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**

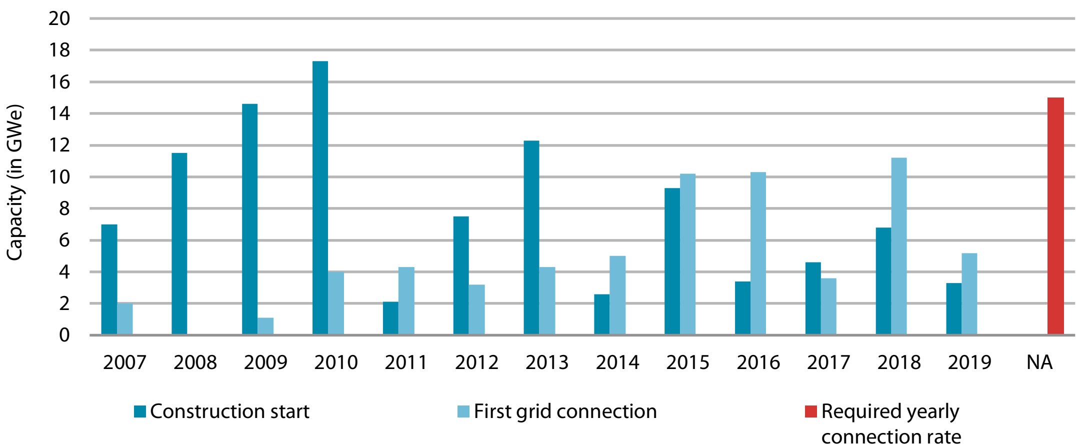
1. Introduction

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).

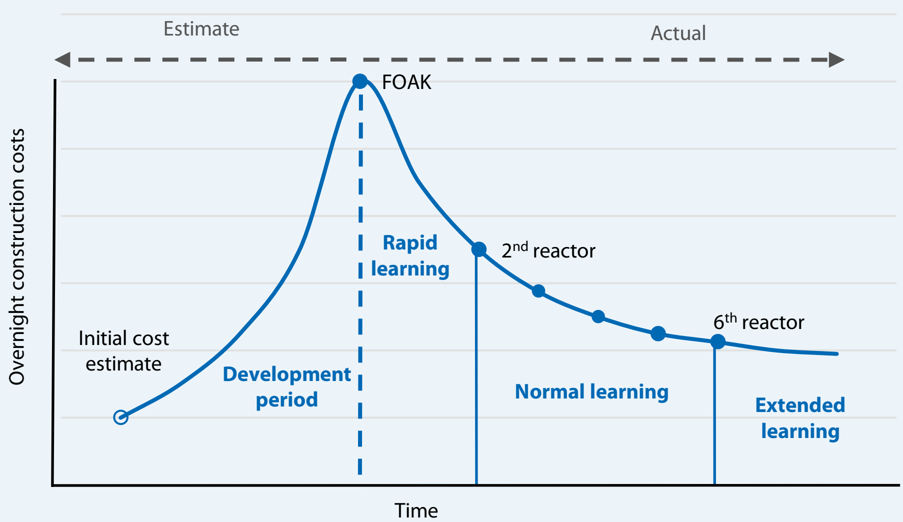
Assuming 60-year operation of most of the existing fleet, around 15 GWe of new nuclear is needed every year to keep pace with the SDS – at least double the current annual rate of capacity additions between 2020 and 2040. Such development is technically feasible, as proven during the first nuclear deployment 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**

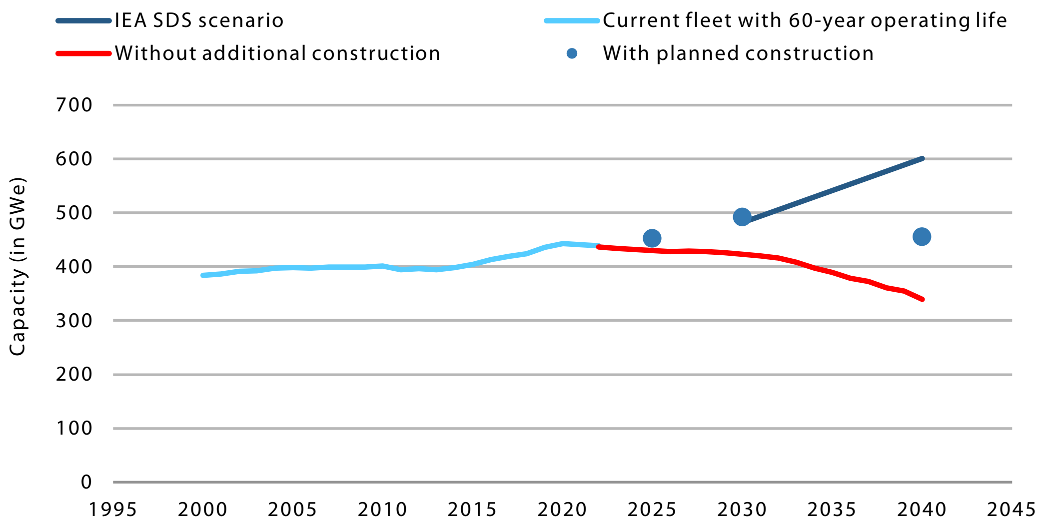


Source: Adapted from Yemm et al. (2012), "Pelamis: Experience from concept to connection."

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.

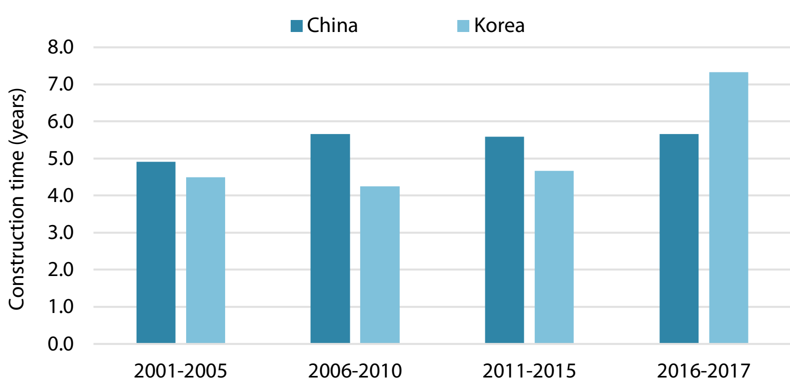
Source: NEA analysis based on publicly available information.

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**

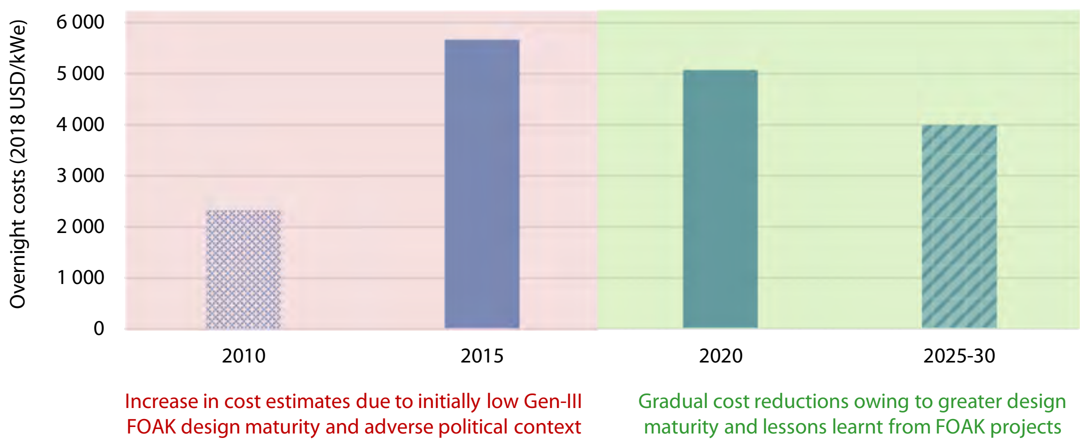


Source: IAEA (2019), Nuclear Power Reactors in the World.

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.

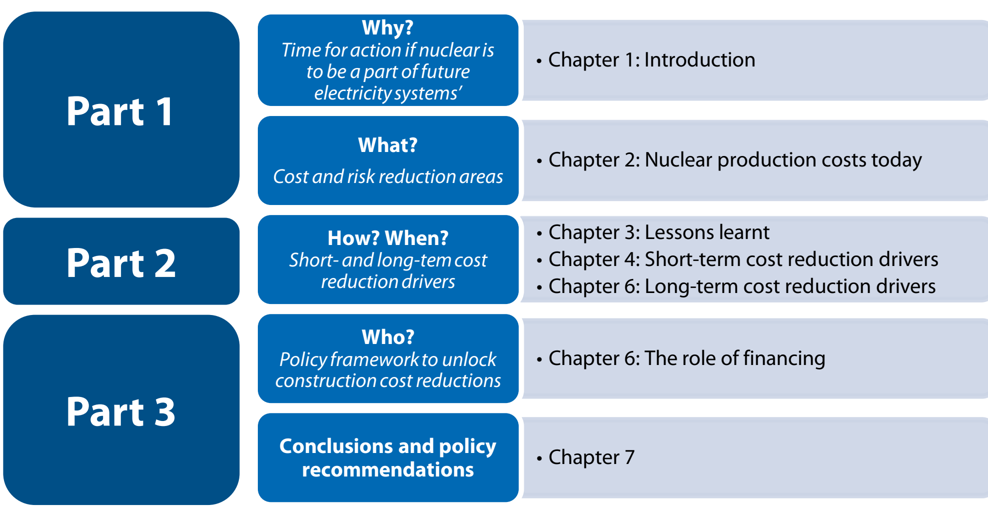
Chapter 3 assesses historical and recent construction projects to identify common core cost reduction drivers. Supported by robust evidence, these lessons learnt are the backbone of the nuclear learning curve. Chapter 4 explores additional cost-reducing measures to accelerate the learning process available 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.

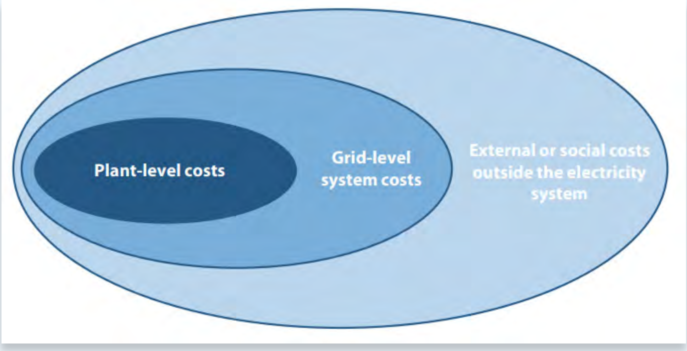
The cost of the electricity provision can be divided into several categories (Box 2), but reducing plant-level costs is the sole object of this report. Any cost reductions in this area will have a direct positive effect on the full cost of electricity provision.

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)*

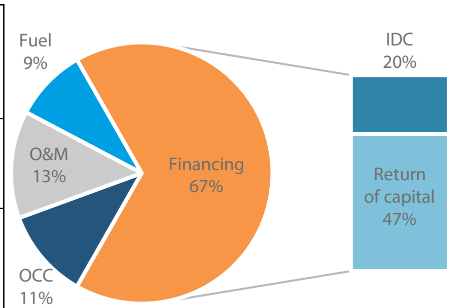
The full cost of energy provision is thus the sum total of all three categories.

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]

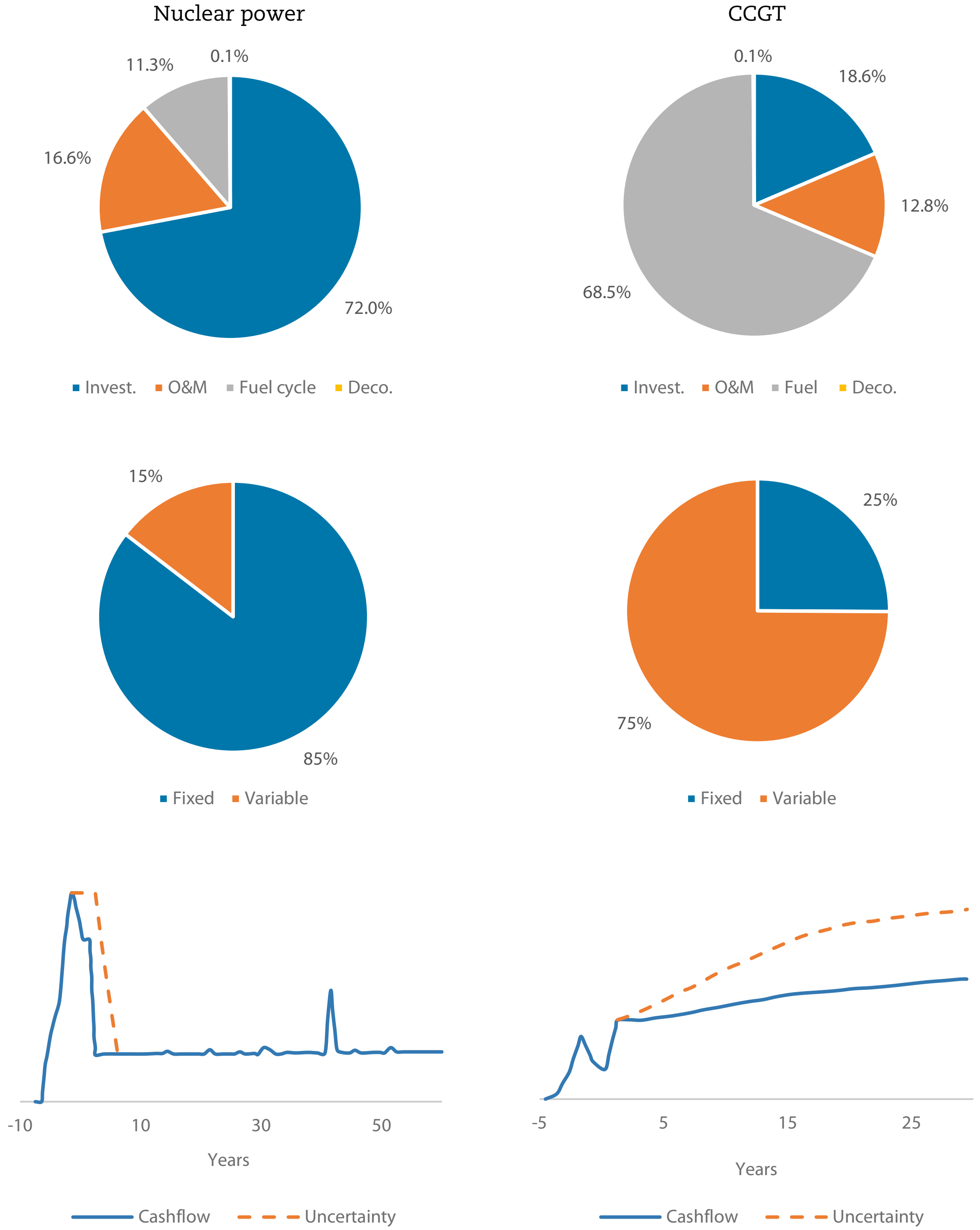
For instance, when wholesale electricity prices are low, both nuclear and CCGT face revenue losses. The difference is that even if nuclear power plants stop operating, they still have to recover a large portion of their fixed costs, whereas CCGT plants may choose to stop operating to avoid further losses,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

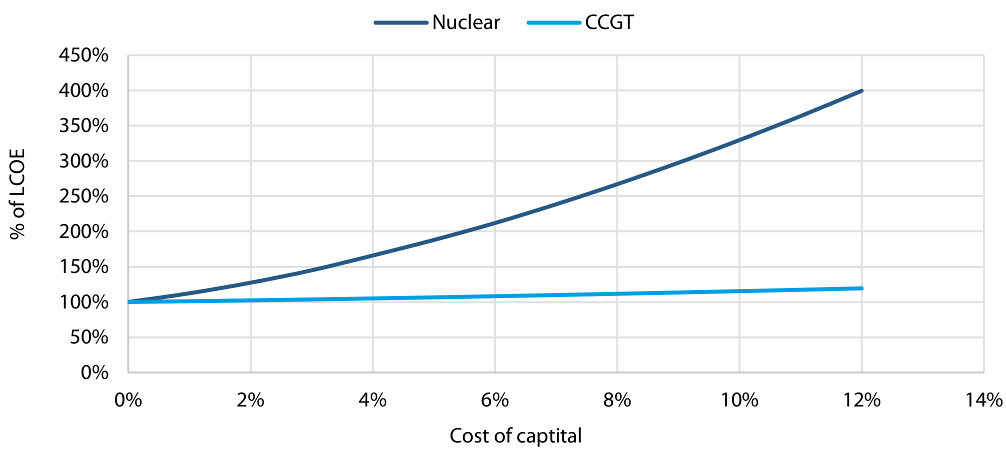


Notes:. Average cost share per megawatt hour (MWh) in OECD countries; real discount rate of 7%.

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.