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Unlocking Reductions in the Construction Costs of Nuclear:

A Practical Guide for Stakeholders

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ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

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The OECD Nuclear Energy Agency (NEA) was established on 1 February 1958. Current NEA membership consists of 33 countries: Argentina, Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, the Netherlands, Norway, Poland, Portugal, Romania, Russia, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The European Commission and the International Atomic Energy Agency also take part in the work of the Agency.

The mission of the NEA is:

- to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally sound and economical use of nuclear energy for peaceful purposes;
- to provide authoritative assessments and to forge common understandings on key issues as input to government decisions on nuclear energy policy and to broader OECD analyses in areas such as energy and the sustainable development of low-carbon economies.

Specific areas of competence of the NEA include the safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

Cover photos: Barakah Nuclear Power Plant, United Arab Emirates (Emirates Nuclear Energy Corporation).

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)

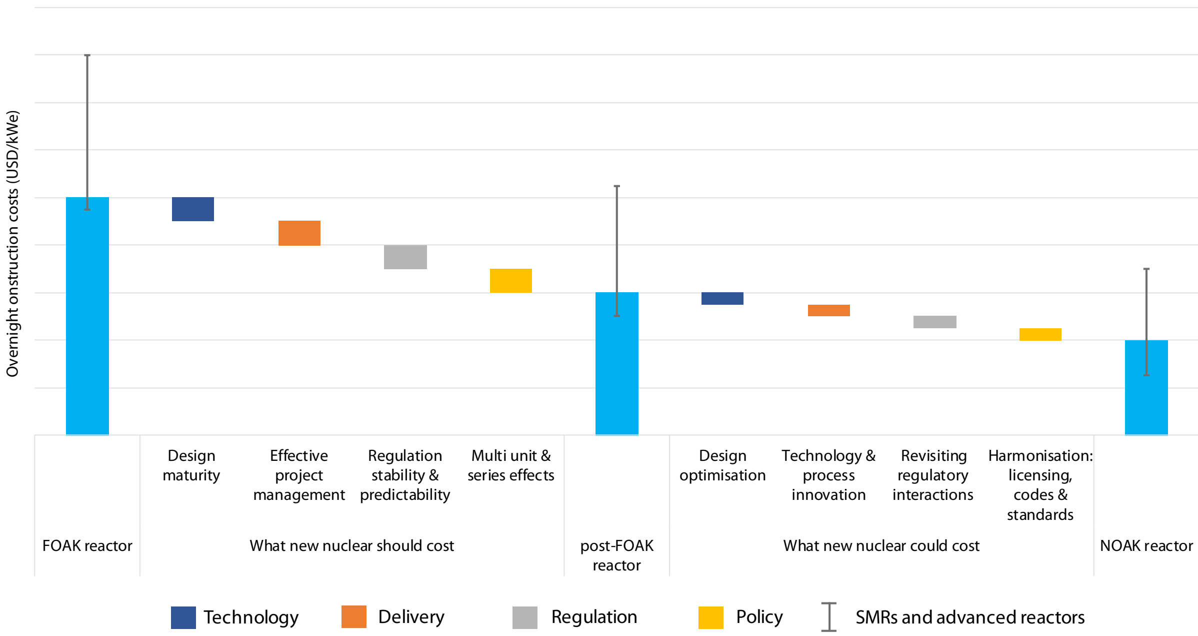
With these drivers and conditions in place, nuclear project costs could be further reduced in the short term. The interplay between plant design and delivery processes presents a range of cost reduction opportunities. These options are not necessarily sequential and can be mobilised even during the early 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.