstrate that other rate-of-return regulatory approaches do not always provide sufficient incentives for risk mitigation, in particular for FOAK projects.

Conversely, a key benefit of the RAB model is that transferring construction and market risks to consumers significantly reduces the risk premium expected by investors, especially infrastructure funds and potentially pension funds seeking long-lived assets. In addition, introducing a rate base from the moment a project is approved avoids interest during construction, which further raises project profitability and reduces final consumer costs.

Recent large-scale infrastructure projects illustrate how the RAB model can be successfully implemented to leverage private financing with a low WACC. For example, it is estimated that the Thames Tideway Tunnel in London resulted in a real WACC of 2.5% (Newbery et al., 2019). Important to the success of this project's financing was the provision that part of the costs overruns would be covered by ratepayers (up to 30%), significantly reducing the level of construction risk for investors while maintaining strong incentives for the project developer to mitigate those risks.

68. For instance, see the 2019 UK inquiry regarding the applicability of the RAB model for future projects: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/825119/rab-model-for-nuclear-consultation.pdf.

It is expected that applying a similar RAB arrangement to a nuclear project in the United Kingdom under a CfD approach would reduce the real WACC from 8% to as low as 3.5% (Newbery et al., 2019). Given the importance of the cost of capital on the LCOE of nuclear power, this reduction in the WACC could significantly reduce the levelised cost by about 50%.[69]

6.3.4 *Implications for future projects*

Depending on the national context and project characteristics, several financial models can be considered for future nuclear new-build projects wherein governments actively help mitigate risks and therefore support financing. This is especially possible given the historically low interest rates and relatively abundant private capital in OECD countries that create a unique opportunity to lower the cost of capital if the right policy frameworks are in place to address construction and market risks.

Governments should also consider taking a direct equity stake in new nuclear construction projects, as the public sector has the lowest cost of capital in most OECD countries. Doing so would also enable governments to be more proactively involved in project governance, including in activating its social benefits. It is particularly important for countries considering large nuclear programmes to be aware that as the risk level falls significantly after construction, additional sources of funding should become available, ultimately reducing the government's overall financial burden.

In addition, the role of government in financing is particularly important for countries restarting their nuclear programmes. Government financial support should, however, be viewed as transitional, as industrial maturity will drive down both risks and costs, reducing financial support needs in the long term (Figure 43).

Figure 43: **Positive cost-risk loop for nuclear new-build projects**

As the various policy support schemes highlighted above are not exclusive, combining them can raise the effectiveness of government action by reinforcing certainty in the government's commitment to new NPPs, further mitigating private investor risks. This is essential to attract new sources of financing as part of public-private partnerships, especially for financial institutions – such as pension funds – that may not have specific expertise in infrastructure assets and are seeking long-term investments that match the time horizons of their liabilities.

Finally, beyond measures aimed specifically at supporting financing, electricity market reforms should also not be neglected, as they can be of considerable help in providing long-term price signals, such as for CO_2 price trajectories. Similarly, policies could be designed to incentivise corporate PPAs for large energy-intensive users, as has been done in Finland with the Mankala model.

69. Reducing the real WACC from 8% to 3.5% under the general hypotheses of a GBP 5 000/kW$_e$ OCC, a 10-year construction lead time and 91% availability factor would translate into an LCOE reduction of GBP 100/MWh to GBP 53/MWh (Newbery et al., 2019).

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7. Conclusions and policy recommendations

It is time for action if countries around the world are to meet their policy goals for environmental and energy security. Building new nuclear plants alongside variable renewable energy (from wind and solar photovoltaic) is a path to decarbonisation of the power sector. As the 2019 Nuclear Energy Agency (NEA) report *The Costs of Decarbonisation* explains, nuclear power will become increasingly attractive owing to its attributes as a low-carbon, dispatchable and flexible technology.

Nevertheless, policy makers are rightly concerned about the cost of nuclear new-build projects. In many Organisation for Economic Co-operation and Development (OECD) countries, the construction delays and cost overruns experienced by first-of-a-kind (FOAK) nuclear projects are serious industrial and policy challenges that need to be addressed for subsequent installations. These delays and cost overruns resulted largely from uncertain political contexts and a lack of design maturity that is somewhat inherent to FOAK projects. Overruns consisted primarily of indirect costs, including the nonrecurrent costs associated with deploying a new generation of reactors. Nevertheless, they have undeniably undermined stakeholder and public confidence in the nuclear sector's capacity to successfully deliver new-build projects.

Against this backdrop, this study reviewed the drivers of nuclear construction costs over time and across countries. The conclusion is that the nuclear industry should be well positioned to learn lessons from the recent completion of FOAK Gen-III reactors and could deliver additional construction cost reductions in the 2020s. While these cost reduction opportunities are at the technical and organisational levels, their effectiveness requires a robust governance framework and greater government involvement.

Transitioning from FOAK to rapidly deliver more competitive Gen-III reactors

Several OECD and non-OECD countries have already progressed beyond Gen-III FOAK projects. China and Russia in particular are now both able to focus on continuously improving nuclear industry performance, in a similar manner to other industries. Historical evidence from France, Japan and Korea confirm that with serial construction and industrial standardisation, new nuclear power plants can be delivered at a competitive cost. More importantly, these countries' experiences demonstrate that FOAK project flaws can be corrected in subsequent projects. Even countries with relatively small nuclear programmes (e.g. the United Arab Emirates [UAE]) can achieve better industrial performance when a reference plant has been established and a well-integrated and qualified supply chain can be mobilised.

In this regard, the successful delivery of the next new nuclear construction projects in western OECD countries will be critical to rebuilding public confidence in those countries. At the policy level, design maturity and regulatory stability should be prioritised to support near-term cost reductions.

In the near term (early 2020s), the most effective way to achieve construction cost reductions in countries with a significant need for fleet renewal is to develop a nuclear programme that implements serial construction with multi-unit projects on the same site, and/or serial construction of the same reactor design on several sites. Costs would be reduced significantly through:

- Reducing indirect construction costs related to design documentation, safety approvals associated with the design, and supplier qualification. For multi-unit projects on the same site, additional cost reductions would result from several units sharing nonrecurring, site-specific, regulatory, planning, and supporting infrastructure costs.

- Mobilising the nuclear supply chain as experience is transferred from one project to another, particularly for construction methods that can be easily repeated once validated. As construction durations shorten, financial costs (i.e. interest during construction) also fall.

Key policy recommendations

1. Capitalise on lessons learnt from recent Gen-III construction projects. With the construction of several FOAK Gen-III nuclear reactors completed, the nuclear industry and its supply chain have in large part redeveloped their capabilities in several OECD countries. By building on these reactor designs, governments have a window of opportunity to realise cost reductions in the early 2020s through timely new-build decisions. Delaying these decisions will prevent the sustainment of capabilities and therefore raise near-term project construction costs.
2. Prioritise design maturity and regulatory stability. Designing policies to support nuclear construction is critical to ensure that new-build projects start in the right conditions. Policy support mechanisms should include requirements for design maturity and, more specifically, construction readiness, and should ensure that the regulatory framework for nuclear safety remains stable and predictable throughout construction.
3. Consider committing to a standardised nuclear programme. For countries considering multiple new-build projects, commitment to a standardised nuclear programme to capitalise on the series effect, multi-unit construction and continuous design and process optimisation is the most promising avenue to effectuate cost reductions.

Cost reduction opportunities are available at several levels

Building on lessons learnt from recent projects, a range of cost reduction opportunities for future nuclear construction (up to 2030) is emerging. In fact, a number of industry initiatives focused primarily on the interplay between incremental design optimisation of Gen-III reactors (particularly simplification and standardisation) and the integration of cross-cutting technologies and innovative enabling and construction processes (e.g. digital transformation, modular construction) are being launched. In many cases, these innovations have already been implemented successfully in other industries.

New co-operative interactions among various stakeholders, particularly regulatory bodies, are also being introduced. At the regulatory level, recent country experiences demonstrate that regulatory interactions can be enhanced without jeopardising safety objectives or regulatory independence.

Finally, the nuclear industry is also developing a number of longer-term (post-2030) opportunities that hold further cost reduction potential, including the harmonisation of licensing regimes, codes and standards; and innovative designs such as small modular reactors (SMRs) and Gen-IV reactors.

Policy makers can support these industry initiatives in a number of ways, with measures to co-ordinate energy and industry policy and to support research and development (R&D), innovation and skill development. For countries with a large enough nuclear new-build market, implementing a standardised nuclear programme is the most effective way to mobilise the various cost reduction drivers.

Key policy recommendations

4. Enable and sustain supply chain development and industrial performance. Industrial and energy strategies for new nuclear plants need to be carefully articulated. For instance, investment in supply chain capabilities requires assurance of long-term energy policy commitment to new nuclear construction to adopt the latest technical and organisational advances under the best conditions. New-build ambitions needs to be adjusted to integrate supply chain constraints and ensure continuous activity to enable and sustain development.
5. Foster innovation, talent development and collaboration at all levels. Governments can support cost reduction opportunities arising from innovative nuclear technologies (i.e. SMRs and Gen-IV reactors) by ensuring the timely development of demonstration projects and the licensing framework required to foster market deployment. Supporting talent development is also essential given the high level of technological expertise needed in nuclear power. National and international collaboration remains a key vector to achieve these objectives.

The governance framework is essential to support competitive new nuclear construction

The governance of nuclear new-build projects is critical to effectively allocate and mitigate construction and market-related risks. Nuclear projects are not different from other sectors and the standard economic principle of allocating each risk to the party most capable of managing it should be followed. In practical terms, this means that the industry (i.e. vendor, owner or supply chain as a whole) will often be best placed to manage technological and organisational risks, whereas risks related to the market and financing framework will warrant some degree of government intervention.

The impact of the cost of capital on the levelised cost of nuclear power and the positive externalities associated with nuclear power provide particularly clear rationale for direct or indirect government financial support in countries pursuing nuclear energy generation. This is especially necessary at the beginning of a nuclear programme to minimise risk perception.

Furthermore, as with other large-scale infrastructure projects, government involvement should extend well beyond specific policy support measures. Given the long-lasting and structural impacts of a nuclear programme on a country's economy and electricity system, governments must consider nuclear plants as national infrastructure projects of strategic importance. This means governments are responsible not only for project leadership but for uniting the various stakeholders, including the public at large.

Key policy recommendations

6. Support robust and predictable market and financing frameworks. Nuclear new-build projects require long-term government planning involving both specific commitments and market regulations. In addition, financial support is currently essential in western OECD countries – at least as a transitional measure – to deliver cost-competitive new nuclear construction.
7. Encourage concerted stakeholder efforts. Governments should create an environment that fosters social contract with industry and society to reduce nuclear construction costs. Recent national initiatives such as the Nuclear Sector Deal in the United Kingdom provide clear evidence of how such frameworks can be developed and implemented.
8. Tailor government involvement to programme needs. The enabling role of governments will differ depending on the nature of the programme. Whereas government financial support in countries considering a fleet programme can be expected to decrease gradually as the industry reaches maturity and the perceived risk level falls, countries restarting a nuclear programme or considering only a single-plant project are likely to require further government support.

Appendix 1: List of experts

This study was written by the NEA Secretariat, Michel Berthélemy and Antonio Vaya Soler based on evidence collected from the different references cited in the report as well as the insights and specific inputs provided the Ad Hoc Expert Group on Reducing the Cost of Nuclear Power Generation (REDCOST) and other experts. The REDCOST members, along with the Working Party on Nuclear Energy Economics (WPNE), supervised the study at all stages and recognised its results. Additionally, the NEA Secretariat conducted individual interviews with senior nuclear industry professionals to collect insights from the industry on selected topics. A list of the different experts that formally participated in the study is indicated below.

Members of the REDCOST expert group:

Country representatives

Mr Celestin Piette	Belgium
Mr Jukka Hautojärvi	Finland
Mr Olivier Bard	France
Professor Dr Thomas Schulenberg	Germany
Dr Tomoko Murakami	Japan
Dr Tae Joon Lee	Korea
Mr Adrian Gabriel Dumitriu	Romania
Mr Dmitry Andruyshin	Russia
Mr Mike Middleton	United Kingdom
Mr Bruce Hallbert	United States
Dr Francesco Ganda	United States

Representatives of international organisations

Dr Saied Dardour	IAEA

Observers

Mr Hasan Charkas	EPRI
Mr David Scott	EPRI
Mr Philippe Costes	WNA

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Unlocking Reductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders

Today, with the completion of First-of-a-Kind Gen-III nuclear reactors, the nuclear sector is at a critical juncture. These reactors have led in several parts of the world to delays and construction costs overruns that have challenged the competitiveness of nuclear power and are driving the risk perception of future projects. Against this background, a review of historical and recent lessons learnt from nuclear and non-nuclear project offers ample evidence that nuclear new build can be delivered cost and time-effectively.

This study assesses the policy and governance frameworks needed to drive positive learning and continuous industrial performance for nuclear new build. The study also explores the risk allocation and mitigation priorities needed to define adequate financing schemes for these projects. In the longer-term, it identifies cost reduction opportunities associated with the harmonisation of code and standards and licensing regimes and new innovative designs (i.e. small modular reactors and advanced reactors).

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