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New Perspectives for Financing Nuclear New Build

Financing New Nuclear Power Plants: Minimising the Cost of Capital by Optimising Risk Management

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NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1 February 1958. Current NEA membership consists of 34 countries: Argentina, Australia, Austria, Belgium, Bulgaria, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, the Netherlands, Norway, Poland, Portugal, Romania, Russia (suspended), the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Türkiye, 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 the 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 NEA competence 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.

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Foreword

Nuclear energy could play a significant role in attaining the net zero targets to which an increasing number of OECD countries are committed. The IEA's *Net Zero by 2050* assumes an increase in electricity generated by nuclear power plants from 2 698 TWh in 2020 to 5 497 TWh in 2050 corresponding to an increase of 415 GW of capacity in 2020 to 812 GW in 2050 (IEA, 2021). Achieving this near doubling of nuclear capacity in the coming years and decades will require the ability to leverage considerable amounts of capital at competitive rates. To facilitate this process, the OECD Nuclear Energy Agency (NEA) and the International Framework for Nuclear Energy Cooperation (IFNEC), in collaboration with the government of Poland, decided in late 2020 to launch the NEA – IFNEC Initiative on Nuclear Financing. This initiative brought together experts from academia, industry and energy policymaking to identify key challenges in the financing of nuclear new build and to identify promising avenues to overcome them.

Informed by their discussions, the NEA is this report exploring a new framework for analysing financial risk in nuclear new build. Minimising the cost of capital depends on optimising financial risk management. The framework proposed in this report allows to draw two key conclusions. First, in a carbon-constrained world, the true capital costs of nuclear energy and other low-carbon generators are lower than customarily assumed due to their ability to offset systemic financial risk. Including low-carbon generation investments can thus reduce overall portfolio risks. Second, there exist effective policies and measures to radically reduce the economic and financial costs of other risk components such as construction risk, price risk and political risk.

The findings of this report apply equally to private and public investments. There do, however, remain important roles for governments. First and foremost, governments need to ensure credible and effective commitments to net zero carbon emissions by 2050. They also need to implement the measures required to eliminate or reduce the economic costs of construction risk, price risk and political risk. Finally, governments may become directly involved as project participants, in cases where they judge that private actors do not realise the full value of a nuclear power project. Beyond the reduction of financial risks, governments have a role in ensuring efficient project management structures in large and complex projects such nuclear new build as well as macroeconomic stability.

If the measures and frameworks indicated in this report are fully implemented to de-risk nuclear power projects in a context of contributing to the attainment of ambitious net zero targets, investors private and public will compete for the opportunity to share in the benefits of dispatchable low-carbon electricity by reducing their required return on capital to significantly lower rates than is presently the case. The Nuclear Energy Agency (NEA) welcomes comment and discussion on this and other forthcoming contributions on the financing of nuclear new build, which is one of the major challenges that need to mastered in order to succeed with attaining ambitious net zero objectives.

Acknowledgements

This report was written by Dr Jan Horst Keppler, Nuclear Energy Agency (NEA) Chief Energy Economist. Diane Cameron, Head of the NEA Division for Nuclear Technology Development and Economics (NTE), and Dr Michel Berthélemy, NTE Nuclear Energy Analyst, provided valuable comments throughout the different stages of the report.

The work on this report benefitted greatly from the contributions to the NEA – IFNEC Initiative on Nuclear Financing launched by the OECD Nuclear Energy Agency (NEA) and the International Framework for Nuclear Energy Cooperation (IFNEC) in collaboration with the government of Poland in late 2020. Expert financing workshops on 14-15 January 2021 and 10 March 2022 as well as webinars on "The Financing of SMRs: Challenges and Opportunities", 18 May 2021, on "Taxonomies, Environment, Social, and Governance (ESG) Criteria and the Role of Nuclear Energy", 19 July 2021, as well as "Contractual Structures and Incentives in Nuclear New Build", 14 September 2021, identified challenges, formulated questions and provided insights. The high-level "Warsaw Conference on Nuclear Financing" on 23 November 2021 brought together many of these contributions, several of which subsequently found their way into this report.

Finally, the report also gained from the oversight and comments of the NEA Committee on Nuclear Development and the Fuel Cycle (NDC) under its Chair Patrick Lederman and the NEA Working Party on Nuclear Energy Economics (WPNE) under its Chair William D'haeseleer and co-chair Brent Dixon.

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List of abbreviations and acronyms

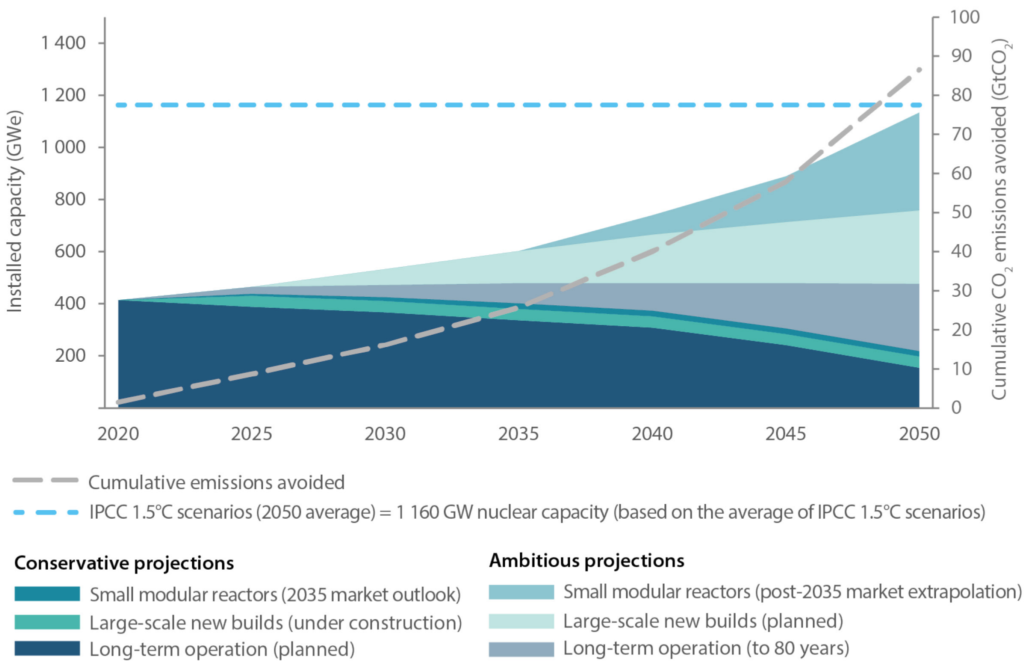
CAPM	Capital asset pricing model
CCGT	Combined cycle gas turbines
CFD	Contracts for difference
CWP	Construction work in progress
ESG	Taxonomies, Environment, Social, and Governance
FIT	Feed-in tariffs
FOAK	First-of-a-kind
IFNEC	International Framework for Nuclear Energy Cooperation
LTO	Long-term operation
NEA	Nuclear Energy Agency
NOAK	Nth-of-a-kind
O&M	Operations and maintenance
OECD	Organisation for Economic Cooperation and Development
RAB	Regulated asset base
SMR	Small modular reactors
VRE	Variable renewable energy
WACC	Weighted average cost of capital

Executive summary

Attaining net zero carbon emissions by 2050 will require financing and developing significant capacity of new nuclear power generation in the coming years and decades. The IEA's *Net Zero by 2050* assumes an increase in electricity generated by nuclear power plants from 2 698 TWh in 2020 to 5 497 TWh in 2050 corresponding to an increase of 415 GW of capacity in 2020 to 812 GW in 2050 (IEA, 2021). Those data are modelled for the Net-Zero Emissions (NZE) Scenario. This corresponds to 7.8% of the global electricity production in 2050 (IEA, 2021). Achieving this near doubling of nuclear capacity in the coming years and decades will require the ability to leverage considerable amounts of capital at competitive rates. The OECD Nuclear Energy Agency (NEA) and the International Framework for Nuclear Energy Cooperation (IFNEC), in collaboration with the government of Poland, have thus decided in late 2020 to launch the NEA – IFNEC Initiative on Nuclear Financing. This initiative brought together experts from academia, industry and energy policymaking to identify key challenges in the financing of nuclear new build and to identify promising avenues to overcome them.

Figure ES.1

Potential contribution of nuclear new build and long-term operation (LTO) to carbon emission reductions by 2050



Source: NEA (2021).

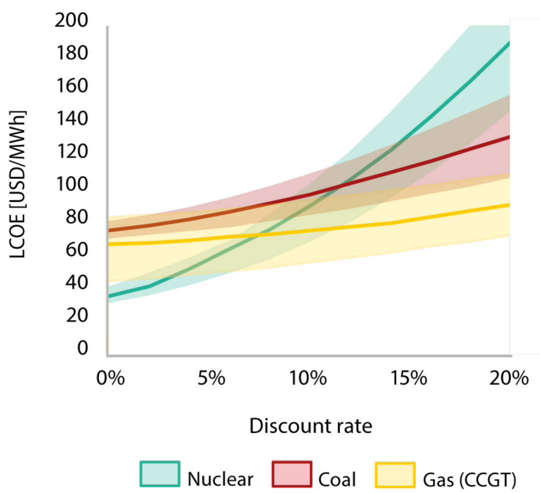
Informed by their discussions, the NEA has written this report exploring a new framework based on the capital asset pricing model (CAPM) for analysing financial risk in nuclear new build. In doing so it is possible to indicate possible avenues to minimise the cost of capital – and hence the overall costs of investment when constructing new nuclear power plants. This framework led to two key conclusions. First, in a carbon-constrained world, the true capital costs of nuclear energy and other low-carbon generators are lower than customarily assumed due to their ability to offset systemic financial risk. Second, there exist effective policies and measures to radically reduce the economic and financial costs of other risk components such as construction risk, price risk and political risk. The findings of this report apply equally to private and public investments. They include the possibility that governments may become directly involved as project participants in cases where they judge that private actors do not realise the full value of a nuclear power project.

As a dispatchable generating technology predictably producing large amounts of low carbon electricity that can be scaled at will, nuclear energy could play a significant role in attaining the net zero targets to which an increasing number of OECD governments are explicitly or implicitly committed[1]. Recent NEA work has shown that nuclear energy could avoid 87 million tonnes of CO_2 globally by 2050 given its competitiveness, in particular when considering the electricity system in its entirety.These emission savings would likely be achieved by a mix of LTO of existing plants and the construction of nuclear capacity in the form of both Generation III reactors and small modular reactors (SMRs).

The cost of capital is a key driver for the competitiveness of nuclear new build

Nuclear power can thus contribute significantly to reducing carbon emissions. This will depend, however, on the ability of governments, project managers and reactor vendors to work together to deliver sufficient numbers of nuclear reactors at an attractive cost. Like other low-carbon technologies such as hydroelectricity, wind or solar PV, nuclear energy is highly capital-intensive. This high capital intensity distinguishes these low-carbon generation technologies from technologies based on fossil fuels such as coal and gas, for which fuel costs and the costs of carbon emissions are the key cost components (see IEA/NEA, 2020 and NEA, 2019, in particular Table B3.2, p. 125, for details). High capital intensity furthermore implies that the cost of capital, that is the rate of return paid to investors, is together with overnight costs and effective project management one of the three key determinants of the overall costs of nuclear new build and of the competitiveness of nuclear energy compared to other baseload technologies such as gas and coal.

Figure ES.2
Competitiveness of baseload power generation technologies as a function of the cost of capital



Source: IEA/NEA (2020), p. 84.

1. As with other generation technologies, the dispatchability of nuclear power is subject to ramping constraints such as limits to the gradient of power changes, minimum up- and downtimes as well minimal power requirements (see NEA, 2019, p. 96, for details).

At low costs of capital (see Figure ES.2), nuclear energy is highly competitive even against gas-fired power generation, with fuel costs for Europe of USD 8 per MMBTU (USD 27.2 per MWh) and carbon costs of USD 30 per tonne of CO_2. This cost advantage disappears rapidly at higher costs of capital. Recent events have driven the costs of both gas and carbon emissions considerably higher and thus improved the competitiveness of nuclear energy. And yet, attaining net zero carbon emissions in 2050 and investing in power generation capacity are long-term endeavours and the assumptions of the 2020 edition of *Projected Costs of Generating Electricity* (IEA/NEA, 2020) remain relevant for energy decision-making.

Successful risk management can reduce the costs of capital of nuclear new build

The cost of capital in nuclear new build, as elsewhere, is a function of risk management and risk allocation. One important principle in this context is that risks should always be allocated to the party that is best equipped to minimise the economic costs of those risks. The ability to minimise the cost of risk is usually tied to either a particular technical competence (utilities managing nuclear power plants should bear operational risk, for example) or to a particular ability to share, diversify and hedge risks. This report introduces an additional consideration: in policy frameworks that aim to reduce carbon emissions in order to achieve net zero by 2050, low-carbon generators such as nuclear power can play an important role in offsetting financial portfolio risk.

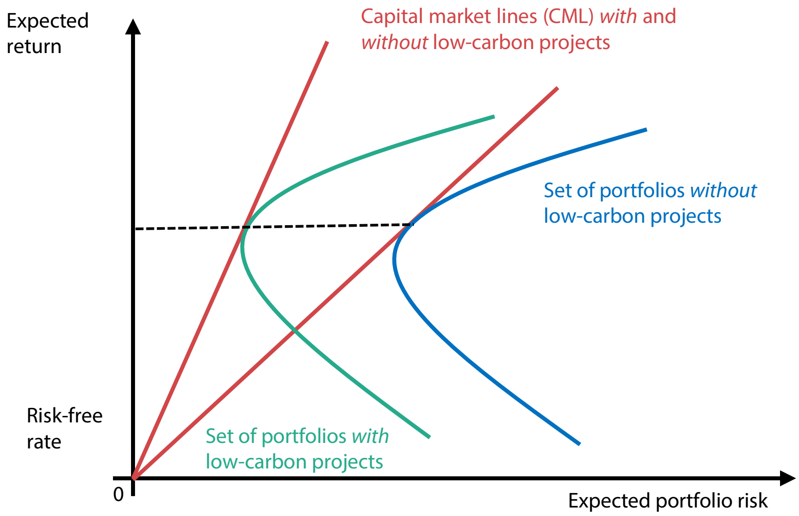
The cost of capital in investment is determined by the costs of risk. The higher the costs of the different types of risk for investors, the higher will be the rates of return that they will seek from the proponents of a project. This principle of financial economics is universal and affects investments in any economic sector. It assumes, however, a particular relevance when investing in capital-intensive low-carbon power generation projects such as nuclear new build. The capital asset pricing model (CAPM), the most widely applied model in financial economics to determine the cost of capital, offers a systematic approach to the analysis of risk. It allows, in particular, to analyse the different dimensions of financial risk in nuclear new build one by one and thus offers both a more complete view of the overall risk as well as the ability to better design measures to manage, reduce and allocate the economic costs of risk in a coherent and transparent manner.

For any given investment project, the CAPM distinguishes the following components of risk: (1) the risk-free rate at which countries with high credit ratings can borrow, (2) the systemic risk of the market and the project's correlation with the systemic risk and (3) different forms of project-specific or "idiosyncratic" risk. In a nuclear new build project, the idiosyncratic risks would typically include construction risk, price risk and political risk. The premise of this report is that the costs of these risks are either lower than habitually assumed or that there exist effective measures to reduce them further. The arguments for each risk category are the following:

1. In real terms, that is net of inflation, the **risk-free rate** at which countries with high credit ratings can borrow for the long term remains at historic lows despite recent increases in short-term rates.
2. In the case of **systemic market risk,** the key parameter is a project's **correlation**. If the latter is lower than average, zero or even negative, investors can lower their overall risk by adding such a project to their portfolios as it offsets the systemic risk of other investments. In a net zero world, this applies to low-carbon generators. As climate change and efforts to combat it intensify, implicit and explicit carbon prices rise. This decreases profitability throughout the economy but increases the profitability of low-carbon investments. In this case, including low-carbon investments will reduce the risk and improve the risk-reward ratio, also called the Sharpe ratio, of financial portfolios (see Figure ES.3). Consequently, investors will accept very low or even zero returns on such investments as their value lies primarily in their hedging function rather than their individual payoff.

Figure ES.3

Including low-carbon projects improves the risk-reward ratio of financial portfolios



3. As far as the **project-specific risks** of a nuclear new build project are concerned, the aim is less to interpret differently the true cost of capital as to implement effective measures to reduce the economic costs of the underlying risks. For the different idiosyncratic risks, it thus holds that:

   a) For the large, complex projects that constitute nuclear new build, **construction risk** is perhaps the most important project-specific risk. If an individual company shoulders that risk, its survival may be at stake. Consequently, investors would demand a hefty bankruptcy premium when exposed to construction risk. As an alternative, measures such as regulated asset base (RAB) in the United Kingdom or construction work in progress (CWP) in the United States have been put forward. Such measures transfer the cost of building the plant to the electricity bills of ratepayers from the moment construction starts rather than from the moment electricity generation starts. Economic theory shows that this implies not just a transfer of risk but, as long as a number of reasonable assumptions hold, a reduction in the economic costs of risk as the amounts in play are a very small portion of each ratepayer's budget.

   b) **Price risk** in the deregulated electricity markets that dominate the electricity sectors of OECD countries has long been recognised as a driver of the cost of capital (see, for instance, NEA, 2015). This is why regulators have proposed in certain instances, price guarantees in the form of feed-in tariffs (FIT) or contracts for difference (CFD). This is, however, only the beginning. In future low-carbon systems, prices will increasingly be set by the zero or very low short-term marginal costs of nuclear and renewables. The budget constraints of generators will require these low prices to be offset by scarcity hours where prices may reach hundreds or thousands of USD. Increasingly, a consensus is forming that in a net zero context, all low-carbon providers will need to benefit from generalised long-term contracts with guaranteed prices at the level of average costs over the complete lifetime of the project.

   c) In the case of **political risk**, the logic that requires allocating risk to the party most apt to minimise and internalise it is, by and large, already respected. Contractual indemnification clauses insure project operators and their investors against changes in energy policy that would limit the use of nuclear power and attributes that risk to national governments.

In summary, this report shows that the cost of capital for nuclear new build projects is either lower than is usually assumed or can be radically reduced through appropriate measures. In the first case, the long-term real risk-free rate is still very low while the correlation with system market risk can be prudently assumed to be zero, as long as net zero targets are pursued with vigour and consistency. In the second case, governments and electricity market regulators have at their disposal effective measures to reduce not only the effective risk for investors but also the overall economic cost of construction risk, electricity price risk and political risk.

The same insight can be formulated in another manner: if nuclear new build projects are thoroughly de-risked in the manner outlined above, this will provide in particular private investors with the stable framework that will enable them to offer capital at lower rates of return to acquire a share in predictably generated low-carbon electricity.

Risk management in nuclear new build in practice and the role of governments

Given the significant sums involved and the number of successfully concluded projects, it is obvious that financial risk management has always been part of nuclear new build. Historically, arrangements were often quite straightforward. In the vast majority of successful nuclear new build projects, utilities were public, which means construction risk was spread in another way, over a large number of taxpayers, and tariffs were regulated. The advent of electricity market deregulation in the 1990s changed all this. Financial risk management needed to become more sophisticated to remain market compatible. The forthcoming NEA report on lessons learnt from the financing of recent nuclear power plant projects will provide a comprehensive overview of such efforts (NEA, forthcoming).

The picture that emerges is that financial risk management in nuclear new build projects in a context of deregulated electricity markets is frequently applied in a partial and sometimes haphazard manner that owes more to national precedent and prevailing political considerations than to systematic analysis. The objective of this report is precisely to provide decision makers with a comprehensive view of financial risk management to allow a more consistent and transparent management and allocation of the different risks to different stakeholders.

This is a task that will ultimately need to be performed by governments. The report's conclusion that the costs of capital for nuclear new build projects can be significantly lower than usually assumed applies equally to public and private investors. Nevertheless, there remain important roles for government in this context.

The first task of governments is to ensure a credible and effective commitment to carbon emission reductions. The decorrelation of low-carbon projects from systemic market risk will not be realised where strong emission reduction commitments are not followed up by actions that have real traction in the economy. Second, governments need to implement the strategies that are discussed above to eliminate or reduce the economic costs of three project-specific idiosyncratic risks: construction risk through risk spreading over ratepayers, price risk through long-term contracts or regulated tariffs and political risk through appropriate indemnification clauses with government. Third, governments may become directly involved as project participants in cases where they judge that private actors do not realise the full value of a nuclear power projects. This does not require an argument based on the public good or strategic objectives such as security of energy supply, technological development, regional cohesion or employment – however valuable they may be. The only relevant market failures would concern the incorrect appreciation of the true costs and benefits of dispatchable low-carbon electricity generated by new nuclear power projects. Fourth, governments have a role in ensuring efficient project management structures in nuclear new build. The interaction of financing structures, project management, incentives and electricity market design in nuclear new build is an issue that will be developed in a future NEA report. At this point, it suffices to say that governments need to ensure that all stakeholders contribute to an eventually shared objective of completing nuclear new build projects on time and to budget. Fifth, governments would need to ensure macroeconomic stability to keep country risk premiums at a minimum. Nuclear generation projects are capital-intensive and large. An increase of one or two percent above the risk-free rate quickly makes a difference in the real costs of these projects.

Governments therefore need to stay involved to create the framework conditions and to implement the measures reducing the economic costs of financial risk. First and foremost, commitments to net zero carbon emissions by 2050 need to be translated into effective action. If these conditions are ensured, there will be a tendency for the costs of capital for nuclear new build projects to approach the risk-free rate plus any required country risk premium. This is not only a conceptual proposition. If nuclear new build projects are thoroughly de-risked as indicated, this will provide in particular private investors with the stable framework that will enable them to offer capital to acquire shares in predictably generated low-carbon electricity at considerably lower rates than is presently the case.

Chapter 1. Context and introduction

1.1. The NEA-IFNEC Financing Initiative in collaboration with the government of Poland

In an effort to help develop the nuclear power generation needed to meet net zero targets by mid-century, the OECD Nuclear Energy Agency (NEA) as part of the 2021-22 Programme of Work of the NEA Committee for Technical and Economic Studies on Nuclear Energy Development and Fuel Cycle (NDC) and the International Framework for Nuclear Energy Cooperation (IFNEC), in collaboration with the government of Poland, launched in late 2020 the NEA-IFNEC Initiative on Nuclear Financing. The Initiative started with the "NEA-IFNEC Kick-off Workshop on Conceptual Issues in the Financing of Nuclear New Build" on 14-15 January 2021, bringing together experts from academia, industry and energy policymaking to identify key challenges in the financing of nuclear new build and promising avenues to overcome them.

Over the course of 2021, a series of NEA-IFNEC webinars helped sharpen both the understanding of the barriers to financing nuclear new build as well as the means to surmount them. Subsequent webinars dealt with "The Financing of SMRs: Challenges and Opportunities" on 18 May 2021, "Taxonomies, Environment, Social, and Governance (ESG) Criteria and the Role of Nuclear Energy" on 19 July 2021, as well as with "Contractual Structures and Incentives in Nuclear New Build" on 14 September 2021.

In parallel, the NEA has been working on a report combining insights from conceptual analysis and empirical experience on nuclear financing, with this background paper providing the first results. The "Warsaw Conference on Nuclear Financing" on 23 November 2021 constituted a first high-point of the NEA-IFNEC Initiative on Nuclear Financing in collaboration with the government of Poland. The Warsaw conference discussed preliminary insights from this work at the policy level in order to make them relevant in the national contexts of the nuclear new build programmes of the participating countries.

Today's efforts to build new nuclear power plants are part of climate change mitigation plans and the ambition of many OECD countries, including Poland and the countries of the European Union, to achieve net zero greenhouse gas emissions by 2050. Recent events have also highlighted the role that nuclear energy, alongside other low-carbon technologies, can play in improving the security of electricity supply as it reduces the need for imported fossil fuels for electricity generation. Nuclear as a reliable provider of dispatchable low-carbon electricity is an indispensable complement to variable renewables such as wind and solar PV. Work by the NEA and others has shown that significant shares of nuclear power generation contribute to reducing the overall costs of attaining ambitious net zero targets.

Due to their high capital intensity, all low-carbon technologies face special investment challenges and would benefit from market design with a stable long-term outlook of electricity prices. Beyond this, each low-carbon technology faces different challenges. Wind and solar PV are variable and hydropower is constrained by the availability of suitable sites. In the case of nuclear generation, the large size of projects and their regulatory and institutional infrastructures would require a concerted effort to launch nuclear new build programmes. Once built, nuclear power plants contribute substantially to carbon emission reductions, air quality and the security of energy supply.

The success of these efforts will depend crucially on the financing conditions for nuclear new build projects. This regards not only the availability of large amounts of capital from private and public sources. As long-term trends indicate a structural overhang of savings over investments, properly structured projects will find interested investors. Like other low-carbon generation technologies such as hydro or variable renewables, nuclear energy has comparatively high capital costs and low variable costs (see IEA/NEA, 2020 and NEA, 2019, p. 125). The key parameter for the successful financing of new nuclear power plants is thus the cost of capital, i.e. the level of remuneration that public and private investors will require. This level of remuneration is directly related to the risk that investors are exposed to in different dimensions. The efficient allocation among private and public stakeholders of risks relating to the construction, pricing arrangements and policy frameworks of new nuclear power plants has indeed emerged as a key theme. Is there a risk that construction takes longer than planned? May electricity prices be lower than expected? What about changes in the political frameworks? The answers to each of these questions will influence the level of risk, the rate of return that investors demand and the costs of nuclear new build projects.

These questions and their answers have not substantially changed in 2022 when electricity prices, driven mainly by gas prices, reached previously unimaginable levels. In Europe, the price for one-year forward delivery of electricity baseload in 2023 was about EUR 200/MWh, far above the estimated levelised cost of electricity (LCOE) of nuclear power plants, even at considerable capital costs. Such a price certainly provides a welcome addition to the revenues of existing plants, nuclear or other, and may even affect the economics of long-term operation (LTO) or lifetime extensions. However, they will have little if any impact on decisions to invest in the construction of new nuclear power plants. The time frames are just too long and the uncertainties, be they driven by geopolitics, domestic concerns, climate change concerns or new technology developments, are just too high.

Through the NEA-IFNEC Financing Initiative and as presented at the Warsaw conference, the NEA has approached these questions in two ways. First, the NEA developed a conceptual framework in which to discuss the question, "What is today the optimal cost of capital for a new nuclear power generation project from a societal point of view?". Combining insights from finance, public economics and energy economics, the NEA is putting forward the new and striking proposal that the socially optimal rate for the cost of capital for a nuclear new build project should be close to the cost of capital of public funds, i.e. the rate at which national governments can borrow in financial markets. Such a result, however, depends on the systematic de-risking of new nuclear projects and thus on a number of assumptions that require careful discussion. For example, eventual nuclear new build projects would need to be a part of a coherent national strategy to protect the economy against the risks of climate change. In addition, construction, price and political risks would need to be handled in a manner that minimises their private and social costs. While fulfilment of these conditions is possible, it will not be achieved without a comprehensive and robust policy effort.

Second, the NEA has empirically studied the financing structures of successful new build projects in the recent past. This work shows that the success of nuclear new build projects historically depended substantially on the de-risking of projects in several dimensions. For example, successful projects have with only few exceptions benefitted from long-term guarantees concerning the level of remuneration in terms of electricity process. Also, projects tend to benefit from close co-operation between relevant stakeholders, not only from the start of the project but many years before "first concrete" is poured. Finally, the articulation between the financial model, procurement choices and ownership structure is key to align stakeholders' interests and thus ensure project success.

The NEA work on nuclear finance is based on the idea that the costs of financing nuclear new build correspond to the sum of the risks of building new nuclear power plants. In this context, this report explores three key hypotheses:

1) The financing costs of nuclear new build can be substantially lowered if price risk, construction risk and political risk are each optimally managed and allocated through different measures to be implemented by governments or public actors.

2) Independent of the fact that risk optimisation will be primarily driven by governments, both public and private investors would benefit from such measures. This may extend to including nuclear power generation in investment portfolios to the extent that they can provide a form of financial hedge against the economic impacts of climate change.

3) Private sector participation in nuclear new build is desirable and often required for various reasons, including to find staff with the appropriate technical, project management or

operational skills. Specific provisions for project management, incentive structures and ownership can help optimise the benefits of public-private co-operation.

This report pursues primarily a normative approach. It thus poses the question, "What should be the cost of capital for building new nuclear power plants under an optimal management and allocation of risks and in the absence of market failures, transaction costs, non-aligned incentives or asymmetric information?" The answer should not depend on whether investors are from the public or private sector. If indeed new nuclear construction projects are systematically de-risked, private actors should be compelled to invest at the same rates of return as public entities.

Many of the observations made in this report on the financing of new nuclear power plants are transferable to the financing of other low-carbon generation technologies such as hydroelectricity or renewable energy sources. The report can thus be read as a general guide to financing new generation capacity in the electricity sector of OECD countries in the context of their ambition to reach net zero carbon emissions by 2050. In particular, low-carbon investments would, in principle, all benefit from a progressive increase in carbon constraints while other investments would tend to be negatively affected. This decorrelation with systemic financial risk would, in principle, favour decreased costs of capital for low-carbon generators in general. While the implications of such new constellations still need to be worked out in detail and, with time, subjected to empirical verification, it is already clear that binding net zero commitments will lead to a new finance and macroeconomics of the energy transition with wide-reaching ramifications. The question of how to approach the financing of new nuclear power plants is at the heart of this transformation.

Of course, this does not mean that all low-carbon technologies face exactly the same financing challenges. Variable sources such as wind and solar PV have to deal with financial risks linked to their autocorrelation, i.e. the fact that all installations of a given technology produce together during a limited number of hours, which generates lower than average value both for the system and themselves. Nuclear power plants have to face the risks of their long and complex construction, which is dealt with carefully in this report. While large hydropower installations or certain offshore wind installations might be comparable in size and complexity as construction projects, beyond some similarities among low-carbon technologies there remain a number of technology-specific challenges even in a general net zero context.

However, even in a world without market failures and transaction costs, governments have a fundamental role. It is governments that decide on the societal allocation of risks and set the framework conditions. Whether price risk is borne by producers or consumers is a question of market design. Whether construction risk is borne by individual parties or socialised depends on the financing models decided upon by governments and regulators. Political risk is by definition a function of the political processes that both determine and are determined by governments.

There are also other situations in which governments may have an important role to play. In the real world, markets are not always complete, transaction costs are high and the incentives of different actors are not aligned, among other things. In particular, the private sector might struggle to adequately price the ability of low-carbon electricity generation to offset systemic economic risk. Such market failures are a textbook example of when government intervention is needed through regulation, fiscal measures or public investment. Needless to say, projects as complex as building nuclear power plants provide myriad possibilities for co-ordination failures that markets cannot adequately address. This is an important issue and has, for instance, been addressed in NEA (2015), *Nuclear New Build: Insights into Financing and Project Management.*

The two aspects of government intervention, optimising risk allocation and remediation of market failures, are discussed in Chapter 2 of this report, which examines at length the issue of reducing the economic costs of construction risk through risk sharing. Transferring construction risk partially or entirely to ratepayers and electricity consumers can be accomplished by way of mechanisms such as regulated asset base (RAB) or construction work in progress (CWP). Clearly there is an element of simply transferring risk from one party to another; however, there is also an element of reducing the economic costs of risk that could not be accomplished by markets alone.

The need for governments to intervene in the construction of new nuclear power plants or other low-carbon generation assets to remediate for market failures over and above the optimal allocation of risk is discussed in a more synthetic manner in Chapter 3. Here the report provides a number of guiding principles for governments to carefully set the framework conditions for the division of labour between the public and private sectors in nuclear new build projects. Future NEA work, building on this report, will provide a more systematic treatment of the role of governments in addressing incomplete markets, transaction costs and asymmetric information.

Under all circumstances, history, culture and national industrial structure will be important. Different countries will thus choose different arrangements. Overall, the public sector has historically been deeply involved in the financing and, to a lesser extent, the project management of nuclear new build in many countries. It is now the time to combine new conceptual insights and empirical experience to develop financing models that can be successfully adapted by member countries.

While reducing the costs of financing is crucial for successful nuclear new build, it is not the only factor necessary to build new nuclear power plants at attractive costs. Proven, or at least fully completed, designs that allow for reasonable overnight costs, i.e. capital costs net of financing costs, are fundamental. The contractual structures of project management and appropriate incentive mechanisms that align the interests of different stakeholders can also be decisive. On overnight costs, *Unlocking Reductions in the Construction Costs of Nuclear* (NEA, 2020) has already provided a number of new perspectives. The second part of this report will comment on contractual structures and incentive mechanisms.

However, there is also a consideration that goes beyond the financing and construction of nuclear energy sources and concerns all low-carbon electricity generation technologies as well as the effort to attain net zero emissions by 2050: it will not be possible to attain this ambitious objective within the current designs for electricity markets. Deregulated markets for low-carbon electricity with marginal cost pricing will display pricing patterns with unsustainable levels of volatility where prices alternate between zero and the level of voluntary or involuntary demand response. This is due to two independent but mutually reinforcing characteristics: first, as indicated above, the high capital costs and low variable costs of all low-carbon technologies and, second, the compression of the generation from wind and solar PV during a limited number of hours. When the wind is blowing and the sun is shining, prices will tend towards zero and if neither is, the case prices will tend towards the level of demand response.

Optimising the cost of capital would thus be a necessary but not a sufficient condition to allow for significant amounts of nuclear new build in order to contribute to net zero targets. Energy market reform and long-term pricing arrangements such as regulated tariffs, contracts for difference (CFD) or widespread power purchasing agreements would thus be a necessary complement to efforts to reduce the cost of financing per se. Yet, the converse also holds true: energy market reform will not be sufficient to ensure the amounts of nuclear new build that net zero requires. Other than price risk and, depending on the context, policy risk, nuclear power plants are subject to significant levels of construction risk. Of course, CFDs could tempt investors to undertake nuclear construction projects even in the absence of specific measures to handle construction risk. However, the levels of such CFDs would need to be so high as to become difficult to sustain at the level of political debate and the workings of the electricity market.

Last but not least, geopolitical upheaval in 2022 has raised questions about markets, prices, and the functions of government in the energy field including ensuring the safety and security of vulnerable energy infrastructures. However, as far as the financing of new nuclear power plants is concerned, these disruptions have re-enforced rather than limited the conclusions of the present report. Alongside the imperative of reducing carbon emissions to reach net zero by 2050, the security of energy supplies is a second non-negotiable priority. Nuclear energy can, of course, play a role in both areas. Current events have also highlighted the fact that in the energy field, despite 30 years of liberalisation, many risks cannot be expressed in the form of the well-defined probability functions that markets rely on to function properly. Governments thus remain the ultimate decision-makers both on the supply and the demand side. For financing of new nuclear power plants, this means that governments have an even stronger mandate to set clear framework conditions in order to allocate risks, which may include geopolitical risks.

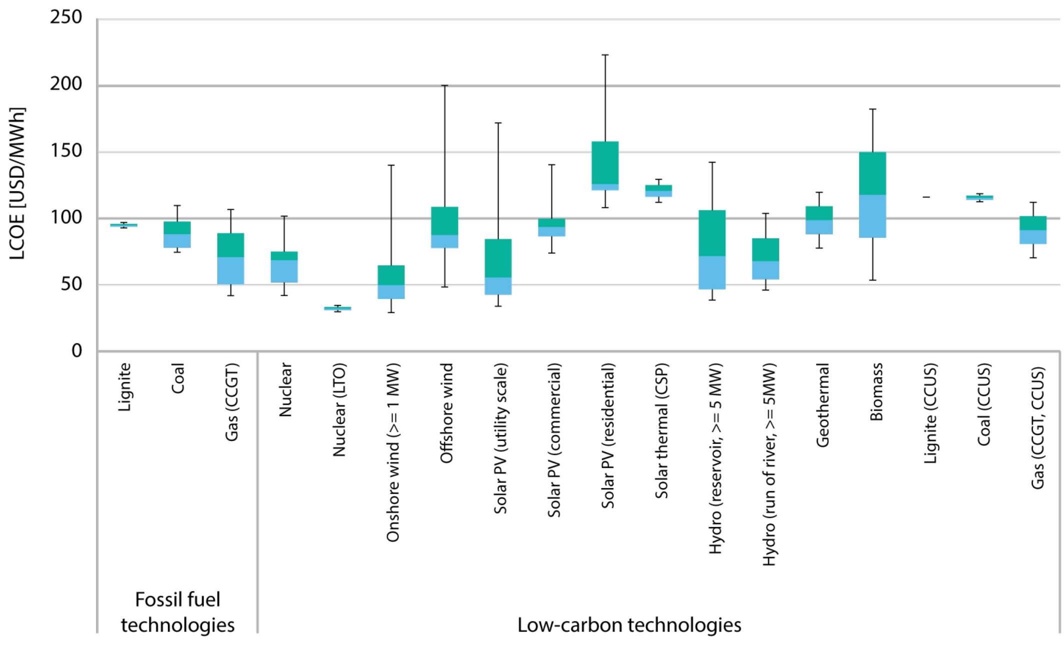
1.2. The role of nuclear energy in mitigating climate change

Depending in particular on its cost of finance, nuclear energy can be a competitive form of low-carbon electricity generation. The widely read reference publication *Projected Costs of Generating Electricity: 2020 Edition* by the International Energy Agency and NEA, for instance, states that nuclear is the dispatchable low-carbon technology with the lowest costs.[2] Only large hydro reservoirs, where available, can provide a similar system contribution at comparable costs. Electricity produced from nuclear LTO is even more competitive and is the least cost option not only for low-carbon generation but for all power generation.

Figures 1.1a and 1.1b below provides an overview of the range of levelised costs of electricity (LCOE) for different power generation technologies on the basis of the data received from participating countries in the *Projected Costs* study. These results are reported below first for a relatively high cost of capital of 7% and then for a capital cost of 0%. The NEA work on the socially optimal cost of capital for low-carbon technologies presented in Chapter 2 of this background document argues that far lower costs of capital should be used in the context of national and regional efforts to achieve net zero emission targets by 2050. Applying such socially optimal costs of capital would not primarily affect the relative competitiveness of different low-carbon technologies such as nuclear, hydro or variable renewables – since all of them are highly capital-intensive – but the competitiveness between low-carbon technologies and fossil fuel-based technologies, primarily coal and gas. The latter's overall costs are primarily determined by the costs for fuel and carbon, so a reduction in capital costs is of lesser importance for them.

Figure 1.1a

LCOE ranges for different power generation technologies at a cost of capital of 7%



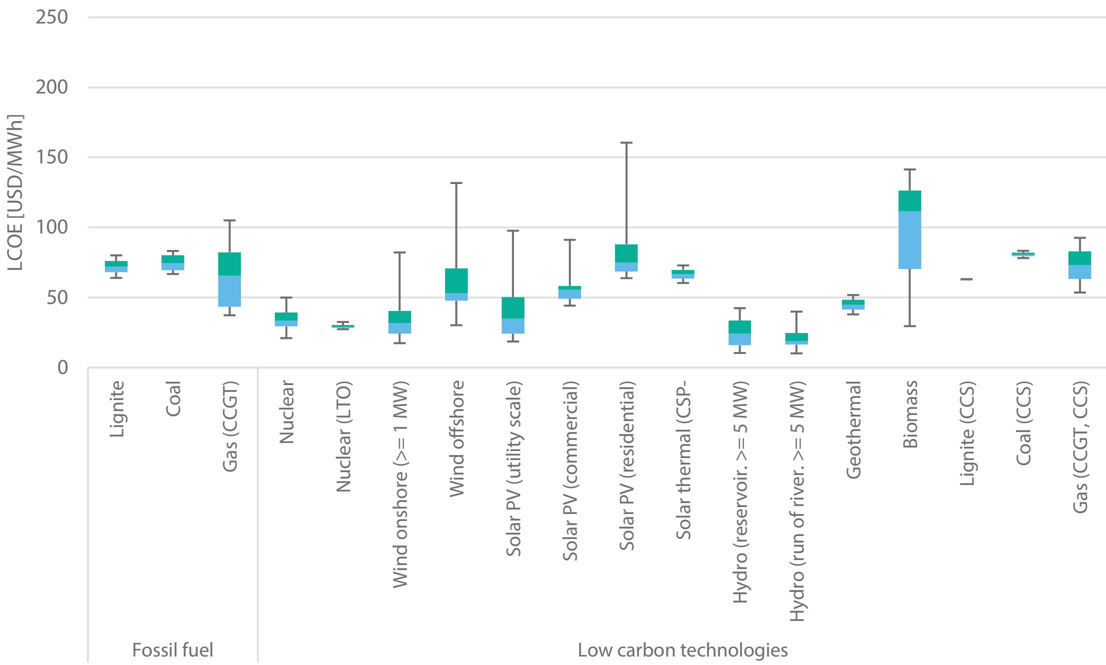
Note: Box plots indicate maximum, median and minimum values. The boxes indicate the central 50% of values, i.e. the second and the third quartile.

2. As with other generation technologies, the dispatchability of nuclear power is subject to ramping constraints such as limits to the gradient of power changes, minimum up- and downtimes as well minimal power requirements (see NEA, 2019, p. 96, for details).

The impact of the costs of capital on the competitiveness of different power generation technologies and, in particular, the competitiveness of capital-intensive low-carbon technologies such as nuclear, hydroelectricity, wind and solar PV against gas and coal-fired power generators is shown in the graph below. It computes the same LCOE at a capital cost of 0%, which is close to the rate at which countries with high credit ratings currently borrow in long-term capital markets. The costs of *all* low-carbon technologies, both nuclear and variable renewables, are significantly reduced, while those of gas and coal-fired power generation change very little. Clearly, the cost of capital is one of the principal drivers for a successful realisation of the clean carbon transition (for nuclear specifically, see also Tables 1.1 and 1.2 below).

Figure 1.1b

LCOE ranges for different power generation technologies at a cost of capital of 0%



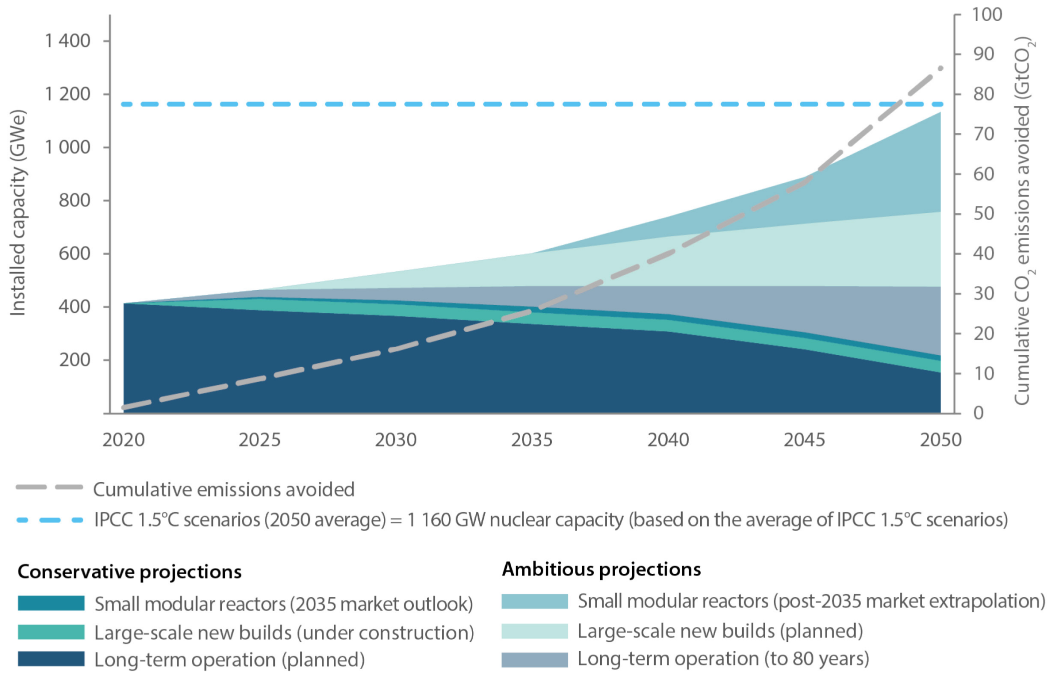
Note: Box plots indicate maximum, median and minimum values. The boxes indicate the central 50% of values, i.e. the second and the third quartile.

Nuclear energy can play a significant role in the reduction of global carbon emissions. Recent work by the NEA has provided an overview of how large such a contribution could be both with conservative and with more ambitious assumptions (see Figure 1.2 below; the left-hand axis shows total installed capacity and the right hand axis cumulatively avoided CO_2 emissions). Under ambitious assumptions, nuclear energy would avoid globally 87.1 million tonnes of CO_2 ($GtCO_2$).

In order to put the contribution of nuclear energy into perspective, global energy-related carbon emissions amounted to 31.5 $GtCO_2$ per year. In other words, realising the full cumulative contribution of nuclear power until 2050 would correspond to roughly three years' worth of energy-related carbon emissions. However, this would require the nuclear sector to realise ambitious targets in all three of its main segments, the LTO of reactors that are already operating today, the construction of new Generation III plants and the deployment of nearly 200 GW of small modular reactors (SMRs).

Figure 1.2

The full potential of nuclear energy to contribute to net zero

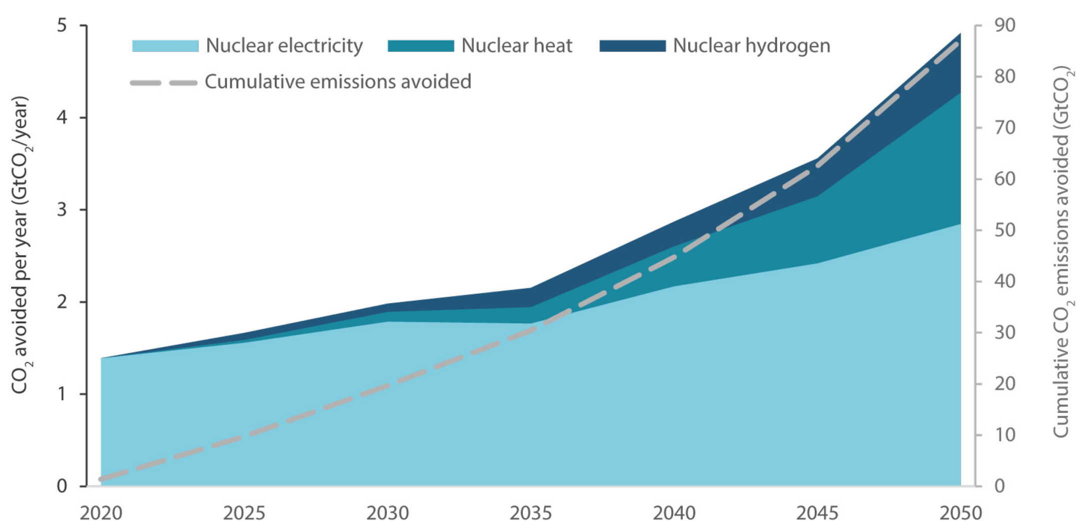


Source: NEA (2021), p.7.

The potential contribution of nuclear power can also be analysed in terms of power and non-power applications. While low-carbon electricity produced by nuclear power will provide the bulk of emissions savings with over 50 $GtCO_2$ avoided, nuclear heat as well as nuclear hydrogen are expected to play increasingly important roles in the low-carbon electricity and energy systems of the future. The key notion here is "sector coupling", as the electricity sector progressively integrates with transport, industrial uses and residential heating.

Figure 1.3

Carbon emissions avoided by nuclear power and non-power applications



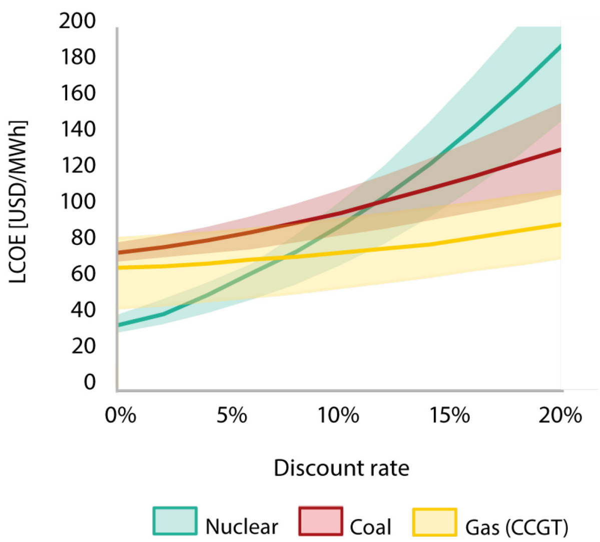
Source: *Ibid*, p. 34.

1.3. The importance of financing costs for nuclear new build

Nuclear power can contribute significantly to reducing carbon emissions. In competitive electricity sectors, realising this contribution will depend, however, on the ability of governments, project managers and reactor vendors to work together to deliver a significant number of nuclear reactors at attractive costs. Like other low-carbon technologies such as hydroelectricity, wind or solar PV, nuclear energy is highly capital-intensive. This high capital-intensity distinguishes low-carbon generation technologies from carbon-intensive generation based on fossil fuels such as coal and gas, for which fuel costs are the key cost component.

Figure 1.4

The competitiveness of baseload power generation technologies as a function of the cost of capital (discount rate)



Source: IEA/NEA (2020), p. 84.

For low-carbon technologies the key cost component is the cost of capital. Figure 1.4 indicates the competitiveness of the principal technologies for dispatchable baseload power generation from nuclear reactors, coal-fired power plants and combined cycle gas turbines (CCGT) in terms of the levelised costs of electricity (LCOE) in function of the real cost of capital (net of inflation) or the private discount rate (in LCOE accounting, these two items are identical and coincide also with the real interest rate).

It is easy to see that at low and very low-interest rates nuclear power is the most competitive technology by a considerable margin. At a cost of capital of zero, a level that corresponds to the risk-free rate for public borrowing in major industrialised countries and is considered in the remainder of the paper the relevant level also for investments in nuclear energy, nuclear power is highly competitive, producing electricity at a cost that is less than half that produced either by a coal-fired power plant or a CCGT. However, this cost advantage quickly dissipates at higher interest rates. At a cost of capital of 5% CCGTs become the least-cost baseload generator and at 10% even coal has a lower cost than nuclear despite the 30 USD/tCO_2 carbon cost that is included in the LCOE of coal-fired power generation.

Keeping the costs of capital low is thus key both for the competitiveness of nuclear energy against alternative baseload generators as well as for limiting the overall costs of the transition to net zero energy systems by 2050. Tables 1.1 and 1.2 quantitatively demonstrate this link. However, it should be emphasised that the cost of capital is not the only parameter determining the successful completion of nuclear new build projects where issues such as electricity market design, project management and incentive structures play important complementary roles.

Table 1.1

Investment costs per kW at different costs of capital (overnight costs correspond to zero interest rate)

Country	Technology	Net capacity (MWe)	Overnight costs (USD/kWe)	Investment costs (USD/kWe)		
				3%	7%	10%
France	EPR	1 650	4 013	4 459	5 132	5 705
Japan	ALWR	1 152	3 963	4 402	5 068	5 633
Korea	ALWR	1 377	2 157	2 396	2 759	3 066
Russia	VVER	1 122	2 271	2 523	2 904	3 228
Slovak Republic	Other nuclear	1 004	6 920	7 688	8 850	9 837
United States	LWR	1 100	4 250	4 721	5 435	6 041
Non-OECD countries						
China	LWR	950	2 500	2 777	3 197	3 554
India	LWR	950	2 778	3 086	3 552	3 949

Source: *Ibid*, p. 49.

Overall capital costs, i.e. the amount of financing that needs to be mobilised by investors, increase considerably when moving from a real cost of capital of zero to 3%, 7% or even 10%. It should be recalled that these funds need to be disbursed before the first MWh is produced and thus do include construction risk as well as other risks. Managing, transferring or sharing this risk will be crucial to keeping financing costs manageable.

The effect of the cost of capital is even more striking when considering its impact on the LCOE. This is due to the fact that intertemporal consistency demands that the cost of capital is equal to the discount rate. At higher discount rates, the revenues for electricity sold many years after the date of commissioning are discounted more heavily. Since the LCOE methodology also requires an identical price for each MWh at each point in time, the two effects combine to yield an algebraic result that is equivalent to discounting future physical output.

Table 1.2

The LCOE of nuclear power plants at different costs of capital (investment costs include decommissioning costs)

Country	Technology	Net capacity (MWe)	Investment (USD/MWh)			Fuel (USD/MWh)	O&M (USD/MWh)	LCOE (USD/MWh)		
			3%	7%	10%			3%	7%	10%
France	EPR	1 650	22.05	47.56	73.31	9.33	14.26	45.27	71.10	96.89
Japan	ALWR	1 152	21.77	46.96	72.39	13.92	25.84	61.16	86.67	112.13
Korea	ALWR	1 377	11.85	25.56	39.40	9.33	18.44	39.42	53.30	67.16
Russia	VVER	1 122	12.48	26.91	41.48	4.99	10.15	27.41	42.02	56.61
Slovak Republic	Other nuclear	1 004	40.37	83.76	127.66	9.33	9.72	57.61	101.84	146.06
United States	LWR	1 100	23.35	50.37	77.63	9.33	11.60	43.90	71.25	98.56
Non-OECD countries										
China	LWR	950	13.73	29.63	45.67	10.00	26.42	49.92	66.01	82.08
India	LWR	950	15.25	32.92	50.74	9.33	23.84	48.17	66.06	83.91

Source: *Ibid* (adapted), p. 58-59.

At such higher discount rates, it thus seems as if total costs were divided by a lower number of MWh. In reality, the number of physical MWh remains the same year after year but MWh generated in far-away future years count increasingly less towards cost recovery than MWh generated in years closer to the date of commissioning. LCOE thus increase doubly with the cost of capital, first due to the increase in the cost of capital during construction until the date of commissioning and, second, due to the decreasing value of future production after commissioning. Whatever the mechanics behind LCOE accounting: keeping the cost of capital low is crucial for the competitiveness of nuclear energy as well as for delivering the energy transition in a cost-effective manner.

Chapter 2. Minimising the economic costs of risk and optimising the cost of capital in financing the construction of new nuclear power plants

2.1. Introduction

Establishing frameworks that allow for cost-efficient financing is crucial for the construction of new nuclear power plants. Without efficient financing, the large number of new plants required to reach the net zero targets of NEA member countries will not be realised, as it will be impossible to mobilise the large amount of capital required. In a world with a structural savings overhang and trillion-dollar stimulus programmes, this is not primarily a question of the availability of capital but of its required rate of return, the cost of capital.

The availability of capital, in principle, does not mean that all desirable projects will automatically be financed. In particular, projects whose social benefits exceed the private benefits, which typically include low-carbon power generation projects such as nuclear energy, will not be financed at socially desirable levels if their cost of capital is higher than socially optimal. Reasons for these high costs can include market failures, such as short-termism or the inability to price in positive externalities, but also market design issues creating high volatility and risks for investors. The principal purpose of this report is precisely to develop proposals for bridging the gap between a general financial environment, in which capital is plentiful and its cost are low, and the specific conditions for investments in low-carbon electricity generation and nuclear energy, where the costs of capital can be considerable.

The cost of capital for a new nuclear power plant thus depends partly on the global savings and investment balance, partly on the view society takes of the nature and role of low-carbon electricity generation and partly on the specifics of nuclear power projects. It may also matter who finances construction, in particular whether investors are public or private entities and what their views are. In all circumstances, the cost of capital is ultimately a function of the risk that investors have to bear or perceive to have to bear. The lower the real or perceived investor risk, the lower the cost of capital.[3] If private investors have a different view from public sector actors concerning the risks of a specific project, their costs of capital will be higher.

In this context, it is necessary to underline the *normative* nature of this report. It indeed tries to establish a framework in order to determine what the cost of capital in financing a new nuclear power plant *should be* once all different risk dimensions have been optimised. It comes to the conclusion that the cost of capital of a de-risked, low-carbon generation project should be close to the risk-free rate plus the risk premium for the country or the enterprise undertaking the project. This conclusion is independent of whether investors are private or public. It results from an economic approach interested in overall welfare maximisation. This conclusion would thus be the view of the policymaker to the extent that he or she is convinced by the economic argument. However, what happens if private investors do not share this view and demand higher rates of return than those implied by the present framework? This would constitute a typical case of market failure, i.e. markets have a selective view of a broader economic reality for various reasons, including policy myopia, transaction costs, the negligence of externalities, herd behaviour around long-entrenched perceptions.

3. Hereafter the terms “cost of capital”, “rate of return” and “discount rate” are used interchangeably. The note also does not distinguish between observed and expected rates and is exclusively concerned with real rather than nominal rates. The different terms are, of course, identical only in a system in long-term equilibrium and may not be identical in the here and now of concrete projects.

In such cases, there are two options. Either governments or public actors undertake the investments themselves or they introduce support measures that bridge the gap between private and public perceptions of risk and the cost of capital. The latter does not necessarily involve financial transfers. Typically, this has taken the form of guaranteeing different risks around a new nuclear new build project, in particular political risk, price risk and construction risk. However, electricity market reforms, carbon pricing or better information and improved transparency can also be used to bring reality in line with the normatively established optimal rate of capital in nuclear new build in the context of attaining net zero carbon emissions by 2050.

One high-profile area in which attempts to bridge the gap between private and public perceptions of projects with good environmental performance have already materialised is so-called ESG investing, which integrates environmental, social and governance considerations to steer private capital into publicly desired sectors or projects. The means to do so is the promise of higher rates of return, either through "halo effects" attracting certain investor groups or by signalling long-term policy risks, including possible differentiated rates for capital gains taxes on ESG and other financial products. One of the most prominent ESG frameworks is currently the EU Taxonomy. In December 2021, the European Council approved the climate-related Delegated Act (DA), confirming into EU law the adoption of Technical Screening Criteria (TSC) for activities that contribute substantially to climate change mitigation and adaptation objectives. A draft version of the Taxonomy proposed by the EU Commission in December 2021 for acceptance by the European Council in summer of 2022 includes both nuclear energy and natural gas as transitional solutions for a limited time. The EU Taxonomy is far from being the only instrument for screening investments for their environmental, social and governance impacts. In June 2021, the United States House of Representatives voted the ESG Disclosure Simplification Act which aims to broaden communication on the impact of climate change and ESG performance. It is currently awaiting Senate confirmation.

Industry-driven rather than government-driven initiatives may also play a large role in this context. The foundation overseeing the evolution of the widely used International Financial Reporting Standards (IFRS) accounting standard announced at the occasion of the COP26 climate change conference the creation of an International Sustainability Standards Board (ISSB) "to develop… a comprehensive global baseline of high-quality sustainability disclosure standards to meet investors' information needs". The new board will include the activities of its current "Climate Disclosure Standards Board (CDSB)".

Discussion of the EU Taxonomy or climate change disclosure is beyond the scope of this report. However, this report similarly tries to answer the question of how the policy ambition to reduce the risk of climate change should be reflected in the cost of capital for low-carbon electricity generation projects. The objective of this report is thus to provide a coherent view of the cost of capital for new nuclear power projects in function of the distribution of responsibilities among different stakeholders and the frameworks that govern construction and operations. Many of the following remarks apply also to other types of low-carbon power generation, primarily variable renewable energy technologies (VRE) such as onshore wind, offshore wind and solar PV, as well as hydroelectric facilities. Of course, each technology has its own specific, or idiosyncratic, risks. For instance, in deregulated electricity markets the intermittency of VRE increases price volatility and hence risk and the cost of capital, both for VRE providers themselves, as well as for the providers of dispatchable low-carbon electricity such as nuclear and hydro (see NEA, 2019). However, as shown below, fully decarbonised electricity systems will require the systematic implementation of measures that insure all low-carbon technologies against excessive market risk. This can take either the form of long-term arrangements that guarantee stable prices or the form of capital cost support. It might also imply a more active management of the overall electricity system in terms of the long-term mix of low-carbon technologies.

This report is particularly concerned with the correct cost of capital assumptions to be adopted in public investments. This does not imply any restriction of the scope of the investigation and no preference for one form of investment over another. The following arguments aim to determine the real cost of capital, i.e. the true opportunity cost of the funds invested, irrespective of whether the investment is made by a public body or a private investor. However, the second part of this paper will provide arguments as to why in the area of nuclear new build centralised decision-making and the involvement of public actors may offer advantages over decentralised decision-making by private actors.

The arguments presented in favour of public investment in low-carbon power generation are based on the advantages of sharing idiosyncratic risks. Idiosyncratic risks are project-specific risks such as construction risk or price risk in the electricity sector to the extent that prices are uncorrelated with economic growth. The argument for public investment presented here does not depend on the difference between public and private discount rates with respect to the time preference of consumption. The latter approach has been explored by Stern (2007), Newbery et al. (2019) and others. Their work leads to similar policy recommendations but adopts a slightly different reasoning regarding the components that constitute the cost of capital.

In the framework of the popular capital asset pricing model (CAPM), this chapter presents the cost of capital as the sum of the risk-free rate, the correlation of an investment project with system market risk as well as with a series of project-specific "idiosyncratic" risks. The risk-free rate is equal for all and refers to the global balance of investments and savings alluded to above. It is currently at historic lows. The systemic market risk instead means that investors need to be compensated for the risk that the market as a whole could melt down. A key element for the cost of capital is thus how investors perceive the correlation of the profits of a new nuclear power plant with overall market returns. If the project evolves with the overall market, fine; investors will price in systemic risk as for any other project. However, if returns should go up when the market goes down or simply evolve independently of the overall market, then a project could contribute to portfolio diversification and investors would be satisfied foregoing any compensation for systemic risk. Idiosyncratic risks are, by definition, project specific and will be discussed below.

The results of this chapter on the cost of capital for nuclear power generation as part of low-carbon infrastructures can be summarised as follows. Given that the correlation of the returns of a nuclear power project with a view to reducing climate change risks with systemic market risk is zero or negative and given the public sector can organise the efficient sharing of idiosyncratic risks, the correct assumption for the cost of capital of a new nuclear power generation is the rate at which national governments can borrow in capital markets. For large industrialised countries with stable fiscal systems such as the United States, this rate is equal to the risk-free rate, which currently is equal to or close to zero. For countries will less favourable financing conditions, the relevant country risk-premium would need to be added.

This result refers to the sum of the true costs of public funds plus the economic costs of shared idiosyncratic risks. However, this reasoning and the mobilising of public funds that it implies apply only in the context of a firm societal and political commitment to the decarbonisation of the electricity sector. The arguments provided in the following can thus not be used to justify a general expansion of the government's role in other economic sectors.

2.2. The conceptual framework: the capital asset pricing model (CAPM)

The cost of capital is determined by the cost of risk. This principle of financial economics is important for any sector but it becomes decisive when investing in capital-intensive low-carbon power generation capacity. To determine the cost of capital, one needs to decompose it into its different components and assess the risk and optimal attribution and management of each one. The most important elements here are (1) the risk-free cost of capital, (2) the systemic risk of the market and (3) different forms of idiosyncratic risk. The first two components, the risk-free cost of capital and the system risk are typically modelled with the help of the CAPM, a standard tool in financial analysis.[4] Idiosyncratic risks are project-specific. Typically, they pertain to construction, market prices or changes in policy for a new build project. They are, in particular, unrelated to the systemic risk of markets.

4. Approaching the cost of capital from the perspective of the cost of risk and the risk aversion of economic agents is consistent with standard microeconomic theory and with the CAPM. However, one must recall that the CAPM neglects any possible divergence between financial markets and the real economy and makes a number of strong behavioural and informational assumptions. It is possible to build bridges between the CAPM and other financial theories such as the theory of the time preference of consumption by Fisher and others. But the CAPM can only with difficulty integrate phenomena such as Keynesian "animal spirits", bubbles due to mimetic investors or informational asymmetries, which are at the heart of either behavioural or value-oriented approaches for evaluating financial assets.

Coming back to the distinction between public and private investments, the risk-free cost of capital and the systemic risk are not affected by whether the investor is a public or a private entity. However, the economic costs of idiosyncratic risk are very much affected by whether the investor is a public or a private entity. In particular, the public sector has an ability through its system of taxes and transfers to share or to spread risks among a large number of citizens, which can reduce the economic costs of idiosyncratic risk. This is the essence of a famous theorem in public economics, the "Arrow-Lind Theorem" (see Section 4.3).

Other than the already-mentioned paper by Newbery et al. (2019), this report builds on the paper by Baumstark and Gollier (2014) and the remarks by Ehrenmann (2021) on the use of the CAPM in assessing the financing of low-carbon energy infrastructures. It also relies on the work of Peluchon (2021) and Keppler and Cometto at NEA (2015) on the market risk of nuclear power plants and, of course, on the seminal article by Arrow and Lind (1970) on reducing the costs of idiosyncratic risks through risk sharing. The principal contribution of this report is thus to integrate complementary insights from financial economics, electricity market economics and public economics considerations to provide a new understanding of the appropriate evaluation of the cost of capital for nuclear power plants in decarbonising electricity systems.

One key insight of the CAPM, which is widely used in financial markets to assess the cost of capital, is that riskier projects must generate higher profits in order to compensate investors for their risk.[5] The second key insight of the CAPM is that the risk of a project is related to its correlation with the systemic risk of the overall market. The reasoning is based on the common sense principle that risks can be reduced by diversifying investments over several uncorrelated projects in different sectors. However, if a project is closely related to the overall risk of the market, such diversification no longer brings any benefits in terms of risk reduction.

The cost of the financial risk of an individual project is thus determined by its correlation with systemic market risk. As pointed out earlier, systemic market risk refers to the risk that the market as a whole could melt down in a major generalised crisis not unlike the one of 2008, although markets have more than fully rebounded since then. Slightly more technically, systemic market risk can be considered as the risk of a perfectly diversified investment portfolio. The key component regarding systemic risk is the correlation of the returns of a nuclear project with systemic market risk. Any positive correlation of the outcome of a project with general market risk requires including the latter proportionately in the project's cost of capital. Typically, this refers to projects whose profits are closely related to general macroeconomic developments, economic growth and the business cycle. However, if the returns of a new nuclear power plants are negatively correlated this allows investors to increase the diversification of their portfolio, which is highly desired. They will thus no longer require to be remunerated for systemic market risk (see also Figure 2.1 in the section on systemic market risk below).

With these introductory remarks, one can now present the basic equation of the cost of capital in the CAPM framework:

$$r_n = r_f + \beta_n * r_s \qquad (1), \text{ where}$$

r_n is the cost of capital of a nuclear power generation project,

r_f is the rate of return of a risk-free financial asset,

β_n is the correlation of the risk of a nuclear power project with systemic market risk, with $\beta_n = \frac{cov\,(r_n, r_s)}{var\,(r_s)}$,

r_s is the systemic risk, i.e. the market risk (r_m or a perfectly diversified portfolio) minus the risk-free rate, that is $r_s = r_m - r_f$.

5. This report ignores here the criticisms of the CAPM by Fama and French (1992) and others. Perhaps the most important criticism is that the CAPM works with historical values but seeks to provide a decision-making framework for future-oriented investment.

Baumstark and Gollier (2014) as well as Ehrenmann (2021) emphasise that a complete assessment of r_n cannot be based only on this first simple formulation under the CAPM but must also include the idiosyncratic risks, i.e. project risks, that have no correlation with systemic risk.[6] Typically, the idiosyncratic risks in the construction project of a new nuclear power plant are policy risk, price risk in the electricity market and construction risk.

While it is clear that construction risk or political risk are project- and technology-specific, the inclusion of price risk among the idiosyncratic risks may come as a surprise. Would increased economic growth not lead to higher demand, higher electricity prices and higher profits at a nuclear power plant? In principle, yes. However, the particularities of price formation in electricity markets, especially in decarbonising electricity markets, which include non-storability, interactions with carbon markets, autocorrelation of VREs, out-of-market financing and other factors, are such that the correlation of a new nuclear project with economic growth is radically limited. Section 4.2 below will come back to this question in detail.

Idiosyncratic risk needs to be included in the true costs of capital of any investment project. To assess the risk of a nuclear power project in a decarbonised electricity system and its cost of capital, it is thus necessary to use an extended formulation of the classical CAPM equation:

$$r_n = r_f + \beta_n * r_s + \sum_i^n r_{INi} \qquad (2)\text{, where}$$

$\sum_i^n r_{INi}$ would be the additional remuneration demanded by investors to compensate for the sum of the project-specific or idiosyncratic risks of a new nuclear power project (political risk, market price risk and construction risk).

Equation 2 establishes the overall framework for the remainder of this note. The different elements that compose the cost of capital of a new nuclear power project, r_n, the risk-free rate, the correlation with systemic risk and the sum of idiosyncratic risks, will be evaluated one by one. It will be shown that under a number of reasonable, and in fact often widely adopted, assumptions each one of these components as well as their sum will be equal to the risk-free rate plus any appropriate country risk premium.

The key element in the above equation is possibly the correlation between the remuneration of an investment in a low-carbon nuclear power generation project and the remuneration of a market-wide portfolio of alternative investments. To the extent that robust carbon emission abatement will increase the former and decrease the letter, the profitability of the two investments may well be negatively related or unrelated. This contrasts with the standard assumption of positive correlation. The point will be discussed comprehensively in the section on system risk.

2.3. The risk-free rate and the correlation of nuclear new build projects with systemic risk

The risk-free rate

This is an uncontroversial issue that can be dealt with in a straightforward manner. Bonds issued by the United States government are widely regarded as risk-free financial assets. The easiest manner to determine the long-term real risk-free rate after inflation as opposed to the nominal rate is to examine the 30-year Treasury Inflation-Protected Securities (TIPS) of the US government. The last auction for such long-dated, inflation-protected US government bonds took place on 17 February 2022. It yielded a return of +0.195% (www.treasurydirect.gov/instit/annceresult/annceresult.htm, accessed 27 May 2022). In other words, even in the current

6. While both contributions argue that the cost of capital should include idiosyncratic risks, they do not share the same motivations. Most importantly, Baumstark and Gollier (2014) point out that the risk sharing effect that underpins the Arrow-Lind theorem does not apply to systemic risk. Transferring project risk from the private to the public sector thus does not reduce systemic risk. Ehrenmann (2021) is most interested in a more comprehensive formulation of project risk in a decarbonised power sector.

environment characterised by increased short-term inflation, investors are happy with annual returns of +0.2% on funds lent to the US government. Vice versa, the American government can today borrow over 30 years while paying annually 0.2% above the amount contracted.[7]

Similarly, the French government, which does not issue inflation-protected securities, regularly publishes the nominal yield of its French 30-year obligation assimilable du trésor (OAT). The latter was +2.04% on 27 May 2022 (www.banque-france.fr/statistiques/taux-et-cours/taux-indicatifs-des-bons-du-tresor-et-oat, accessed 27 May 2022). In March 2022, the French core inflation rate, which excludes fiscal transfers as well as volatile energy and agricultural commodities, was estimated at +2.5% for the year 2022 (https://publications.banque-france.fr/projections-macroeconomiques-mars-2022). Such year on year inflation is different from long-term inflation expectations over 30 years. Nevertheless, in the absence of statistics on long-term inflation expectations, the real return on long-term French government bonds can still be assumed to be slightly negative or very close to zero. Gollier (2015) even estimates that the real return of French government bonds is likely to be at around -1% over the long term.

The most striking example, however, is provided by the United Kingdom. On 3 November 2021, an auction for 50-year UK gilts (bonds) indexed on inflation resulted in a real yield of -2.39%. Even in May 2022, in an environment of gradually increasing real rates, the implied real rate on 40-years UK gilts as calculated by the Bank of England was still at -1.3% (www.bankofengland.co.uk/statistics/yield-curves accessed 27 May 2022). As central banks the world over move from a period of quantitative easing to a gradual tightening of monetary policy, historically low long-term real rates are gradually moving up. Yet, as decisive as central bank policy is for short-term rates, its influence on very long-term rates is much more limited. Here investors' expectations of long-term growth rates of the economy and the balance between the supply and demand of capital for investment are decisive.

In short, in a first estimate it can be assumed that the real risk-free rate as measured by the returns on long-dated government bonds in countries with low or no risk of default is very close to zero, if not below zero. The reasons for this unprecedented situation have less to do with the COVID-19 crisis, whose impact over 30 years from now is likely to be negligible, but with expectations of major global balances between investment opportunities, economic and demographic growth in different countries as well as, crucially, savings rates. The virtualisation of part of the economy, with its network effects and thus a tendency to monopolisation, as well as the progressive scarcity of certain natural resources can also weigh on the prospects for growth and profitable investment opportunities. This situation is unlikely to change soon. Newbery et al. (2019) cite an influential paper by Rachel and Summers (2019) who maintain that the need to balance a global savings surplus with scarce investment opportunities will require negative real rates for the risk-free rate, which is the anchor of the global financial system, for a considerable period of time.

It must be mentioned, however, that such highly favourable financing conditions are only available to borrowers in currencies of countries with very low default risks. Borrowers in currencies of other countries will need to price in so-called country risk. The latter includes, to the extent that international investors are concerned, currency risk as well as the risk that the country will default on all or part of its debt directly or indirectly, e.g. by creating capital controls.

Systemic market risk

The question of systemic risk is key to correctly assessing the risk and hence the cost of capital of capital-intensive investment projects. As implied by the general formula of the CAPM, the impact of systemic risk on the costs of capital depends on the correlation of a project's net benefits with the overall evolution of financial markets and the underlying economy they represent. In other words, the question is whether investing in a particular project will make it possible to diversify the overall risk of an investment portfolio or, instead, will reinforce existing risks.

7. In the open market, real rates on 30-year Treasury Inflation-Protected Securities (TIPS) have since increased to +0.64% by the end of May 2022. The inflation rate implied by the difference between inflation-protected and regular 30-year bonds is 2.55% per year (https://fred.stlouisfed.org/series/T30YIEM).

When assessing the impact of systemic risk on the cost of capital of a new nuclear power generation project, the value of β_n, i.e. its correlation with systemic risk, is thus usually more important than the level of the systemic risk itself (see Gollier (2021) for a discussion). If the profitability of a nuclear power plant evolved in line with economic growth and thus in line with the increase in the value of all other financial assets, this would obviously imply $\beta_n > 0$. In other words, investing in nuclear power would not significantly help to diversify an investor's portfolio and the systemic risk must therefore be incorporated into the cost of capital of a nuclear power project. This is one possible view, but there is the alternative view that a new nuclear power plant would generate higher benefits and profits precisely when the rest of the economy is adversely affected by climate change or policies to protect against it.

The profitability of low-carbon generation investments such as a new nuclear power plants and its correlation with the wider market can thus not be decided upon without taking into account the broader societal and political context. By definition, the correlation of the risk and profitability of a low-carbon investment with the risk of a broader market portfolio is based on a long-term judgement concerning the evolution of the economic system as a whole, including the latter's vulnerability to climate change. Such a judgement is of a social or political nature as much as of an economic or financial one. This does not imply that the following reasoning applies only to the public financing of nuclear power plants. However, it means that the correlation with overall market risk of a low-carbon power generation project such as a new nuclear plant depends on social and political framework conditions inasmuch they (1) imply an appreciation of the true risks of climate change and (2) determine the economic environment under which both a nuclear power plant and the wider market operate.

Concretely, the profitability of a nuclear power plant, the profitability of the set of alternative investments that constitute the broader market and, crucially, the correlation between the two will differ in a country that has credibly committed itself to reaching a target of net zero emissions compared with a country that has not committed itself in like manner. Such a link between policy commitment, risk and profitability may, for instance, be mediated by the price of carbon. As policies are implemented to ensure net zero emissions, the explicit or implicit carbon price will rise. Other things being equal, this will increase the profitability of nuclear power plants and other low-carbon generators at least until some residual coal- or gas-based generation remains in the electricity system or the wider energy system. The same increase in carbon prices, however, constitutes a constraint on the rest of the economy, not only on fossil fuel-based generation. It will affect through increased input costs and newly required substitutions and adaptations all economic activity as measured by GDP, even though of course it enhances overall well-being according to broader welfare metrics.

Policies to ensure robust carbon emission reductions will thus increase the long-term profitability of low-carbon investments while decreasing that of all other investments. Such opposing movements of profitability result precisely in what is referred to in the framework of the CAPM as a negative β_n between an investment in low-carbon power generation and a market portfolio of alternative investments. In other words, including low-carbon power generation such as nuclear into this kind of broad-based market portfolio would diversify the latter's overall risk and reduce the volatility of the portfolio at each level of profitability, which is a quality highly sought after by investors. If it is proven that including low-carbon investments reduce long-term portfolio risk, the attractiveness of such investments would also become obvious to private investors. There are no public good or externality arguments invoked here other than the strategic policy choice to reduce carbon emission in a framework of realising net zero emissions.

This report will not argue on the basis of a negative β_n but will adopt the less radical assumption of $\beta_n = 0$. While the former is not unthinkable, it would imply that investors on average would accept slightly negative returns investing in low-carbon generation as the loss would be more than outweighed by the benefit of diversifying their portfolios. This would require an exceptionally high degree of confidence in negative long-term correlations. There are also limits to the negative correlation argument. Very strong carbon emission reduction policies might cause the economy to contract and electricity demand and prices to decline and so forth. Nevertheless, the principal argument that emission reduction policies will drive a wedge between the profitability of low-carbon generation investments such as nuclear power and other investments is sound. A zero correlation is an appropriate central assumption, based on which investors can make their own assessments.

While $\beta_n = 0$ may seem like a strong assumption even given the above considerations, an important empirical argument will help to put it into perspective. Already today, US electric utilities (non-water utilities) have a lower than average correlation with the remainder of financial markets, i.e. $\beta_n < 1$ (see New York University [2022] or Ehrenmann [2021]). The fact that a portion of the revenue of electric utilities comes from regulated sources plays a role in this lack of correlation with the overall market. This correlation further decreases with an increase in the share in the generation mix of capital-intensive low-carbon generation technologies such as nuclear, since the latter's revenues are likely to be regulated. The stable cash-flow of a low-carbon emitter's electricity, provided for instance through a long-term contract for difference (CFD), will be uncorrelated to wider market developments. As will be argued further below, in the section on idiosyncratic price risk, low-carbon electricity markets will need to be hybrid markets in which investment returns are financed through different forms of long-term guarantees for stable electricity prices. This will further de-correlate the returns from low-carbon investments from the evolution of GDP and the profitability of other financial investments.

If the correlation β_n of nuclear power generation projects with overall market risk is indeed zero, the size of the latter no longer matters for determining the cost of capital for such investments. Nevertheless, it is useful to recall the nature of systemic market risk to better understand the difference between the financing conditions for low-carbon investments and the financing conditions prevailing in the rest of the economy.

Technically speaking, systemic risk corresponds to the residual risk that is present even when a portfolio of financial assets is optimally diversified. It is thus a risk that concerns financial markets and the economic activity they reflect as a whole. It depends, among other things, on the mimetic behaviour of investors over different assets, which is the degree to which diversification brings benefits, on the general level of confidence in the financial and economic system, and on the policies of central banks. Determining quantitatively the level of systemic risk is a highly technical and empirically a largely complex area of research with certainties. One manner to approach the issue is to consider the cost of bank reserves determined by financial market regulators as sufficient for withstanding a major macroeconomic shock. Baumstark and Gollier (2014) are among the few authors willing to present a concrete figure and estimate the systemic risk rate at $r_s = 3\%$ (*ibid.*, p. 48).[8]

The key question is now to which extent the financial risk of a low-carbon investment, such as the construction of a new nuclear power plant, correlates to the general systemic risk in the rest of the economy under conditions of implementing policies to achieve net zero carbon emissions. Attaining net zero will have substantial economic costs, regardless of affirmations to the contrary put forward for political or commercial expediency. In other words, attaining net zero will increase the risks and reduce the average profitability of investments throughout the economy. However, what is likely to happen with the risk and average profitability of low-carbon generation projects under such conditions?

Ultimately, this is an empirical question. However, there are good grounds to assume that under policies to reach net zero the risks of essential low-carbon generation options will decrease rather than increase or, at the very least, will be de-correlated from the economic risk of undifferentiated investment projects. As indicated, electricity market reform moving towards stable long-term revenues for low-carbon generators would further strengthen this argument. Figure 2.1 schematically indicates such a contrary movement of respective risks.

If the general argument of a decorrelation of the risk profiles of general investments and of low-carbon generation investments is accepted, the more formal financial argument is quickly made. Including low-carbon in an investment portfolio will reduce the latter's overall volatility and risk at any given level of average profitability. Technically speaking, including low-carbon generation investments will reduce the standard deviation of a portfolio's returns and increase its Sharpe ratio (returns divided by the standard deviation, see Figure 2.2).

8. Newbery (2021) indicates an equity risk premium (ERP) of 5%-6%. While the equity risk premium refers only to the relatively more volatile stock market and systemic risk would include all financial assets, in particular also bonds, the figure provided nevertheless further confirms an order of magnitude.

Figure 2.1

General investment risk vs. the risk of low-carbon investments in a net zero context

1. As climate change and efforts to combat it intensify, implicit and explicit carbon prices will rise.

2. This will *decrease* profitability throughout the economy…

3. …but will *increase* the value of low-carbon investments.

4. If this holds true (1), including a low-carbon investment will reduce an investment portfolio's Sharpe ratio already with $\beta_n = 0$ or reduce its standard deviation the $\beta_n < 0$.

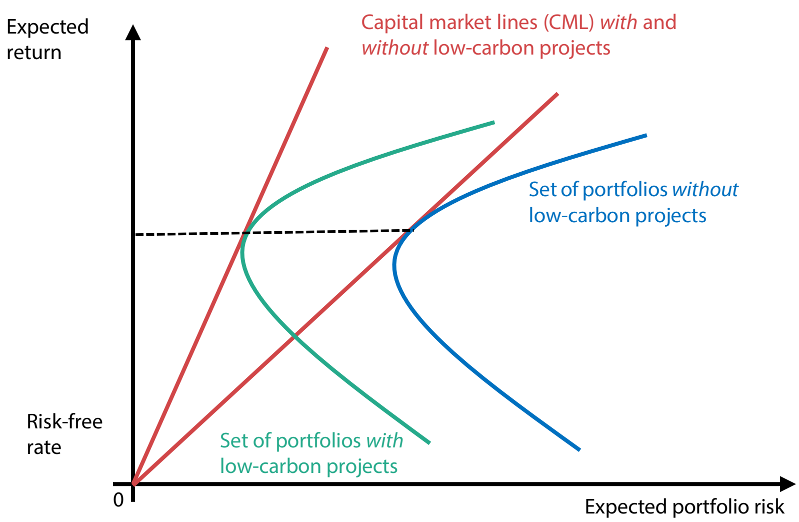
5. If this holds true (2), investors will accept very low returns on low-carbon investments since they will reduce overall portfolio risk and provide portfolio insurance.

"High-emitting assets are significantly more sensitive to economy-wide fluctuations than low-emitting ones… Our results suggest that carbon emission reduction might serve as valuable risk mitigation strategies (Trinks et al., 2022)."

Of course, with the current level of experience with net zero policies, alternative assumptions are legitimate. For instance, one might consider the impacts of the net zero transition on risk profiles as modest. Or one might argue that lower overall growth will lead to lower electricity prices in general, which will affect low-carbon generators just like anybody else. If, on the other hand, one is convinced the implementation of policies to achieve net zero emissions by 2050 will reduce the risk of low-carbon generators and, other things being equal, increase their profitability, then the point of view proposed here applies.

Figure 2.2

The inclusion of low-carbon projects improves the risk-reward ratio of financial portfolios[9]



The choice between the two points of view ultimately depends on political and societal choices. Such choices must be properly prepared. This includes providing information on the likely economic and financial impacts of strategic orientations such as net zero emissions as well as organising the relevant societal decision-making mechanisms. Another question is the role of policies to ensure the security of energy supply, which has gained greater priority in recent months. In principle, any enhancement of the security of energy and electricity supply would

9. The slope of the capital market line (CML) for a portfolio P with an expected return r_P is the latter's *Sharpe ratio* (SR_P) with $SR_P = \frac{r_P - r_f}{\sigma P}$.

strengthen the decorrelation argument. To the extent that measures are taken to facilitate investment in this area as the economy is negatively affected by actual or potential supply interruptions, the profitability of low-carbon generators would tend to increase, precisely when the profitability of the rest of the economy decreases and, in fact, systemic risk increases.

Since more detailed analysis on these issues is currently not available, this note considers $\beta_n = 0$ as the appropriate assumption for the correlation of the investment risk of low-carbon electricity generation with systemic risk. This implies not taking into account systemic financial risk when assessing the cost of capital of a new nuclear power plant. The latter's profitability might be either independent or even negatively correlated with the rest of the economy and would thus serve to hedge financial systemic risk in any portfolio.

Conceptually at least, even a negative correlation of low-carbon generators with systemic risk remains conceivable. Imagine a drastic policy shift in which all emission-producing activities, which implies large swathes of industry, mining and agriculture, were forced to switch to low-carbon electricity. However, as the likelihood of such dramatic shifts also remains uncertain, a zero correlation seems for now a prudent and appropriate assumption. Of course, such a choice is only justified due to the low-carbon nature of nuclear power. The same reasoning would hold also for other low-carbon generation technologies. However, the cost of capital of a gas turbine and even more so of a coal-fired power plant should continue to include its correlation with systemic risk, in particular as long as carbon pricing is insufficiently robust or of uncertain duration.

2.4. The three idiosyncratic risks of investing in a nuclear power plant

As mentioned earlier, idiosyncratic risks are the project-specific risks that are entirely unrelated to the performance of other investments. They pertain, for instance, to the project management inside the perimeter of the firm. In other cases, they may pertain to specific political or legal provisions that only apply to a given project or industry. In the case of an investment in decarbonised electricity generation capacity such as a nuclear power plant, one can distinguish three types of idiosyncratic risk, (1) political risk, (2) market price risk and (3) construction risk. As argued in further detail below, each of these three risks can be reduced or neutralised with appropriate measures.

Frameworks for reduced political risk, price risk and construction risk are set by governments or public actors. It will also be shown below that political risks are best carried governments, while managing price risk or construction risk may involve risk sharing with large numbers of ratepayers or taxpayers. Such risk spreading among a large number of agents, in cases where markets are unable to perform this function, can reduce the economic costs of risk. Risk spreading is necessarily organised by governments or public authorities. Typical mechanisms in the field of low-carbon generation, other than direct public investment, are guaranteed tariffs to neutralise price risk for investors or mechanisms called regulated asset base (RAB) or construction work in progress (CWP) in the case of construction risk.

None of this implies that the public sector is always better than the private sector in managing risks. Markets and the private sector are highly efficient in managing risks as soon as the latter can be quantified in terms of a well-defined probability function. However, in the case of the deep decarbonisation of the electricity and energy sector with the help of new nuclear power plants, the public sector possesses specific instruments and risk management means that no private party has.

As far as political risk is concerned, it is obvious that its management should be located in the public sphere. As far as price risk is concerned, only a public authority could implement a market design that would substitute energy-only markets marked by volatile prices with a long-term financing arrangement guaranteeing the stable prices required by capital-intensive, low-carbon technologies. Highly volatile prices in a decarbonised electricity market, alternating between zero and the price of demand response, would strongly increase the costs of capital. Finally, as regards construction risk, the idiosyncratic risk par excellence, the logic of wide risk sharing through a public agency, embodied in the Arrow-Lind Theorem, applies. With appropriate public intervention, risks in all three dimensions can thus be radically reduced. This means that also project-specific idiosyncratic risks will make a contribution to the postulate put forward in this report that, with proper risk management, the cost of capital of a new nuclear power plant will tend towards zero.

Focussing on financing and the optimal risk allocation in the construction of new nuclear power plants, this chapter will not elaborate on operational risk, i.e. the technical risks of operating an existing nuclear power plant, and hence the question of its continuous availability for generation. Not only is this question not within the scope of this study, it can also be answered quite succinctly: operational risks must be borne by the operator. The latter is clearly the party best placed to reduce and manage operational risks, hence it should bear the costs and benefits of such management. This argument is symmetric to the one that states that political risk should be borne by public decision-makers, i.e. government (see next section). However, things are not so straightforward for price and construction risk. Their discussion thus naturally constitutes the greatest part of this chapter.

Box 2.1

Does it make a difference whether the private or the public sector assumes risks?

Risks are real! Changes in the allocation of risks between the private and public sectors, or between investors, ratepayers and taxpayers, do not directly have an impact on the magnitude of risks. For example, a fixed tariff for electricity provision will eliminate long-term price risk for generators, which, other things being equal, will increase the amount of investment. However, the same fixed tariff will transfer the risks of the real costs of electricity generation to ratepayers or taxpayers. Wind blowing at low demand hours, solar PV not contributing to peak demand, a rise in gas prices, limited short-term flexibility of nuclear power, residential consumers resisting demand response, a technical problem or a meteorological event… these are all real events with real costs. If generators are no longer compelled to react to them through changing prices, network operators will have to handle them and bill consumers or taxpayers for the cost of the compensating measures. The same reasoning applies to construction risks. So risk allocation does not seem to matter other than for questions of distribution.

Does this imply that the strategies for de-risking the costs of capital for investments in nuclear power plants that are put forward in this report just amount to a transfer from the private to the public sector? Yes, and no. "Yes", because indiscriminate transfers of the burden of risks do not reduce the magnitude of the underlying risks. However, also clearly "No", for three reasons:

1. A transfer will not change the underlying physical or structural risk as such but can reduce its economic cost if it is allocated to the party best able to carry it. In particular, the public sector has an ability to reduce the costs of risks through risk spreading that private investors do not possess in the same manner (see below the section on the Arrow-Lind Theorem).
2. A transfer of risk to the party best able to manage the underlying physical risk can also have an impact on the magnitude of the risk itself. Power plant operators should thus assume operational risk in order to minimise it. Efficient markets would ensure such an outcome. But transaction costs, asymmetries of information, rent seeking or inept regulation might all impede it.
3. Finally, in a very general manner, private markets can only deal with certain kinds of risks. Risks can only be traded if they can be expressed in a well-defined probability function. Markets cannot deal with un-codified non-probabilistic risk, which is also referred to as residual risk or uncertainty. Public institutions or national governments are required to deal with such residual risks.

In short, incidence does ultimately matter. Allocating risk to the party that is best able to carry or handle it can reduce the real economic cost of risk. Of course, issues of efficiency and fairness must be considered in each instance.

Political risk

The strategic orientations that determine the organisation of the electricity system are political and rightly so. The fight against climate change and the energy transition, with the decarbonisation first of the electricity sector first and then of the energy system, are in most countries priorities at the national level as well as at the global level. More specifically, the decisions to support renewable energies over the last two decades and to promote or phase out nuclear energy are eminently political.

The precedence of the political sphere in the area of investing in low-carbon technologies in general and nuclear energy in particular is thus out of the question. However, this same precedence creates specific economic and financial risks. The capital costs of investing in a new nuclear power plant with a duration of operations of 60 years or more are not the same if one has to take into account the possibility that it might not reach the end of its projected operating lifetime for political reasons. In such a case, where is the risk best allocated? In a static optimum with perfect information and no transaction costs, the question is moot. However, in a world with dynamic decision-making, informational asymmetries and transaction costs, it assumes great importance. In this case applies the well-known principle of efficiency in the field of public economics and more precisely in the sub-field of law and economics that legal and financial responsibility should be assumed by the actor best placed to manage, reduce and bear the risk in question (see, for example, Calabresi [1961] for a general introduction or NEA [2021] for the application of this principle to the back end of the nuclear fuel cycle).

In the case of political risk to capital-intensive low-carbon investments, the actor best placed to assume political risk is the government itself. Only the latter has the ability and legitimacy to organise the relevant decision-making mechanisms while taking into account the stranded costs of prematurely abandoned assets. This would include compensating third-party investors and adding the stranded costs to its balance sheet. In such a case, however, the cost of capital would remain equal to the rate at which the government can borrow in the markets, i.e. in countries such the United States or France the risk-free rate, while other countries might have to add a small country-specific risk premium. In many countries, the cost of capital would thus remain close to the risk-free rate except in the unlikely event that the liabilities incurred are of such a magnitude that by themselves they affect the cost of financing the debt.

Price risk

Price risk in the electricity market is a complex subject that has been studied extensively, not least in previous work by the Nuclear Energy Agency, such as NEA (2015). It raises two important questions on this topic. The first is, "Why consider price risk in electricity markets as an idiosyncratic risk?" In other words, why would a nuclear power plant not be an industrial and financial asset like any other, positively correlated with the evolution of the whole market and thus to be treated in a CAPM framework with a positive correlation with systemic risk? This would typically be the case, if one assumed that electricity prices over the years evolved in parallel with economic growth.

There is little doubt that the electricity sector sits at the heart of modern knowledge-based economies. Might higher electricity prices thus affect economic growth? Hardly, as the current cost of electricity makes it a small share of the value added of most goods and services, exceptions including electro-intensive steel, aluminium or paper production. Conversely, does higher economic growth increase the demand for electricity and thus its prices? Only very partially and in the short run. In the long run, electricity prices are shaped far more by sector-specific policies. Recently, the introduction of large amounts of wind and solar PV capacity in Europe or the availability of low-cost shale gas in the United States have had far more impact than any correlation with overall economic growth. Reaching net zero carbon emissions has and continues to have an impact on electricity prices, yet as has been argued above, this will primarily drive a wedge between the profitability of low-carbon generators and the rest of the economy.

This holds also in other contexts. The geopolitical dislocations of 2022 clearly have a negative impact on the growth prospects of the economies of OECD countries. Yet, in the electricity sector the debate is about ad hoc windfall taxes as, for a variety of reasons, prices hit historic highs. Thus, by and large, electricity price risk is indeed an idiosyncratic risk already largely decorrelated from the systemic financial risk in the rest of the economy. As regulation and long-term contracts will increasingly dominate the sector, this decorrelation is likely to become even more pronounced.

The second question is, "If it is established that price risk in a decarbonised electricity system is indeed an idiosyncratic risk, how can one best manage this risk to minimise its impact on the cost of capital and the cost of decarbonised electricity altogether?" The answer to this question will essentially constitute the remainder of this section. The reason is that under current market design, a move towards net zero emissions would generate price volatility to an extent that would make investment in capital-intensive low-carbon generation no longer viable. Decarbonising the electricity system thus requires forms of financing other than their remuneration in deregulated energy-only markets. For instance, this could take the form of auctions for long-term contracts, regulated prices or technology-specific CFD, such as those that have been obtained for new nuclear power projects in the United Kingdom. The technological mix would in this case be decided by the government, a regulator or an independent system operator (ISO). Such centralised organisation of long-term investment financing would most likely coexist with a decentralised system co-ordinated through a competitive market for the day-to-day dispatch of electricity from individual plants.

This is far less radical than may appear at first sight. Already today, the overwhelming majority of investments in low-carbon capacity, including nuclear, is financed through pricing arrangements that guarantee a given level of electricity prices to producers. Feed-in tariffs (FIT), CFD, regulated tariffs, etc. reflect the need for capital-intensive low-carbon generators, all technologies included, to obtain a financially sustainable remuneration through guaranteed prices. Around the world, only a small fraction of renewable projects has been realised on the basis of fluctuating market prices. In the case of nuclear energy, the Flamanville power plant in France is the only nuclear new build project ever undertaken without the guarantee of regulated tariffs for the entirety of its output.[10]

Achieving net zero carbon emissions by 2050 will require market designs that support low-carbon electricity generation through predictable long-term remuneration at the level of average costs. Financing the energy transitions on the basis of marginal costs pricing at marginal costs would lead to high price volatility, increased investor risk and far higher costs overall than necessary. The challenge is to move from "exceptional" arrangements to stable general frameworks that allow an adaptation of risk perceptions and the emergence of investment patterns and supply chains. In the fully decarbonised electricity systems of the future, long-term contracts with guaranteed prices to finance investments will inevitably become the rule. For countries that are serious about achieving net zero targets, it is indispensable to come to terms with this reality and to announce and implement the required changes in electricity market design with clarity and conviction.

In decarbonised electricity markets, especially if they include significant shares of VRE, prices established by short-term marginal cost will cease to be economically sustainable. This is due to the fact that the short-run marginal costs of VRE and hydro are zero and those of nuclear probably close to zero, although the latter point is a question of research and discussion.[11]

10 A number of nuclear power plants that were constructed under market designs built around regulated tariffs have since transitioned to deregulated markets. Similarly, feed-in-tariffs for VRE are usually limited in time. However, construction requires some form of price guarantee to cover at least the financially crucial first years or operation.

11 One must distinguish here between short-run marginal costs (the costs of running a plant for one additional hour) and the annual costs for operations, maintenance and fuel. All technologies, including wind and solar PV, have non-negligible annual O&M costs. Spread over annual production, these are sometimes referred to as marginal costs. In the case of nuclear, one would need to add fuel costs. As an accounting convention, this can make sense. However, the resulting "marginal costs" have no influence on the economic dispatch of a plant in reaction to the electricity price. Assume a case in which "marginal costs" for a nuclear power plant on the basis of annual O&M and fuel costs are, say, USD 20/MWh and that the electricity price drops due to a surge in wind production during one hour from USD 30/MWh to USD 5/MWh. In such a case, it would be highly unusual that nuclear generation would be interrupted for one hour. The matter might be different if prices remained consistently at USD 5/MWh for several days. But in terms of the hour-to-hour price setting typical for deregulated electricity markets, the short-term marginal costs of nuclear power reactors are close to zero. They may even be negative in the sense that it is cheaper to keep the plant running than to interrupt or modulate production. The counter-intuitive phenomenon of negative prices is a case in point.

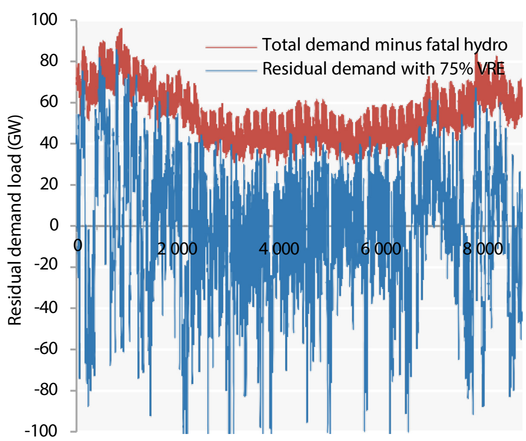
Establishing prices that fully finance the capital costs of generation capacity has always posed particular challenges. Due to non-storability and the absence of differentiation, prices in competitive electricity markets are strictly equal to the variable costs of the marginal plant. This leads to the "missing money" problem, which means that the fixed costs of the marginal technology and a corresponding amount of the fixed costs of the other technologies are only recovered during scarcity hours with rolling blackouts, also referred to as involuntary demand response, when prices reach the value of lost load (VOLL). In other words, with free exit and entry, generators will deliberately under-invest to recuperate their fixed costs during high demand hours when demand exceeds supply. During such scarcity hours, economic prices are undefined (in graphical terms, the demand and the supply curve do not cross) and market prices are set by the regulator and can be as high as USD 10 000 per MWh. Implementing such a system is not easily compatible with standard notions of security of electricity supply and is thus experienced as highly destabilising by consumers and politicians (Keppler, 2017). It remains, however, a cornerstone of modern electricity market design.

In decarbonised electricity systems, prices would then alternate permanently between zero or even negative prices on the one hand and the cost of voluntary or involuntary demand response on the other. This effect will assert itself regardless of whether the mix consists of high shares of renewables, hydroelectricity or nuclear energy. In addition, all low-carbon technologies have high fixed costs. The difficulty of recuperating the high fixed costs of capital-intensive technologies thus exists in all low-carbon electricity markets. Price volatility will, however, be particularly high in markets with large shares of wind and solar PV capacity. The latter's output is concentrated during a limited number of hours due to the fact that all wind-turbines in a given region or country turn at the same time and the solar PV installations produce during the same few hours (autocorrelation effect). Hours with excess renewable generation thus alternate with deficit hours, during which dispatchable means of low-carbon generation are needed (see Figure 2.3 below). This is expensive for the following reasons:

1. Due to the high capital intensity of nuclear power or hydroelectricity, limiting their production as dispatchable low-carbon operators to deficit hours will increase their average costs (LCOE);
2. Voluntary load shedding, whose costs are high but manageable, is only available for a limited number of hours and a limited number of GW; involuntary load shedding, with rolling blackouts and scarcity pricing, has considerable economic and social costs;
3. Intermittency between surplus and deficit hours leads to high price volatility and uncertainty, which increases the cost of capital;
4. Repeated and massive ramps increase stress in the technical management of the system.

Figure 2.3

Hourly demand in a low-carbon electricity system (50 gCO_2/kWh) with 75% wind and solar PV



Source: Cometto and Keppler (NEA, 2019).

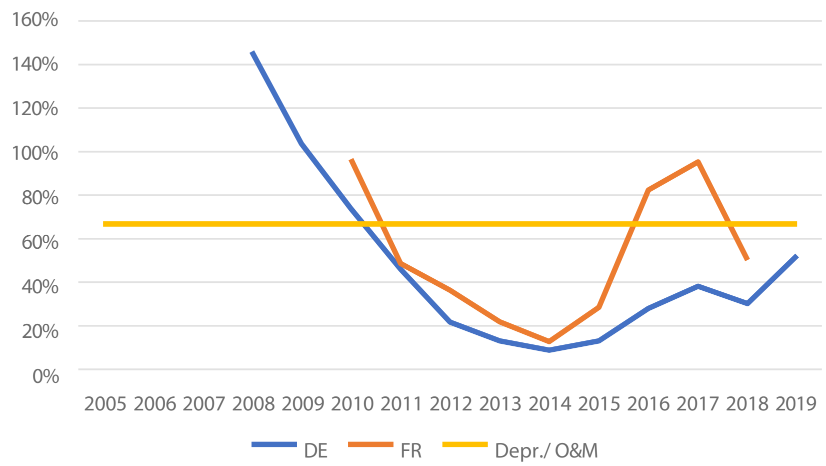
The hourly volatility in dispatchable production by and large corresponds to price volatility, as prices will be positive only when dispatchable production is operating since variable renewables have zero short-run marginal costs. Figure 2.3 starkly shows this effect for high shares of variable renewables such as wind and solar PV. For investors, hourly volatility might be manageable as long as average annual returns are guaranteed. During the past decade, at least in European markets, this has been far from the case. Figure 2.4 shows that for combined cycle gas plants full cost recovery was achieved in a single year in France and not even in a single year in Germany (the yellow line indicates annual fixed costs, capital costs and fixed O&M). The logical consequence was a reduction in capacity through the moth-balling of CCGT capacity. According to the same study, nuclear power plants did somewhat better, but the results heavily depend on assumptions of historic financing costs.

The key point of Figure 2.4, however, is not so much the absolute level of returns but the very strong annual volatility. Markets where returns might be negative for several years in a row before eventually, maybe, returning a profit clearly imply higher risks and capital costs. Part of the reason for this state of affairs has to do with the uneasy coexistence of public and private decision-making in today's electricity markets. Another part is structural. Electricity demand is very inelastic and electricity is difficult to store in large quantities at reasonable costs. Thus even small differences in investment patterns, availability of capacity or weather can make for disproportionate changes from one year to the next. The advent of weather-dependent renewables and the shift towards capital-intensive low-carbon technologies in general exacerbates these tendencies.

Electricity markets are therefore at a crossroads. On the one hand, high gas prices or price-induced voluntary demand response can reduce the number of scarcity hours and are often cited as examples for the workability of deregulated electricity markets. On the other hand, decarbonisation massively intensifies this challenge by requiring ever higher numbers of scarcity hours, implying ever higher volatility to allow for the full recuperation of the fixed costs of investment. There is a growing consensus that deregulated energy markets with marginal cost pricing are inappropriate for the deep decarbonisation of the electricity sector and require alternative market designs.[12]

Figure 2.4

Full cost recovery of combined cycle gas plants in France and Germany (percent, 2008-2019)



Source: Weale (2021).

12 For more details, see Keppler, J.H., M. Saguan and S. Quemin (2021), "Why the Sustainable Provision of Low-Carbon Electricity Needs Hybrid Markets: The Conceptual Basics", www.ceem-dauphine.org/assets/wp/pdf/WP50_Why_the_Sustainable_Provision_of_Low-Carbon_Electricity_Needs_Hybrid_Markets.pdf.

The most advanced considerations in this field theorise the notion of "hybrid markets", which would combine short-term dispatch with long-term capital cost support that would remunerate electricity generation at average rather than at marginal cost. There are two principal options for such long-term arrangements, which may also be used in a complementary fashion:

a) Competitive auctions for long-term contracts guaranteeing either a price (feed-in-tariff or FIT) or a top up to market prices (feed-in premium or FIP) for each MWh produced. For large-scale nuclear projects, which are often sui generis, negotiated solutions such as CFD at average costs are the preferred solutions.

b) Direct public support for lowering the cost of capital. There exist different options for this such as governments taking direct equity stakes, loan guarantees or low-cost capital provided by a public investment bank. This is also the solution advocated in Newbery (2021). It has the advantage of not affecting the dispatch decisions of the operator.

The costs for the long-term contracts or the capital support would be borne either by electricity consumers or by taxpayers. In a world of incomplete contracts, such long-terms contracts would shift some real risks to these stakeholders – imagine reduced wind speeds when contracts have been negotiated under the assumption of higher wind-speeds or design faults that only reveal themselves after commissioning. There are nevertheless good reasons to believe that such changes in risk allocation are welfare-improving. First, risk spreading will allocate only a very small portion of the overall risk to any given individual, which does not reduce the risk per se but the economic cost of risk (see also next section). Second, in a sector as sensitive to even minor changes in the generation mix as is the electricity sector, improved overall certainty due to the fact that the mix is now determined in a centralised fashion benefits all parties. Box 2.2 below provides the results of a dedicated modelling effort to determine the respective costs of reaching net zero carbon emissions once in a deregulated market and once in a market with long-term contracts.

Box 2.2

The impact of price volatility on the cost of capital

In a net zero world, electricity markets will need to be profoundly redesigned. The price volatility due to the remuneration of electricity on the basis of spot market prices based on variable costs alone will otherwise choke off investment. The cost of capital investing in low-carbon technologies based on market prices alone would become unsustainable. This can be shown convincingly by applying the CAPM framework to the correlation of the revenues of generation technologies under different market designs (see Peluchon [2019] and [2021] for full details).[13] In a CAPM framework, the lower a technology's variable costs, the more stable its revenues will be and the lower its cost of capital. In this approach, nuclear and VRE with low variable costs hold an intrinsic advantage over fossil fuels with their higher variable costs. In a liberalised market of today, which would still include gas and coal-fired generation, a simulation thus yields the rates for the cost of capital indicated in Figure 2.5.

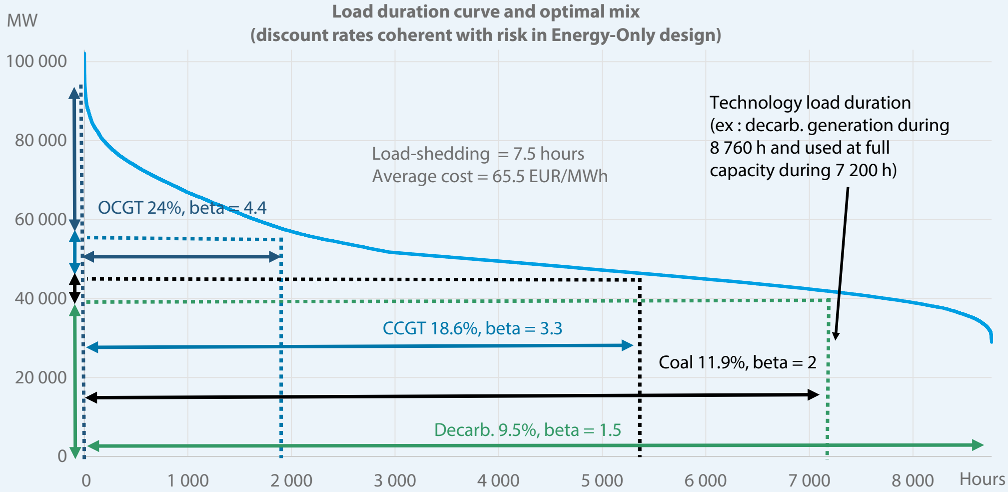
In a fully decarbonised net zero market, however, low-carbon technologies such as nuclear energy become themselves marginal and thus suffer from the volatility between zero prices and either voluntary demand response at USD 1 000 per MWh with a maximum capacity of 20 GW, or enforced load

13. The CAPM is not the only possible approach to assess the risk and cost of capital in investing in power generation assets. It is an approach based on the assumption that historical volatilities will remain stable and thus also apply to future investments. Keppler and Cometto (NEA, 2015) instead proposed an approach that valued the real option held by low fixed cost technologies such as gas when facing price disruptions due to structural changes without mean reversion, for example when prices durably go down due to energy policy changes. In a similar spirit, Newbery, Nuttal and Roques (2008) analysed the value of the implicit hedge of gas-fired power plants, which as marginal generators maintain a stable rate of profit even when prices change. It is beyond the scope of this report to comment on these approaches in detail. Peluchon's work makes it possible to highlight in a widely recognised framework the inevitable increase in price volatility and thus the need to progress towards alternative market designs in decarbonised electricity systems.

shedding at USD 20 000 per MWh. The number of scarcity hours would increase to 52 hours per year and average MWh costs would increase by more than 80%. A deregulated electricity market with only capital-intensive low-carbon technologies quickly becomes economically unviable.

Figure 2.5

Costs of capital and correlation with systemic risk (beta) with residual carbon emissions

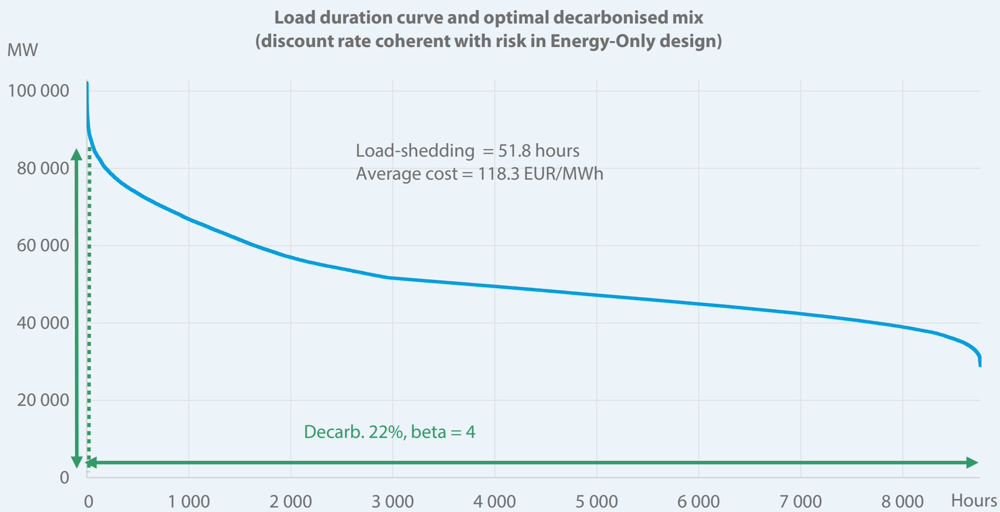


Source: Peluchon (2021).

The alternative would be a market design based on long-term contracts guaranteeing stable prices. This would reduce the cost of capital from 22% to 3.2% as investors no longer have to fear not recovering their outlays. The number of scarcity hours priced at the value of lost load (VOLL) of EUR 20 000 would fall from 52h to 3h and the average cost of the system would drop by more than 40% to EUR 82.5 per MWh. The latter is here a pure effect of the decrease in the cost of capital as the generation mix remains unchanged.

Figure 2.6

Costs of capital and correlation with systemic risk (beta) in a net zero system



Source: Peluchon (2021).

In short, if lowering the cost of capital is the objective of a market design adapted to decarbonised electricity systems to avoid the alternation between zero price and cost of default, the guarantee of long-term prices is one of the principal solutions to encourage investment and lower costs for the entire system. Such a market design would radically reduce price risk while removing any correlation with the overall economic evolution. An assumption of $\beta_n = 0$ would thus be appropriate following the elimination of price risk.

At this point, one can return to the initial question of whether electricity price risk is part of systemic risk or constitutes a particular form of industry-specific (idiosyncratic) risk. The preceding paragraphs support the argument that in low-carbon electricity markets, electricity prices evolve according to logics that are only very indirectly related to economic growth or general profitability of investment. This would hold for both deregulated markets with marginal cost pricing and markets where long-term contracts remunerate average costs. In other words, electricity price risk would indeed be an idiosyncratic risk and would not imply closer correlation with systemic financial risk.

In deregulated markets, price risk is primarily a function of the share of variable renewables, the availability of flexibility resources and the strength of the carbon constraint. This holds independently of whether the carbon constraint comes in the form of a limit on emissions per kWh or in the form of a carbon price. In markets built around long-term contracts, prices will correspond to cost. In either case, economic growth and the overall demand for electricity will play a very limited or no role at all in the determination of the level and the volatility of prices. In the absence of any correlation with systemic risk, β_n remains equal to zero. Of course, absence of correlation with systemic risk does not imply absence of price risk, quite the contrary. As shown earlier, electricity price risk in low-carbon markets can be significant. However, policymaking should address it directly as a specific risk for investing in low-carbon generation primarily by allowing for long-term cost-based contracts potentially established through competitive auctions. In the nuclear sector, CFD have been the instrument of choice. Once neutralised in this manner, price risk will no longer impact the costs of capital of nuclear new build projects.

However, a consensus is forming that CFDs guaranteeing a long-term price close to the average cost of production are not enough to provide sufficient incentives to build the large amounts of nuclear capacity that are required to reach net zero by 2050. This is due to the particularly high financial risk of constructing new nuclear power plants (see following section). This is why CFDs, at least at levels anywhere near politically and socially acceptable levels, i.e. close to average costs as well as close to existing electricity prices, are on their own insufficient instruments. They remain necessary, however, to ensure against price risks even if construction risks are optimally managed.

Construction risk

The construction risk of new power plants, particularly of nuclear power plants, is an idiosyncratic risk par excellence. The reason is simply that the object in question is not yet a tradable financial asset and therefore has no correlation with other assets. In other words, during construction a project is still within the sphere of the firm, but not yet in the sphere of the market. Construction risk is no less real, though. Indeed, construction risks can bring individual companies to their knees if cost overruns get out of hand. The corporate fates of Areva and Toshiba-Westinghouse are cases in point.

Construction risk as an idiosyncratic risk does not enter into the considerations of systemic risk under the CAPM framework. Thus construction risk cannot be diversified and private investors are likely to ask for considerable risk premiums to be compensated. The strike prices negotiated for the electricity generated by the Hinkley Point C plant were therefore considerably higher than electricity market prices at the time. This was due to the fact that no other effective risk mitigation element was on offer. Construction risk had to be insured through prices on future output.

However, idiosyncratic risks permit the application of another important building block of economic theory, which is the theorem (or principle) of Arrow and Lind. They established in 1970 that if a public entity undertakes a risk project but then shares the costs and benefits among a large number of individuals, the economic costs of the idiosyncratic risks of that project will essentially fall to zero and enable the project in question to be undertaken at the risk-free rate.

The Arrow-Lind Theorem is based on three key assumptions, all of which are quite reasonable. First, people are risk averse. This one is particularly uncontroversial as without risk aversion, there would be no added costs due to the riskiness of a project. Second, project returns and costs are only a small part of each individual's income, which is of course what is accomplished through risk spreading. Third, the absence of a correlation between project outcome and income or economic growth. In other words, the logic of the Arrow-Lind Theorem can only be applied to truly idiosyncratic and non-tradable risks.

There is a fourth assumption that was, however, rarely evoked at the time as theorists and policymakers were understandably fascinated by the wide-ranging implications of the work by Arrow and Lind: existing financial markets are unable to perform risk spreading by themselves. If financial markets had zero transaction costs and information was perfect, including for retail investors, an investor could sell small parts of a project to millions of individuals whose collective willingness to accept its risks would be lower than that of the investor.

The decisive fact is, of course, that the construction risks of a large infrastructure project such as a new nuclear power plant cannot be traded. If that risk was tradable, information was perfect and transaction costs in financial markets absent, risk spreading could be realised by individual investors themselves. Yet, construction risk is difficult to codify in the form of the well-defined probability functions that markets require to operate. Construction risk is akin to what Frank Knight, one of the founders of the Chicago School of economics, called "uncertainty", i.e. a non-codifiable, non-measurable and non-monetisable residual of risk. Such untradeable, and hence non-diversifiable, risk needs to be taken on by non-market actors, typically governments, or in Knight's vision by buccaneering entrepreneurs willing to act as un-hedged insurers of last resort. Clearly, the size of the required investment has a bearing on the question of what kind of actor is best placed to substitute for the market.

The question of whether markets or governments are the more appropriate medium for risk spreading is ultimately an empirical one. Smaller projects, efficient retail investment markets and easily communicable risk-reward structures would seek to employ the market mechanism. Instead, a very large and complex project such as a new nuclear power plant that has a bearing on non-monetisable public goods such as regional development, the security of energy supply and climate change would require public authorities to implement risk sharing.[14]

After carefully analysing under which circumstances public risk sharing organised by governments or public regulators is appropriate, the politically loaded question of whether this constitutes a form of subsidy can also be answered. Risk sharing organised from the centre is appropriate if it is the only way to get a socially desirable project off the ground. In other words,

14 In the economic literature, such motivations for government action are sometimes linked to the "incompleteness" of the set of markets for risk. Formally, this is correct. If there was a market for every utility-relevant aspect of life no alterative allocation mechanisms would be required. However, the language of market completeness implies that it suffices to create the relevant market to solve an issue and make public intervention obsolete. This obscures the fact, emphasised by Knight, that some hazards are uncertain, i.e. intrinsically untradeable. Of course, the dividing line between tradeable risk and untradeable uncertainty can shift over time. The aerospace sector is sometimes cited as an example. However, at least for another decade, the construction of new Generation III+ reactors, a fortiori of Generation IV reactors, can be safely considered to contain large amounts of uncertainty whose costs cannot be diversified by markets alone.

Voluntary market creation as opposed to autonomous market emergence also has a patchy record. The paradigmatic example of recent years is the markets for carbon emissions. While the latter are easily measurable and monetisable, their dependence on politically set emission caps and long-term climate policies has prices depend on anticipation and sentiment rather than on abatement costs as postulated by theorists. If carbon markets play a useful role as a signal of long-term commitment, there will always be issues in the energy and climate field where market incompleteness is inescapable.

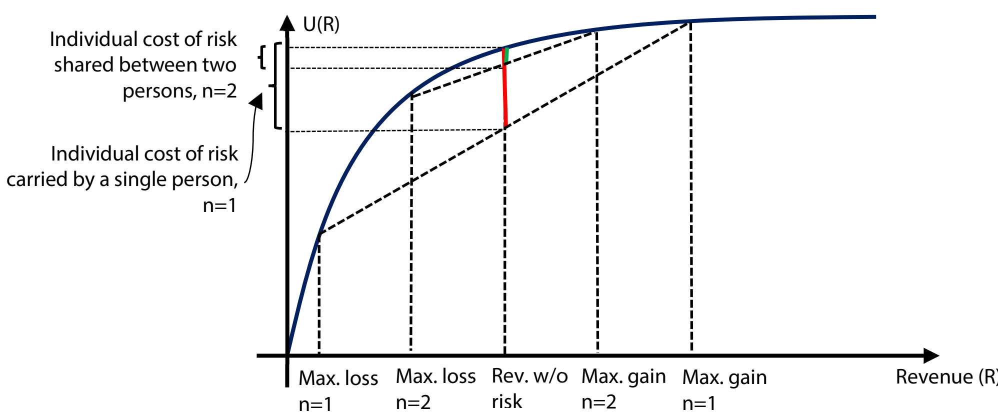
if the transaction costs for sharing risks in a decentralised fashion through private markets prove too high, most notably because a project's benefits cannot be priced, risk sharing or direct public finance remains the economically optimal way forward.

That said, any risk sharing arrangement implies a new distribution of costs and benefits. Distributional considerations thus need to be carefully considered from the start. Only in a world without transaction costs and perfect information will total de-risking bring down the economic costs of risk, and hence the cost of capital, close to the rate at which governments can borrow. The interests of those who will carry the remaining cost of the risk in risk-spreading arrangements, typically electricity ratepayers or taxpayers need to be carefully protected to avoid the charge of providing implicit or explicit subsidies.

If this is ascertained, it is thus appropriate that for certain socially desirable projects governments implement the sort of risk spreading that sees the economic cost of risk approach zero if the number of individuals involved is large enough. However, how does the underlying economic mechanism actually work? The fact that spreading a given risk over two or more individuals reduces its economic cost is due to risk aversion or, equivalently, to the decreasing marginal utility of income. A simple example might illustrate this: for a risk averse individual, the loss in utility or the economic pain of losing USD 100 is more than twice as high as the loss in utility of losing USD 50 (see also Figure 2.7 below).

Figure 2.7

Reducing the economic cost of risk when sharing it between two agents[15]



In other words, spreading the loss between as many actors as possible will decrease the economic cost of the risk. If the number of agents was infinite, the cost of the risk would be zero.[16]

15. The graph shows income changes, in the form of either a gain or a loss, from a risky project on the horizontal axis and the corresponding loss in utility or well-being on the vertical axis. The function linking income and utility is logarithmic due to risk aversion, as each unit subsequent unit of additional income translates into ever smaller increases in utility. For a risk-neutral person, the function would figure as a straight line. The riskiness of the project thus induces a utility loss indicated by the bold red line. What the graph also shows is that if the same project is shared equally between two people, the corresponding gains or losses would logically be halved. This has implication also for the magnitude of the utility loss. The individual utility loss is now *more than halved* as the range of possible outcomes is reduced. In other words, risk sharing ensures that the sum of the utility losses is smaller than the original individual utility loss for the same range of gains and losses.

16. Gollier and Baumstark (2014) point out that according to the Arrow-Pratt approximation the cost of risk is roughly proportional to its variance or, equivalently, to the square of its size. Hence if each of n agents bears $1/n$ of the risk of a project, then each of them bears a cost of the risk that is proportional to $1/n^2$. This in return will yield a total economic cost of risk proportional to n/n^2 or $1/n$ of the original economic cost of the project risk when one agent bore the entire risk alone. The total cost of the risk thus tends to zero as the number of agents tends to infinity.

Of course, eliminating the economic cost of the risk does not eliminate the underlying costs of the project net of risk. But the Arrow-Lind Theorem states precisely that the decision for a project to go ahead should be based on a cost-benefit analysis that uses the risk-free rate as the cost of capital. The graph below shows how the reduction in utility loss following the spreading of a given amount of risk between two agents is a function of the shape of the utility function.

The Arrow-Lind Theorem is a powerful argument for reducing the economic costs of risk by transferring it to either ratepayers or taxpayers in cases where the nature of said risks does not allow sharing through the financial markets. However, it does not justify an indiscriminate increase in public funding. First, the question of managerial efficiency constitutes a fundamental limitation of the Arrow-Lind Theorem. Indeed, not all risks, even if they are idiosyncratic, should be socialised. The only projects that should be transferred to the public sector are those where the gains from reducing the economic costs of idiosyncratic risk through risk sharing are greater than the loss of incentives and of technical efficiency due to public ownership.

Second, one needs to ensure that the risks in question are indeed idiosyncratic. The economic benefits of certain construction projects may be tradable on financial markets and may also be correlated with income, growth and the broader market. In such cases, the logic of the CAPM would reassert itself and public investment would simply mean socialising risks without any additional benefits due to risk sharing. A similar effect would arise if different idiosyncratic risks were correlated. However, as argued above, there are good reasons to believe that investing in new nuclear power plants under a firm commitment to decarbonise the electricity sector has particular characteristics that will continue to argue for public involvement.

Third, any risk sharing mechanism involving the general public must be mindful of distribution and fairness. It would be calamitous for the social acceptability of any project to give even the impression of socialising risks in order to de-risk private profits. This requires, in particular, respecting two general principles. First, upside risks, i.e. higher than expected benefits, must be shared, for instance through rate reductions, in the same manner as downside risks. Second, there must be backstop provisions in order not to hold the public liable for infinite financial risks of ill-conceived or otherwise no longer realisable projects.

In order to develop an intuition for the potential benefits of such involvement, it is instructive to look at specific numbers. In their study of the financing of the planned Sizewell C nuclear power plant, Newbery et al. (2019) calculate the cost reduction resulting from the transfer of construction risk from the project company either to the government through a direct equity investment or to consumers. In the latter case, the costs of construction would be integrated into the regulated electricity tariff, a provision that is referred to as the RAB in the United Kingdom. The inclusion of the cost into consumer tariffs would start at the moment of breaking the ground for the project. This distinguishes the RAB-model, for instance, from a CFD, which imputes costs into consumer tariffs only after commissioning. In other words, a CFD will share only price risk among consumers but leave construction risk with the primary contractor and its shareholders. A RAB instead will share construction risk among ratepayers.

The impacts of such a risk transfer can be considerable. With purely private financing, the weighted average cost of capital (WACC) of Sizewell C would be 8% and the LCOE of the completed plant GBP 96 per MWh. With a 60% share of public investment in the project, the WACC would drop to 3.5% and the LCOE to GBP 52 per MWh. Finally, including construction costs into the electricity tariff under the RAB-model from the start and assuming a public discount rate of 2%, the LCOE of the plant would drop as low as GBP 50 per MWh. The additional cost of this pre-financing of construction costs for each one of the 27 million UK households would amount to GBP 4 per year (Newbery et al., p. 48). The total costs of the project for each household would be GBP 10.5 per year (*The Times*, 8 July 2021).

These figures can be interpreted in different ways. On the one hand, the reasoning of Arrow and Lind applies. The rather small increase in electricity bills should indeed have a limited impact on the well-being of consumers (even multiplied by 27 million) and must be weighed against the benefits of an additional 3.2 GW of capacity for dispatchable low-carbon electricity. On the other hand, where does such reasoning end? If the argument of risk sharing takes absolute priority, the logical consequence would be to move towards a fully planned economy in which the state organises all investment.

As mentioned earlier, there are two limits to the argument of systematic sharing. First, the incentives provided by such ex ante financing guarantees must still ensure that project managers make every effort to complete construction on time and on budget. For this reason, Newbery et al. (2019), propose a hybrid RAB. This means that the risk of a cost overrun is shared between consumers and the private investors behind the project manager. Their example calls for a 60/40 split between the two parties, up to a cap of a 30% cost overrun. Beyond that point, all cost risks would be borne by consumers (Newbery et al. [2019], p. 20). However, up the 30% cap, the project manager's payoff would be a function of his or her effort and thus provide the right incentives. Beyond this limit, reputational effects would potentially provide residual incentives to strive to maintain deadlines and meet budgets.

The second limit of the Arrow-Lind reasoning comes back to the question of the correlation of the expected benefits of the project with economic growth and systemic risk. If all investments were financed by the public hand, even modest sums would quickly add up, correlation with income and consumption would become inevitable and higher costs of capital would be required. The answer here comes back to the question, "To what extent is financing a nuclear power plant as part of an infrastructure of decarbonised electricity generation a protective investment with the objective of moderating future climate shocks that is uncorrelated to the profitability of other investments?" In other words, the Arrow-Lind Theorem applies only to a specific class of investments and cannot be generalised.

If we accept the argument that a new nuclear power plant is part of a broad societal effort to cushion the impacts of climate change, then sharing the construction risk, either through direct public financing or through integration into consumer tariffs via a RAB is the right way forward. The framework proposed here would suggest even lower financing costs than those calculated by Newbery et al. (2019). The results quoted above are based on (a) a mix of public-private financing and (b) the assumption that the costs of public financing are equal to the social discount rate, i.e. the rate at which the cost of capital should be included in the cost-benefit analysis of public investment projects, at 2%. The latter, however, was set by the British government at a time when both the risk-free rate and private borrowing costs were considerably higher than today.

The present framework makes it possible to go further in terms of assessing the socially optimal rate for the costs of capital of a new nuclear construction project. First, full public financing, through either direct investment or a combination of a RAB with a CFD, might be considered. The potential moral hazard issues arising with such a choice and the instruments to address them are discussed in the next chapter. Second, even more straightforwardly, in times where the risk-free rate at which governments with good credit risk can borrow is essentially zero, also the social discount rate (SDR) should be set to zero. Maintaining the construct of a social discount rate for guiding public investments, be it 1.4% (Stern), 2% (Newbery et al.) or 2.5% (France), is no longer justified when the real long-term cost of public borrowing is far lower.

Social discount rates below the cost of public borrowing were introduced during the 1970s and 1980s, when both nominal and real borrowing costs were high, in order to better reflect the interest of future generations. This reflected the wish to provide an implicit subsidy to projects with a longer-term view, as future benefits would weigh heavier in the cost-benefit calculation. This is, of course, still a very relevant consideration. On the benefit side, reducing climate change is a long-term issue that will primarily affect future generations. On the cost side, low-carbon assets such as a nuclear power plant or a hydroelectric installation can be expected to have a lifetime of 80 at least years. The year 2050 is a fundamental reference for all net zero efforts.

However, as far as the cost of capital is concerned, the situation is fundamentally different today. Current low real rates in the capital markets ensure that even cost and benefit streams reaching far into the future are automatically reflected in the decisions of private investors today. It would be absurd to override such a state of affairs with a social discount rate defined in entirely different historical circumstances and that would value the well-being of future generations less than market rates. In fact, as far as low-carbon projects in a context of striving for net zero emissions are concerned, the socially optimal cost of capital for low-carbon projects as defined in this report, i.e. the rate at which governments can borrow in the bond markets since correlation with system risk is zero, is also the relevant social discount rate.

The full public financing of the construction of a new nuclear power plant would thus allow funds to be raised at the long-term cost of capital for governments, which for countries with high credit ratings remains close to zero. The alternative option is that construction risk is borne not by the national government but by electricity consumers first through a RAB and then a CFD. However, even in this latter case, the risk-free rate as the appropriate social discount rate should apply. Assuming a social discount rate that is higher than the cost of money established by the markets would imply devaluing the needs of future generations for the benefit of the present generation. It would not only be paradoxical, but unjustifiable, if governments valued the interests of future generations less than financial markets did. Reducing the economic cost of construction risk through risk sharing following the logic of Arrow and Lind would thus imply very low discount rates close to the risk-free rate plus any appropriate country risk premium.

Conclusions on idiosyncratic risks

One can summarise the arguments concerning the impact on the cost of capital of the three principal types of idiosyncratic risk – political risk, price risk and construction risk – in a new nuclear construction project as follows. First, by definition, idiosyncratic risk implies an absence of correlation with broader economic development and hence with system risk. Second, in a new nuclear construction project, the three relevant idiosyncratic risks are optimally managed in the following manner:

a) ***Political risk*** can and should be internalised by the only competent actor in this field, which by definition is a public body, usually a national or provincial government. Hence the relevant cost of capital is the long-term borrowing cost of the government in question, which corresponds to the risk-free rate plus any appropriate country or provincial risk premium.

b) ***Price risk*** is a function of electricity market design. As shown, deep decarbonisation of the electricity sector with capital-intensive low-carbon technologies requires market designs that include some form of long-term price guarantees to operators, which neutralises price risk for investors. Depending on the specific design of such guarantees, this means transferring the risk of changes in the price and the value to consumers or taxpayers. To the extent that a specific social discount rate is no longer applicable, the relevant cost of capital is again the long-term borrowing cost of government, which corresponds to the risk-free rate plus any appropriate risk premium.

c) ***Construction risk*** as a project-specific risk allows the reduction of the economic costs of that risk through risk sharing as indicated by the application of the Arrow-Lind Theorem. The construction risks of large-scale electricity generation projects can be shared either by consumers through the electricity tariff or by taxpayers through direct public financing. In the United Kingdom and the United States, the provisions of a RAB or of CWP imply spreading the economic costs of construction risk among ratepayers from the moment construction starts. Given that taxpayers and electricity consumers form the vast majority of the population, the economic costs of construction risk can be spread very widely. The relevant cost of capital would again be the social discount rate, which as explained should be equal to the risk-free rate plus any appropriate risk premium for the jurisdiction concerned applies.

For the reasons presented, each of the main project-specific, or idiosyncratic, risks facing the construction of new nuclear power generation projects – political risk, price risk and construction risk – can be managed in a manner that implies very low or even zero real capital costs. As indicated at the beginning of this chapter, operational risks that should be borne by the operator are not considered here. These arguments pertaining to idiosyncratic risks in nuclear new build are part of a broader framework that considers investing in new nuclear power plants as part of a coherent and credible low-carbon infrastructure. The latter condition is indispensable to be able to disregard systemic risk, which otherwise would increase financing again. Systemic risk would become relevant if a nuclear power plant was simply part of portfolio of different assets seeking maximum financial returns under commercial conditions.

Finally, it is important to note that the above arguments never appealed to the notion of using a public or social discount rate instead of the market rate. Thus, the assumption of construction risk and political risk by public bodies, as well as a reorganisation of the market adapted to decarbonised electricity systems, does not operate through a simple transfer of private risk to the community, but primarily through a real reduction in the economic cost of idiosyncratic risks.

The limits of the arguments put forward on idiosyncratic risk

Public investment and the transfer of certain risks to electricity consumers, ratepayers or taxpayers can thus reduce the economic cost of the idiosyncratic risks pertaining to politics, prices and construction of nuclear power generation. However, the arguments advanced would be limited if the following two underlying assumptions were not fulfilled:

1. Risk transfer does not affect the incentives of agents nor the technical efficiency of investment execution. In other words, the efficiency of the construction process and the efficiency of dispatch would change depending on the arrangements designed to minimise risks and to lower the cost of financing. This would typically be the case, if the project manager does not strive to build on time and to budget since they have no longer any stake in the outcome (see also Chapter 3).
2. The indicated idiosyncratic risks, in particular price risk and construction risk, remain uncoordinated with other risks contracted by consumers, taxpayers or the governments. Otherwise, new kinds of systemic risks would arise. The indicated risks must also not reach a level at which the fate of an individual project or of the nuclear industry could affect the government budget and thus the cost of a country’s debt.

The first point just applies a ceteris paribus condition, albeit an important one. The issue of incentives and managerial efficiency is perhaps one to be discussed elsewhere in an extension of this work. The second point confirms what was said earlier: the diversification of idiosyncratic risks and, in particular, the application of the Arrow-Lind Theorem is only possible as long as the risks in question are uncorrelated with systemic risk and must not be of a size where they can have systemic effects.

2.5. Synthesis

The preceding sections can be summarised as follows. Given that the rate of return on risk-free assets is historically low, given that the correlation of the returns of a nuclear power project as part of a coherent national low-carbon infrastructure designed to mitigate climate change risks with systemic financial risk is zero or negative, and, finally, given that the public sector can organise the efficient sharing of idiosyncratic risks for new nuclear power generation projects, the correct assumption for the socially optimal cost of capital for investments in new nuclear power generation projects is equal to the risk-free rate plus any appropriate country risk premium.

This conclusion refers to the true social cost of public funds plus the costs of shared idiosyncratic risk. Once again, mobilising such public funds can only be justified in the context of a firm societal and political commitment to the complete decarbonisation (net zero emissions) of the electricity sector. Similarly, the hurdles for justifying societal risk sharing for industrial projects remain high. The arguments made here therefore cannot be used to justify any expansion of the government’s role and of public financing in other economic sectors.

However, if the limiting conditions are not considered too restrictive and the proposed framework is accepted as a basis for practical application, the implications are quite far-reaching both for governments and the private sector. Further steps can be grouped in two broad categories:

- Confirming the absence of or a negative correlation of the returns of low-carbon electricity generators and economic growth and systemic risk. More study is needed in this area. An empirical article in the *Energy Journal* (2022) provides some support when it states:

  > “High-emitting assets are significantly more sensitive to economy-wide fluctuations than low-emitting ones… Our results suggest that carbon emission reduction might serve as valuable risk mitigation strategies (Trinks et al., 2022, p. 181).”

If low-carbon investments provide a hedge against systemic financial risks, private investors should compete for such projects at low costs of capital. To the extent that the absence of correlation or negative correlation is confirmed but private investors still hesitate, this would constitute a market failure, where governments would be called upon to intervene, either by investing themselves or by subsidising the capital costs of low carbon projects, e.g. by offering loan guarantees or low-interest loans through public investments banks.

- Implementing the strategies for reducing the economic costs of risk outlined above. Internalising political risk at the level of political institutions is straightforward. Implementing market designs with long-term price visibility that are appropriate for capital-intensive low-carbon generators will be more challenging. While many low-carbon technologies, including nuclear energy, have already benefitted from such measures in the past, investors would need assurance by way of a broader strategic re-orientation of today's deregulated markets that long-term pricing arrangements are widely available and here to stay for the long run. Finally, the reduction of the economic costs of construction risk through socialisation by way of risk spreading needs to be not only implemented but also adequately communicated, motivated and accompanied in order to ensure that issues of fairness and moral hazard are adequately addressed.

If measures of de-risking are adequately addressed in both categories, the cost of capital for new nuclear power projects will have been reduced to the lowest possible and socially optimal level. Two concluding remarks are due in this context. First, in principle, the arguments advanced in this report do not distinguish between private and public investments. A thoroughly de-risked nuclear new build project will be highly attractive also for private investors. Of course, transaction costs, asymmetries of information and herd behaviour can always drive a wedge between private and public optimality, in particular in an area as complex and as paradigm-shifting as the net zero carbon transition. However, believing that de-risking can minimise the cost of capital does not per se imply a belief in the necessity of public investment. It does, however, require that the public sector as game-keeper and rule-setter implement the relevant de-risking strategies.

Finally, access to low-cost capital is a necessary but not a sufficient condition for successful nuclear new build projects. The first complementary condition is the availability of attractive, fully completed designs that can deliver competitive overnight costs. Overnight costs are capital costs at zero interest. No amount of financial engineering or societal de-risking can compensate for designs that are incomplete, unattractive for technical reasons or too expensive. It is not the purpose of this report to comment on this issue at length. Previous NEA work, notably the 2020 report on reductions in the costs of nuclear construction, has provided perspectives on how to decrease the costs of nuclear construction. The second complementary condition is the implementation of efficient organisational structures and coherent incentive systems when undertaking a nuclear new build mega-project. While this is not the same as optimising the cost of capital, repeated mention has been made of the fact that there are potential intersections between the two challenges, which is why the next chapter will briefly comment on this issue. In conclusion, with attractive designs, a solid project structure and a framework for de-risking the cost of capital, low-carbon nuclear power generation will indeed be able to fulfil its potential as a pillar of the net zero transition.

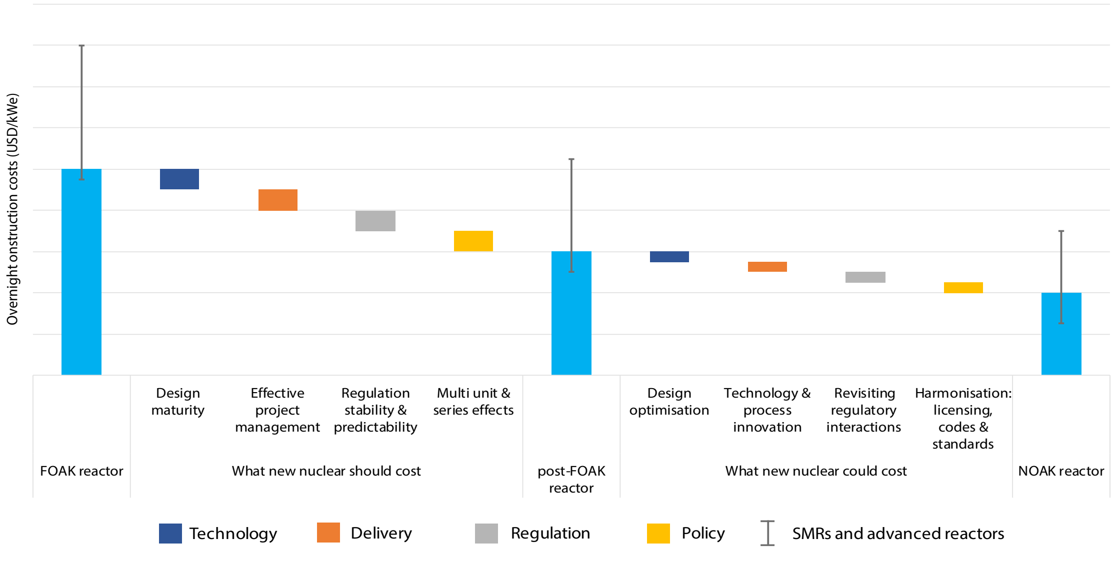
Chapter 3. Remarks on overnight costs, incentive compatibility and project structure

Chapter 2 dealt with arranging for the financing of the construction of new low-carbon generation capacity in general and of new nuclear generation capacity in particular at the lowest possible cost of capital. However, minimising the overall costs of a large construction project is not only a question of financial engineering. It is also a function of three interrelated additional factors: overnight costs, the compatibility of incentives and the project structure. While none of the three is the main topic of this report, they all interact with the financial area in various ways. Future work is planned on these issues at the OECD Nuclear Energy Agency (NEA). This chapter provide an overview of the possible perspectives this work might adopt and indicates the links between these issues and the question of financing. They concern only the construction of nuclear new build projects.

3.1. Overnight costs

First, the costs of a nuclear new build project are, quite obviously, not only a function of capital costs but also a function of the sum of the incompressible costs of the various inputs, the so-called overnight costs, which would need to be disbursed even if financing could be arranged at zero cost of capital. Elsewhere, the NEA has studied the options to reduce overnight costs by way of a mix of technical and organisational processes, from individual first-of-a-kind (FOAK) plants to series with n^{th}-of-a-kind (NOAK) plants (see *Unlocking Reductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders* [NEA, 2020]).

Figure 3.1
Options to reduce overnight costs in nuclear new build



Source: NEA (2020), p. 15.

It is thus presumed that realising all the options for cost reductions in a favourable organisational and regulatory environment could reduce the headline overnight costs that correspond to those indicated in *Projected Costs of Generating Electricity: 2020 Edition* (see Chapter 1) by more than half. While not all options will be realised in all contexts, the report sets out pathways for the most relevant and promising ones.

3.2. The challenge of incentive compatibility

Incentive compatibility relates to the challenge to ensure that all contributors to a construction project make their best possible effort to deliver the project on time and on budget. More specifically, incentive compatibility refers to the need to align the true interests, in terms of income or reputation, of each contributor in order to ensure project delivery on time and on budget. This is less obvious than it seems. Participants may well conform to their contractual duties and still might not contribute to the overall effort in an optimal manner. A supplier would want to get a high price for its goods or services, when the project would benefit from lower prices. Workers or engineers with a stable salary but on a fixed-term contract may put in a reasonable effort but may not go the extra mile as they have no stake in the final project outcome. A tier 2 or 3 contractor will deliver on verifiable project milestones but will pay scant attention to the question how the deliverable slots in with the overall project.

The question of incentive compatibility is clearly everywhere in economic transactions. However, in many routine transactions the issue does not arise as goods and services are fully specified or codified and readily observable. Habit and cultural norms also play their roles in either minimising the issues or, if they arise, in making it possible to efficiently deal with them. This does not apply in large, complex, international projects. It does, in particular, apply when none of the participants has much experience with the issues that will inevitably arise during a vast multi-year effort around technologies that are either partially or entirely new. In those cases, an important insight from institutional economics must be kept in mind: it is impossible to draw up ex ante complete contracts, i.e. contracts that specify the verifiable obligations for each party under all contingencies.

There is a large literature on the "moral hazard" that arises in economic transactions. The best studied field is the design stock option schemes for chief executives in order to align their own incentives with the long-run interests of shareholders. Such incentive schemes, however, can clearly be very imperfect in practice and they can raise additional issues by skewing incentives in new and unforeseen manners.

How can one then ensure that all parties behave in a manner that contributes to the success of the overall project at each important juncture? There are essentially only two principal mechanisms, to borrow the title of a well-known book on the issue: hierarchies or markets. In other words, command and control or financial incentives. Hierarchies seem to function to avoid transaction costs, asymmetries of information and issues with incentive compatibility in large, complex engineering projects. However, they do suppose long-term relationships that leave sufficient time for the establishment of authority, trust, responsibility, both assumed and delegated, as well as an implicit understanding over how to deal with unforeseen, non-codified or even non-codifiable tasks. On the organisational side, the distinction between the construction of FOAK and NOAK plants attempts to capture precisely the gains from working with experienced teams that have established routines and responsibilities as well as with reputations to maintain between now and the next project.

In the absence of functioning hierarchies and stable long-run relationships, financial incentives must be designed in a manner that aligns the legitimate interests of all individual parties with the overarching need to advance and deliver the project. An obvious example would consist of nested bonus schemes, in which each worker not only would receive a monthly salary but would also be eligible for a bonus if certain milestones are met at the level of the team, division and overall project. There is abundant experience with such schemes in industry and finance. This is not the place to discuss their size and structure in detail. Let it just be said that the successful construction of advanced boiling water reactors (ABWRs) in Japan, which were delivered on time and on budget in the early 2000s, used very high-powered bonus schemes. Also, loyalty bonuses or regular career advancement provide added stability to construction teams and to some extent span the gap between fostering long-lived teams and providing incentives for good performance even when the full output of an individual or a team can only be imperfectly monitored and evaluated. The history and culture of large parts of the nuclear industry has not favoured the adoption of such schemes. This requires treading a fine line between existing modes of operation and organisational innovation.

The above considerations about incentive compatibility are not unique to the construction of new nuclear power plants. They are, however, exceptionally important in this field due to the complexity, length and, often, sheer newness of the projects. The gap between what can be codified ex ante in a legal document or a technical design and what is required on-site is hence particularly large. Careful thinking about incentive compatibility and project structure (see below) is thus indispensable for successful project delivery on time and on budget in the nuclear sector.

3.3. Project structure: How to best leverage the relative strengths of the public and private sectors

The challenge in determining the appropriate organisational structure for a nuclear new build project is (a) to combine the relative strengths of the public and private sectors and (b) to provide incentives for all project participants to make the greatest possible effort to perform efficiently, both by satisfying established norms and benchmarks and by seeking further, as yet unknown, efficiency improvements. In other words, a good project structure will combine the ability of the public sector to mobilise funds at very low costs of capital, to set appropriate political framework conditions and to spread even non-codified risks over a large number of parties with the ability of the private sector to perform efficiently, especially in competitive environments when tasks are well-codified and non-diversifiable residual risks are small. The following is a brief discussion of three aspects of the structuring of a nuclear new build project: (a) the financing and framework setting, (b) construction and (c) operations and marketing.

Financing, ownership and framework setting

As spelled out in Chapter 2, government can under certain circumstances hold an advantage in organising financing by being able to borrow directly at the risk-free rate plus any relevant country risk premium. Governments will also decide on general framework conditions, most notably the establishment of low-carbon infrastructure to reduce greenhouse gas emissions in order to protect the economy from climate change impacts, which would radically reduce or even inverse the correlation of project risk with systemic risk. The protection in this case relates both to the physical protection from the impacts of rising global temperatures and to economic protection as carbon-intensive production is progressively discontinued. Finally, government can internalise policy risks, reduce price risk through electricity sector reform and share construction risks among a large number of stakeholders.

As shown, these different dimensions could be de-risked one by one while ultimately leaving private parties to arrange for the financing and ownership the project at comparable costs of capital. This, however, would generate intertwined issues of transaction costs, fairness and incentives. In terms of transaction costs, direct public financing and ownership at least up to the date of commissioning can offer some advantages. In terms of acceptability, public ownership until commissioning can assist in convincing all stakeholders that the near-complete financial de-risking of a multi-billion investment project is indeed a reality.

However, the financing, ownership and oversight also need to be perceived as consistent with the institutions, history and culture of the country in which the nuclear new build is to take place. In many instances, private sector participation in one form or another will be seen as an objective. However, any arrangements will ultimately need to strike a balance between the benefits and the points noted on transaction costs, incentives and transparency.

A simple and potentially attractive option would be to leave ownership of any new nuclear power plant with the public sector up to the date of commissioning. The moment of commissioning constitutes a pivot point in terms of the perception and reality of financial risk and, as will be argued below, a transfer to private parties at this moment would make sense.

Contracts signed before first concrete could already anticipate the partial or complete transfer of the plant to the private sector under specified conditions contingent on the timing and the context of commissioning. An interesting model for such a progressive transfer from public to private ownership as construction progresses and risks diminish is presented in Sawicki and Horbaczewska (2021). Future NEA work is likely to return to the questions of ownership, financing structures and project management in a more systematic fashion.

Construction

Who is better at constructing new nuclear plants and delivering them on time and on budget given the inevitable residual idiosyncratic risks of large complex engineering projects with infrastructure aspects: governments, public enterprises, private enterprises or dedicated public-private special purpose vehicles? The verdict is still out. No party has an unblemished record in this field. Outcomes depend on national circumstances and historic experiences. Whoever is responsible for construction would benefit from stable circumstances and learning over time. Whatever worked well several decades ago, may no longer work so well today. There are no simple, general answers in this area.

However, successful construction ultimately depends on appropriate incentive structures. This means incentives need to be clearly announced and reliably implemented. In some cases, these will be hierarchical structures, either as a direct extension of government or assimilated to it. Such structures would reward loyalty over the long term with well-defined career paths and promotion possibilities. In other cases, integrated bonus structures would give each individual a stake in the performance of larger ensembles and in successful project delivery. From a conceptual point of view, neither has an intrinsic advantage. However, whichever incentive structure is chosen, it needs to be applied with rigour and clarity. Mixing two or more incentive structures will blunt the efficiency of both of them. Anecdotal evidence from recent new build experiences seems to validate this point. More empirical work in this area is required. Commercial confidentiality clauses will cover some of these items, but working with trusted third parties such as international organisations should be able to reduce some of the reticence to provide information on the details of project management.

Under all circumstances, a final arbiter for disputes or strategic questions of project management needs to be designated. If this is a public project, it will be the minister of energy or of public works. In a private project, it will be the CEO. This is necessary as somebody needs to take responsibility for residual, non-codifiable issues that will inevitably arise in complex projects. In other circumstances, such capability has been identified as "leadership", which may be an appropriate term also in this context. The key is that the leader, who may be well rewarded for the work, assumes responsibility if things do not turn out as expected and is the anchor of the incentive structure in any large and complex project. Other aspects of successful nuclear new builds such as design completion, working with local communities and setting up supply chains in anticipation of construction have by now been well identified. They are an intrinsic part of successful construction and are discussed in some detail in NEA (2015) and NEA (2020).

Operations and marketing

When a nuclear power plant has been commissioned and connected to the grid, the enterprise sector, whether in the form of a public, part-public utility or private enterprise, should come into its own. Competitive enterprises are good at responding to market incentives, "sweating assets" and eking out operational efficiency while optimising an asset's use over time. Even when electricity prices are regulated, operators may identify new streams of revenue for system services, heat or hydrogen production. Overall, even in a field as technically complex as nuclear power generation, the risks and rewards, challenges and options in the context of operating a nuclear plant in an integrated power system are well defined and relevant incentive structures are so engrained that they are no longer identified as such. These are private sector issues.

In addition, there is money to be made. There are very few instances in which a working nuclear power plant has lost money for its owners. The rare cases where plants were shut down for economic reasons before the end of their operating licences are confined to the severely buffeted electricity markets of recent years, where the entry of zero marginal cost-renewables with out-of-market finance or super-cheap shale gas made even working nuclear plants unprofitable. However, even this is an industrial risk that private or quasi-private parties can take on at reasonable costs and are willing to acquire at commensurate prices. History has amply confirmed the capability and commitment of both private and public utilities to operate and exploit existing nuclear power plants in the great majority of countries.

Integrating financing, construction and operations in coherent project structures

The challenge is to connect, in a legal and contractual manner, the phases of financing, construction and operation. If the public sector holds a relative advantage in financing and, under some circumstances, construction, the private sector holds a relative advantage in operation. Projects in the nuclear field tend to be marked by a tension between the public and private sectors, whether they have been explicitly identified or not.

This means that the interface of the two sectors needs to be organised in advance in a far more systematic manner than has been the case so far. For example, the handover of a commissioned plant to a consortium of private long-term investors and operating utilities needs to be legally codified at the moment of arranging financing. The conditions under which financial investors and operators arrange themselves are, in principle, a matter of private negotiation and commercial contracts. However, given the enormous size of such projects and the public interest in a smooth handover, the public sector might want to maintain, at least at the beginning, the role of moderator and arbiter in the form of a golden share or similar arrangements.

Of course, the interests of the operating utilities, which will need to prepare their strategies and capabilities well in advance, will also need to be taken into account from the beginning. Comprehensive service and maintenance contracts spanning several decades will need to be carefully specified in terms of performance and remuneration. These are no doubt considerable challenges. Nevertheless, they seem surmountable. More importantly, these challenges pale in comparison to the costs and complexities of financing the construction of a new nuclear power plant without a strong commitment of the public sector to set the necessary framework conditions and to participate, whether through direct participation or risk spreading among ratepayers, in the financing of the construction of a new nuclear power plant up to the date of commissioning.

Chapter 4. Experiences to date with the financing of nuclear new build and policy conclusions

This NEA report sets out a framework for assessing the costs of capital in the financing of nuclear new build projects. It builds on the well-known capital asset pricing model (CAPM) that is widely used by financial analysts. Following the CAPM, it analyses the costs of capital as a function of overall investor risk. The costs of capital are thus determined by the sum of the risk-free rate, the correlation with systemic risk as well as project-specific (idiosyncratic) risks. This report further develops the CAPM framework by providing an in-depth analysis of the correlation of nuclear new build projects with systemic risks under net zero carbon constraints as well as the different risk pertaining specifically to nuclear new build projects. The most important of these risks are construction risk, price risk and political risk.

Furthermore, the report provides perspectives for allocating and managing these risks in a manner that minimises their economic costs and hence the overall cost of financing nuclear new build projects. If fully implemented, these measures would make it possible to reduce the cost of capital to close to the risk-free rate for countries with a high credit rating. This surprising result is due to two factors. First, in a net zero world operating a strong carbon constraint, low-carbon generation such as nuclear energy can provide portfolio insurance to risk-averse investors. As system-wide constraints begin to operate, putting pressure on rates of return for carbon-intensive and even carbon-neutral activities, low-carbon operators will benefit from such constraints or, at the very least, will remain unaffected. Second, risk spreading for construction risks, long-term contracts or regulated tariffs for price risk and neutralisation of political risk through appropriate contractual structures can effectively reduce or eliminate the different dimensions of project-specific, idiosyncratic risk. Both factors together make for very low overall financial risk.

The same insight can be formulated in another manner: if nuclear new build projects are thoroughly de-risked, investors, whether private or public, will offer capital at lower rates of return to acquire the rights predictably produced ow-carbon baseload electricity.

In conclusion, it is useful to briefly return also to two horizontal issues that have implicitly or explicitly been part of the background of the preceding discussions. The first is the confrontation of the conceptual considerations developed in this report with the concrete experiences made in the financing of historical nuclear new build projects, recently concluded projects or those yet to be completed. The second is the question of whether the above considerations fully apply to public and private sector investors alike and, depending on the answer, what the precise role of national governments should be in nuclear new build.

With regards to the nature of financing structures of real-world nuclear new build projects, one general insight can be formulated, even if particular aspects will differ between countries and projects: no nuclear power plant has ever been constructed with pervasive de-risking through the appropriate management and allocation of risks in different dimensions (see also the forthcoming Report 2 of the NEA-IFNEC financing series on *Lessons Learned from Financing New Nuclear Power Plants in Practice*).

In the past, this has often taken the form of direct public financing or guarantees on the debt and balance sheets of publicly owned companies that would then proceed to finance nuclear new build at costs of capital close to those of sovereign debt. Such public financing was combined with (a) regulated tariffs set at average costs and including a rate of return on capital invested agreed to by regulators, (b) vertical integration that guaranteed a stable customer base and (c) long-term political commitments to nuclear power generation. As a result, the costs of capital for nuclear new build projects were low not only from the point of view of the electric utility undertaking the investment, but also in terms of the total economic costs at the societal level.

Such forms of direct finance have, however, fallen progressively out of favour as the vast movement of electricity market deregulation took hold during the 1990s. It is no coincidence that the construction of new nuclear power plants in OECD countries slowed considerably during that period. Many of the reasons for electricity market deregulation at the time were sound as vertically integrated utilities benefitting from regulated tariffs set at comfortable levels had become complacent with rampant over-investment and a lack of entrepreneurial and technological dynamism. However, at the same time, capital-intensive low-carbon generators such as nuclear, hydroelectricity or wind and solar PV were at a structural disadvantage. They had to take on substantial construction risks on the basis of their balance sheets only and suddenly had to cope with both price and quantitative demand risk. Less capital-intensive gas-fired power plants were easier to finance for risk-averse investors. Governments also rapidly decided to provide out-of-market support to variable renewables such as wind and solar PV. This left nuclear energy and hydroelectricity to fend for themselves in an environment they were structurally unsuited for.

The evolution of electricity markets of OECD countries over the past 30 years shows that competitive dispatch with marginal cost pricing is a powerful tool to "wring" additional efficiencies out of existing assets, including existing nuclear power plants, but that it is only now gradually understood that it is an inappropriate manner to finance new investment. It is a bitter irony that markets were deregulated just as countries were making their commitments to cut carbon emissions. Those commitments require massive amounts of new capital-intensive low-carbon capacity, something the new electricity markets struggled to deliver.

The current situation requires finding forms of financial risk management that are compatible both with today's electricity markets as well as with the needs of investors in low-carbon generation. This is precisely the challenge that this report set itself. It requires both a coherent conceptual framework to understand the financial risk pertaining to nuclear new build and its components as well as a broad set of risk management measures that can be adapted to the policymaking contexts of individual countries to master this challenge.

As indicated above, current nuclear new build projects already apply powerful tools for risk management. Measures such as contracts for difference (CFD) in the United Kingdom, regulated tariffs in the United States or long-term contracts to take off electricity at average costs in the Finnish Mankala model are all tools to neutralise price risk once the plant operates. Measures to lower capital costs directly exist explicitly in the form of loan guarantees or implicitly in the form of partial or total public ownership of the utility concerned. Political risk is routinely internalised through appropriate contractual arrangements.

Due to a number of recent experiences, the question of construction risk has received increasing attention. Given the long time frames, high capital costs, potential delays and cost overruns, allotting the full economic costs exclusively to an individual utility can threaten the latter's economic survival no matter what the level of the price arrangements. Spreading the costs of construction over a large number of ratepayers and electricity consumers reduces under certain circumstances the economic costs of the risk for participants individually and collectively. This insight has been translated into practical application under the monikers of construction work in progress (CWP) and regulated asset base (RAB) in the United States and the United Kingdom, respectively.

It then depends on the exact legal codification and the level of the different financial flows whether, for instance, a CFD and a RAB arrangement are substitutes or complements or blend into each other around the date of commissioning. Intrinsic links such as these often blur the debate and can mask the fact that price risk and construction risk are separate. Economic cost minimisation would require in either case specific management measures as well appropriate forms of cost allocation and compensation.

Financial risk management is thus already ubiquitous in nuclear new build. However, it is frequently applied in a partial and, sometimes, haphazard manner that owes more to national precedent and political considerations prevailing at the moment of discussion than to systematic analysis. The objective of this report is precisely to provide decision-makers a more comprehensive view of financial risk management in nuclear new build.

This leads to the second horizontal issue that has been present in the background throughout the report. Do the considerations put forward pertain also to privately funded projects and, if yes, is there a remaining role for governments? The answers are yes and yes. The points made in this report do pertain fully to private investments and, nevertheless, there remain decisive roles for national governments to be played.

In particular, the fact that in a world of robust carbon constraints and, even more so in a net zero economy, low-carbon generation provides portfolio insurance, i.e. is not or is negatively correlated with systemic market risk, applies also to privately funded projects. If such projects do indeed reduce portfolio risk, private investors will also accept very low rates as the projects improve the performance of their portfolios. Of course, myopia, inertia or herd behaviour by private investors may delay the full realisation of this effect. From the point of view of governments, who with good reason think otherwise, this could qualify as a market failure, which could, under clearly defined circumstances and conditions, i.e. that the portfolio insurance effect is empirically demonstrated, justify also direct government financing of low-carbon generation projects.

The argument that with comprehensive financial risk management the real economic costs of a nuclear new build project could be close to the rate of sovereign debt at no point makes use of an exogenously set social discount rate (SDR) or social time preference rate (STPR). Such concepts were introduced in the 1970s, when private real interest rates were high, in order to justify publicly financed projects with the argument that lower interest rates would better ensure that the well-being of future generations is adequately taken into account. However, as private real long-term rates are still close to zero (recent rises in nominal interest rates have either not fed through to longer dated securities or are more than offset by inflation), social discount rates, typically in the range of 2% to 3% real, no longer provide guidance for decision-making. It could even be argued that the “risk-free rate plus the country risk premium” is today the appropriate (welfare optimising) social discount rate.

If private market rates for the cost of capital remain the sole reference for judging the cost of capital of nuclear new build project, what is then the remaining role for governments? One could also turn the question around, asking why the merchant power model proposed for nuclear energy in the early 21st century, predicated solely on private market investment, did not come to fruition. A key role for governments is to put in place the frameworks under which comprehensive risk management can take place.

First and foremost, this concerns the credible and effective commitment to carbon emission reductions. The decorrelation of low-carbon projects from systemic market risk will not be realised where strong emission reduction commitments are not followed up by actions that have real traction in the economy. Whatever the announced objectives, low-carbon generation projects will bring added value only when all other options to procure electricity or energy services, as well as goods relying on them, are foreclosed or, at the very least, gradually phased out over credible timetables. Effectively operating carbon constraints, however, has significant structural effects not all of which have yet been fully appreciated. In particular, significant carbon emission reductions are likely to fundamentally impact the correlation of different assets with systemic financial risk.

Second, governments need to implement the strategies discussed above that eliminate or reduce the economic costs of three project-specific idiosyncratic risks: construction risk through risk spreading over ratepayers, price risk through long-term contracts or regulated tariffs and political risk through appropriate indemnification clauses with government. Questions of managing and allocating large-scale risks are inevitably political questions as they not only regard efficiency but questions of distribution and fairness. These questions will also be addressed in different terms and in different ways in individual countries.

Third, as mentioned earlier, governments can also come in as direct project promoters in the case of market failures when private actors do not realise the true economic value of a nuclear power project, especially in its ability to offset financial portfolio risk. However, one needs to be clear about the nature of the market failure. At no point does the above framework argue for subsidies or support for nuclear new build projects on the basis of public good or strategic objectives such as security of energy supply, technological development, regional cohesion or employment, however valuable they may be. In the present financial framework, the only relevant market failures would concern only the correct appreciation of the economic value of the production of low-carbon electricity. Such a market failure is not necessarily likely. If construction and price risk are indeed credibly neutralised, private investors would compete with reductions in their rate of required returns to acquire the rights to the value of predictably produced low-carbon electricity.

Fourth, governments have a role in ensuring efficient project management structures. While efficient management structures are usually thought of as a comparative strength of the private sector, recent experiences have shown that such management structures cannot be considered independently from the arrangements for financing and risk allocation and the incentives that spring from them. Nuclear power projects are large and complex and involve many players both private and public, at all levels of government. Informational asymmetries are rife and offer scope for gaming even among large entities and experienced professionals. Governments need to ensure that ultimately all stakeholders contribute to the shared objective of completing nuclear new build projects on time and to budget.

Fifth, governments need to ensure macroeconomic stability to keep country risk premiums at a minimum. Nuclear generation projects are capital-intensive and large. An increase of one or two percent above the risk-free rate quickly makes a difference in the real costs of projects. In smaller countries where the investment volume constitutes a noticeable share of the national budget, such considerations are of course even more relevant.

There are thus five important areas in which governments need to stay fully involved in order to enable successful nuclear new build projects. However, they concern framework setting rather than direct investment, except in the case of market failures or the pursuit of public good and strategic objectives, which has not been the topic of this report.

Successful nuclear new build requires combining the contributions of the public and private sectors in a manner that does not blunt their respective strengths but leverages them fully. Only the development of robust frameworks as outlined above will make it possible to leverage the capital, the competence and the entrepreneurial spirit of the private sector. Successful construction will depend also on the clear allocation of responsibilities and risks. The approach presented in this report shows that appropriate de-risking can radically reduce the real financial costs of nuclear new build projects, especially when taking into account the ability to offset systemic financial risk. Viewing the financing of such projects in the comprehensive manner advocated here would not only clarify the issues at stake for governments, investors, project managers and stakeholders but also, if appropriately implemented, reduce the real costs of nuclear new build.

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Financing New Nuclear Power Plants: Minimising the Cost of Capital by Optimising Risk Management

Realising the contribution of nuclear energy to achieving net zero carbon emission in 2050 will require raising significant amounts of capital at competitive rates. On the basis of work under the aegis of the Nuclear Energy Agency (NEA) – International Framework for Nuclear Energy Cooperation (IFNEC) Initiative on Nuclear Financing, this report explores a new framework for analysing the cost of capital for nuclear new build projects. Its key insight is that capital costs can be substantially lowered if the different risks pertaining to such projects such as construction risk, price risk or political risk are properly understood, optimally managed and fairly allocated. In a carbon-constrained world, the true capital costs of nuclear energy and other low-carbon generators will also be lower than customarily assumed due to their ability to offset systemic financial risk. The findings of this report apply equally to private and public investments. Governments nevertheless have important roles to play in ensuring credible net zero commitments, implementing frameworks for optimal risk management and by becoming involved as project participants, in cases where they judge that private actors do not realise the full value of a nuclear power project.

This report is the first in the collection *New perspectives on financing nuclear new build*, highlighting complementary aspects of financing nuclear new build. Other volumes in the series address the financing frameworks and risk allocation strategies proposed or adopted for recent or ongoing nuclear new build projects, environmental, social and governance (ESG) criteria and the electricity market design, project management and incentive structures necessary for nuclear new build projects to succeed.

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