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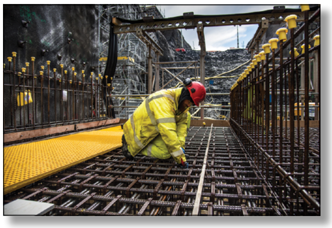
New Perspectives for Financing Nuclear New Build

Financing, Market Design and Project Management in Nuclear New Build



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Nuclear Technology Development and Economics

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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, Czechia, 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

Realising ambitious net zero objectives requires large amounts of new low-carbon electricity generation capacity. As the only dispatchable low-carbon technology that is scalable at will, nuclear energy is poised to play an important role in this context. Solutions for economically, socially and politically sustainable financing of new nuclear construction are thus being formulated at the highest policy-making levels, including at the Nuclear Energy Agency (NEA) Roadmaps to New Nuclear conference series and at the Conference of the Parties (COP) of the United Nations Framework Convention on Climate Change (UNFCCC).

While the potential contribution of nuclear energy is well identified, the challenge of financing and completing complex, multi-billion nuclear constructing projects in rapidly changing electricity systems is also increasingly well understood. This latest report of the NEA collection "New Perspectives for Financing Nuclear New Build" aims to assist decision makers in rising to this challenge. This will involve treating the financing and the management of new nuclear construction projects as interrelated issues in the framework of electricity systems with designs attuned to the needs of the energy transition.

A key point of this report is the notion that financing costs are outputs as well as inputs of nuclear new build projects. If better project management reduces construction and completion risk, this will lower risk premiums and financing costs. This will require that both government, as the insurer of last resort, and private investors play more active roles in the organisation and oversight of new nuclear construction projects in the framework of appropriately designed electricity markets. Already, electricity markets in many countries are beginning to evolve into "hybrid markets", more conducive to capital-intensive low-carbon investment. Maintaining short-term competitive dispatch, such hybrid markets introduce complementary long-term financing modules to support investment targets consistent with least-cost generation mixes identified through careful system modelling.

Improving market designs for trading and remunerating electricity is necessary but not sufficient for nuclear energy to realise its potential in contributing to net zero emissions. As the world has learnt in the past three decades, correctly remunerating electricity generation is one thing; it is quite another to finance the construction of large amounts of low-carbon electricity capacity. Optimally allocating the construction risks of complex large-scale projects such as new nuclear power plants or hydroelectric installations remains essential. Currently, these risks remain too large or cannot be assessed in a manner that would allow pricing and hedging, which means that the public sector will need to complement the private sector, in particular during the early phases of construction.

This report argues that as the public sector assumes a greater role in the financing of nuclear construction projects, it will also need to play a stronger role in overseeing the efficiency and robustness of actual project management to ensure successful nuclear new build. In addition to traditional dimensions of nuclear project management such as advance planning, design completion, supply chains and ensuring the availability of a skilled workforce, future projects will need to prioritise in particular the issues of leadership, independent project advisory and, perhaps most importantly, efficient incentive structures at every level of the value chain.

A greater role in assuming the risks of new nuclear construction projects also requires a sense for the limits of public action and involving the private sector as soon as that the latter can handle the risks of building and, in particular, operating new nuclear power plants. As a nuclear construction project advances, the residuals also become progressively easier to evaluate, to manage and to hedge. There is thus a case for dynamic refinancing during a nuclear construction project, in which the private sector acquires, at a fair price, progressively larger shares of ownership at each successfully passed project milestones. At the date of commissioning, a nuclear power plant should be fully in private hands.

Consistent with its objective to contribute to mastering the challenges posed by new nuclear construction projects, this report concludes with a checklist of ten points that require discussion and resolution before starting a nuclear new build project. We look forward to a lively debate on the crucial issue of optimising financing, market design and project management so that nuclear energy can fulfil its potential to help reach net zero carbon emissions by 2050.

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Acknowledgements

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The work on this report benefitted greatly from the presentations and discussions at the NEA Workshop on "Financing Market Design and Project Management in Nuclear New Build" held in Paris on 11 July 2023 and the conference on "Financing Nuclear New Build Today" organised in collaboration with the government of Czechia and held in Prague on 13 June 2024. Among others, the contributions by Tomáš Ehler, Anurag Gupta, Milt Kaplan, John Parsons, Iain Smedley, Simon Taylor and Charles Weymuller helped to shape the overall framework and highlighted key issues.

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 (Belgium), as well as its co-chairs, Brent Dixon (United States) and Jieun Joo (Korea). The final draft was further improved by highly valuable comments received from Markku Lehtonen, Simon Taylor, the European Commission, the International Atomic Energy Agency (IAEA), as well as from the governments of Austria, Canada and Spain.

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List of abbreviations and acronyms

BWR	Boiling water reactor
CAPM	Capital asset pricing model
CCGT	Combined cycle gas turbine
CFD	Contracts for difference
COP	Conference of the Parties
CRM	Capacity remuneration mechanism
CWP	Construction work in progress
ECI	Early contractor involvement
EPC	Engineering, procurement and construction
EPR	European pressurised reactor
FIP	Feed-in premium
FIT	Feed-in tariff
IAEA	International Atomic Energy Agency
IWACC	Initial weighted average cost of capital
LCOE	Levelised cost of electricity
NEA	Nuclear Energy Agency
NSSS	Nuclear steam supply system
PPA	Power purchase agreement
PWR	Pressurised water reactor
RAB	Regulated asset base
RWM	Radioactive waste management
SMR	Small modular reactor
VRE	Variable renewable energies
WACC	Weighted average cost of capital
WNA	World Nuclear Association
WPNE	Working Party on Nuclear Energy Economics (NEA)

Executive summary

The demand for economically, socially and politically sustainable financing solutions for nuclear new build is now being formulated at the highest policy-making levels. The energy ministers assembled at the Roadmaps to New Nuclear conference, co-hosted by the Nuclear Energy Agency (NEA) and France's Ministry of Energy Transition on 28-29 September 2023, put adequate financing at the centre of their efforts to create the conditions for successful nuclear new build. The financing of new nuclear capacity was also considered an important topic at COP28 (30 November to 12 December 2023).

This report on *Financing, Market Design and Project Management in Nuclear New Build* continues the work undertaken in the earlier NEA report on *Financing New Nuclear Power Plants: Minimising the Cost of Capital by Optimising Risk Management* (NEA, 2022). It is also complementary to the NEA report on *Effective Frameworks and Strategies for Financing Nuclear New Build* (NEA, 2024a). All three reports are part of the programme of work on financing nuclear new build supervised by the NEA Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC). The specificity of this report is to link the question of financing with the questions of electricity market design and project management, all three of being closely intertwined.

In all three dimensions, the relationship between the public and private sector will need to be redefined to realise the substantial increase in nuclear energy capacity that is part of the clear and achievable path to meet ambitious net zero objectives. Currently, the deregulated electricity markets that have become the default market design in NEA countries continue to favour, due to their intrinsic price uncertainty, carbon-emitting technologies with low fixed costs over capital-intensive low-carbon technologies including nuclear energy. Even with more stable revenues provided by long-term arrangements, construction risks for the large baseload installations that will provide the backbone of future low-carbon electricity systems, such as nuclear energy and hydroelectricity, will need to be de-risked by the public sector as they are currently not privately insurable. In project management, public and private investors will need to work together to bring the scrutiny and experience to bear to raise cost control and efficiency to the levels achieved in comparable industries. By exploring these three dimensions of the construction of new nuclear power plants as well as their interactions, this report aspires to contribute to the discussion laying the groundwork for successful nuclear new build.

Financing costs are outputs, not inputs, of nuclear new build projects

While building on earlier work, this report abandons the assumption of a fundamental separation between the internal workings of a new nuclear construction project on the one hand and an optimised financing arrangement on the other. In other words, it opens the "black box" of the nuclear construction project itself to explore its impact on construction and completion risk and hence on the cost of capital. Financing costs as an indicator of risk are thus an *output* of the project itself, its technology, its management, its role in the overall electricity system, as much as they are an *input*, determined by outside forces.

The recognition of this fact has important implications for the role of the governments of NEA member countries as the ultimate sponsors of nuclear new build. Beyond setting the legal framework, complementing the private sector where the latter is unable to take on the financing of nuclear construction on its own and ensuring against political risk, governments also need to ensure that electricity market designs are compatible with nuclear energy. This responsibility has been increasingly recognised in recent years and has translated into a wide-ranging tolerance for different forms of revenue-stabilising long-term contracts. As the discussion advances, the next step will be to recognise also that construction and completion risk and hence project management are currently the most critical parameters in nuclear new build projects.

If the energy transition and net zero carbon emission objectives are to be achieved, providing sufficient amounts of dispatchable low-carbon capacity, primarily in the form of new nuclear and hydro power plants, is required as a form of public infrastructure provision. Like in other areas, this does not preclude the participation of the private sector. However, the majority of the risks of building this highly capital-intensive backbone of future low-carbon electricity systems will need to be primarily borne either by ratepayers or taxpayers. Such cost socialisation will in return require new forms of public oversight, participation and sharing in the eventual benefits.

The fact that nuclear energy will play a key role in efforts to reduce carbon emissions is leading to new forms of industrial policy. Providing systematic revenue stabilisation, de-risking the construction of new power plants and direct public investment and involvement complement and complete the existing arsenal of industrial policymaking in order to constitute a new paradigm fit for an age of rapid decarbonisation of the energy and electricity sector.

Increasingly, governments will thus be required to provide or to support "leadership" in highly complex nuclear new build projects, where not all contingencies can be adequately codified into contractual obligations before the start of the project. Leadership is effective only as long as it is broadly supported. A strong societal consensus regarding the long-term role of nuclear energy in a country's electricity and energy system, supported by active government involvement, is thus essential. This requires thorough and well-prepared societal discussion processes. Identifying key parameters in these necessary discussions, while at the same time pointing out the constraints of cost minimisation and welfare optimisation from an economic perspective, is the purpose of this report.

A new approach to risk management in the financing of nuclear new build

Financing, market design and project management are strongly linked to each other. Fully understanding and managing these links requires first a full understanding of financial risk management in nuclear new build as developed in NEA (2022). On the basis of the widely used capital asset pricing model (CAPM), this earlier report decomposed overall project risk into the following components: (1) the risk-free rate at which countries with high credit ratings can borrow; (2) the systemic risk of the market and a project's correlation with this systemic risk; and (3) project-specific or "idiosyncratic" risks. In a nuclear new build project, the idiosyncratic risks would typically include construction risk, price risk and political risk.

The premise of NEA (2022) was 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 with overall market risk. If a project is uncorrelated or negatively correlated with general market risk, then overall risk is lowered by adding such a project to an investment portfolio. In a net zero world, such negative correlation with systemic market risk precisely applies to low-carbon generators such as nuclear energy. 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. Such a countermovement of the rates of return offers a highly sought-after opportunity for offsetting risks and increasing overall portfolio performance.

3. As far as the project-specific risks (political risk, price risk and construction risk) are concerned, specific measures to de-risk the different dimensions need to be mobilised:

   a) **Political risk** will be insured by government, the party most apt to minimise and internalise such risk through contractual indemnification clauses that insure project sponsors and investors against changes in energy policy that would limit the use of nuclear power.

   b) **Price risk** can be neutralised through electricity market designs that allow for long-term contracts such as regulated tariffs, power purchase agreements (PPA) or contracts for difference (CFD). This implies a move away from marginal cost pricing towards average cost pricing and the inclusion of some regulated elements inside competitive electricity markets.

   c) **Construction risk** will need to be socialised through risk-sharing arrangements such as regulated asset base (RAB), construction work in progress (CWP) or direct government financing. Such measures transfer the cost of construction and the risks of cost overruns to ratepayers or taxpayers. This implies not only a transfer of risk but also a reduction in its economic costs, as the amounts in play are a very small portion of each household's budget.

If nuclear new build projects are thoroughly de-risked in this manner, the financial risks to investors, whether private or public, are radically reduced, which lowers the rates of return on their capital they will require. In combination with the decorrelation of the returns on low-carbon electricity capacity from financial market trends, such de-risking establishes nuclear new build as a far more attractive investment option than is usually assumed.

While de-risking reduces the overall economic costs of risks, essentially by spreading them over large numbers of households, those risks do not disappear. The question of risk allocation thus needs to be discussed in a fair and convincing manner. This discussion needs to lead to decisions on allocating risk not only between taxpayers and ratepayers but also between different groups of ratepayers, such as industry and households. In return for such socialisation of risks, society as a whole will receive vital infrastructure that provides large amounts low-carbon baseload electricity around the clock. Yet, the scales are such that governments need to manage discussions on the allocation of costs and risks carefully and with large lead times.

Electricity market designs supporting investment in low-carbon generation technologies

Reducing electricity price risk in order to facilitate investment in capital-intensive low-carbon technologies, which include nuclear energy but also wind, solar PV hydro and others, is possibly the one dimension in which the discussion has advanced the most and has led to the first concrete advances. This discussion involved both points of principle and specific points related to electricity generation. In principle, competitive markets with marginal costs pricing provide efficient frameworks for optimising resource use, minimising costs and incentivising individuals to perform to the best of their abilities. This holds true, at least in approximation, in many economic sectors. However, for a number of specific reasons, competition based on short-term marginal costs on its own does not constitute a satisfactory design for electricity markets. The most important of these reasons can be grouped under five headings:

1. **Political and social choices**: Electricity is often considered too important a good to let its supply structure be determined entirely outside of the political and social sphere. On the demand side, electricity is often considered a merit good of which all consumers should at least be able to consume minimum amounts. On the supply side, climate objectives and the support for variable renewable energies (VRE) such as wind and solar PV have moved electricity markets far from system-wide economic or social optima.

2. **The non-storability of electricity**: Despite demand side response and battery storage, the bulk of electricity must be produced at precisely the same time at which it is consumed. In combination with inelastic demand, non-storability makes for volatile prices and

difficult predictions as even small changes in the generation mix or in demand can have disproportionate impacts on prices both in the short and medium term.

3. **“Too big to fail” creating irreversibilities**: Competitive markets allow for efficiency-enhancing trial and error. If, however, single investments, for instance the costs of a nuclear power plant based on existing technologies, a large hydropower installation or a major grid extension are measured in the billions or tens of billions of dollars or euros, trying and failing is no longer an option for investors. Being condemned to succeed inevitably requires market interventions, with government acting as backstop.

4. **The capital intensity of the energy transition**: The energy transition will be based on low-carbon sources of electricity and energy. All of these, whether nuclear energy, hydroelectricity or renewables, even storage and fossil fuels with carbon capture, utilisation and storage (CCUS) are substantially more capital-intensive than technologies based on gas, coal or oil. This has fundamental implications for electricity market design as high capital intensity increases the need for predictable returns on investment.

5. **The high costs of the energy transition**: The energy transition implies significantly higher costs than is usually anticipated. As technology breakthroughs cannot be decreed and costs can no longer be hidden in the form of small reductions of economic growth rates, the intensity of the debate on how to distribute the costs of the transition is increasing. A particularly important question in this context is whether costs will be borne by taxpayers or by ratepayers. The nature of the measures to accompany the financing of low-carbon capacity are an intrinsic part of this debate.

These five reasons require a fundamental rethink of how electricity markets should work. This is not primarily about “competition” versus “regulation”. Also, electricity markets fit for the energy transition can contain competitive elements, even if they may, at times, take the form of competing “for the market” rather than competing “in the market”. Also, competitive electricity markets have their roles. Liberalisation, for example, increased the operational efficiency of nuclear power plants in the United States. However, the fundamental change that electricity markets need to operate is to switch from *short-term marginal cost pricing* to *long-term average cost pricing*. Only thus can electricity markets bring forth the large amounts of capital-intensive low-carbon capacity required for the transition.

Figure ES.1. **Future electricity markets will require a mix of incentive measures for different technologies**

<table>
<tr><th>Time horizon and purpose</th><th>Allocation mechanism</th><th>Contract type</th><th>Technology</th><th>Challenge</th><th>Why should we care?</th></tr>
<tr><td>Short term for dispatch</td><td>Competitive spot markets</td><td>Pay-as-clear at variable cost of marginal technology (EUR/MWh)</td><td>All technologies</td><td>Missing money, no investment in LC technologies</td><td>Efficient dispatch, “sweating assets”</td></tr>
<tr><td colspan="6">In conjunction with targeted top-up payments to incentivise investment</td></tr>
<tr><td rowspan="3">Long-term investment with centralised decision-making on the electricity mix</td><td rowspan="2">Competitive auctions for long-term contracts</td><td>Capacity payments at fixed cost of marginal technology (EUR/MW)</td><td>CCGT, dispatchable REN, storage, demand response</td><td>Quantity risk due to high variable costs</td><td>Reliable capacity at reasonable cost</td></tr>
<tr><td>Feed-in tariffs (FIT) or feed-in premia (FIP) (EUR/MWh)</td><td>Variable renewables (wind, solar PV)</td><td>High price risk due to auto-cannibalisation</td><td>Low-carbon electricity, high social preferences</td></tr>
<tr><td>Case-specific long-term agreements</td><td>CFD, RAB, CWP, local concessions at avg. costs (EUR/MWh)</td><td>Nuclear energy, hydroelectricity</td><td>Construction risk, political risk</td><td>Reliable low-carbon baseload electricity</td></tr>
</table>

Long-term average cost pricing requires instruments such as power purchase agreements, contracts for difference, feed-in tariffs or even regulated electricity tariffs that provide stable remuneration for electricity over time. In some cases, the UK RAB model, similar to the US CWP model, a pre-financing of construction costs by consumers, can constitute an alternative. Capacity remuneration mechanisms provide additional stability of revenues for less capital-intensive flexibility providers. Some of these long-term contracts will be allocated through competitive auction for centrally determined shares of carbon-free electricity.

This makes careful system planning and modelling of low-carbon electricity systems, as set out in the series of NEA reports on the system cost of electricity systems, a prerequisite. Furthermore, such long-terms contracts will work in tandem with the existing wholesale markets, which will continue to organise least-cost dispatch based on variable costs. Experts thus frequently talk about hybrid markets. Figure ES.1 provides an overview of the landscape of the different incentive measures that interact in the low-carbon hybrid markets of the future. The composition of the capacity mix will here be decided by the strategic choices of national governments, regulators and network operators rather than by individual investors.

The role of the public sector in assuming risks in the construction of nuclear new build projects

As indicated, electricity market designs affect the allocation of the costs and risks of capital-intensive low-carbon generation between taxpayers (public institutions), ratepayers (electricity consumers), project operators and private investors. The NEA has long argued that risks should be borne by those who are best able to carry them as well as best able to manage and reduce them. This is primarily central government and society at large, at least as far as the construction of large reactors based on existing designs is concerned.

The conceptual justification of public sector involvement in the financing, and eventually also the construction, of large-scale investment projects with infrastructure characteristics was provided by Arrow and Lind (1970). They argue that the economic costs of risks can be reduced to close to zero and that projects can hence be evaluated at the risk-free rate, if project costs are spread among a sufficiently large number of individuals. The two key assumptions in this reasoning are that individuals are risk-averse and that project outcomes are uncorrelated to the overall systemic risk of the economy. The fact that in a carbon-constrained economy the returns on low-carbon investment are likely to move opposite to the returns on general investment constitutes thus a potent argument for applying the Arrow-Lind argument to investments in nuclear power capacity.

Risk spreading can be operated either through direct public financing, in which case costs are spread among taxpayers, or through mechanisms in which costs are pre-financed by consumers paying regulated tariffs, such as in the UK RAB or the US CWP. The Arrow-Lind argument has not gone unchallenged. One frequently made point is that financial markets precisely perform this kind of risk sharing, allocating the risks of large single projects to large numbers of retail investors through instruments such as exchange traded funds (ETF).

However, this confuses risk sharing and risk diversification. Financial markets are indeed the principal instrument for risk diversification. Yet risk sharing in the spirit of Arrow and Lind goes beyond financial market diversification as it is also the systemic market risk that no longer needs to be included in capital costs and thus constitutes a potent argument for public engagement. In this case, practice validates theory. Literally all nuclear power plants have been constructed either with direct or indirect government financing, tariff-based pre-financing through consumers or with wide-ranging public guarantees de-risking projects to the point that third parties consider the project investable. This holds for both the market economies of OECD and NEA countries.

The role of project management: How to better manage

If financing costs are a function not only of optimised financing and public sector involvement but also of project management, the logical question is "what do project managers need to do in order to reduce the risks and the costs of nuclear new build projects?" There are three answers to this question. First, management structures need to be aligned with the project's financing model as well as the electricity market design. Second, they will need to pay attention to the classical, often invoked dimensions of nuclear new build projects, which are advance planning, design completion, supply chains and ensuring the availability of a skilled workforce. Third and most importantly, they need to make a priority of the issues of leadership, independent outside project advisory and efficient incentive structures.

During the past three decades, the electricity systems of most OECD countries have evolved from rate-regulated, vertically integrated monopolies to competitive wholesale markets. In the old system, generators were frequently also builders and financiers of new capacity, drawing on a deep pool of qualified engineers with lifetime employment and a network of long-standing suppliers, an arrangement helped by generous rate-setting by regulators, which generated profits that could be shared among all stakeholders. The management model associated with competitive markets was the engineering, procurement and construction (EPC) model, where an independent logistics provider would competitively source the required services for EPC. While this model based on ad hoc contracts extended in theory also to nuclear new build, it never fully caught on. The informational asymmetries in such complex projects allow for too much gaming between self-interested parties aware that "there is no such thing as a complete contract" (Hart, 2003).

In parallel to the progressive introduction of stable, long-term pricing arrangements in electricity markets, the benefits of the integrated owner-builder-operator model are also being newly appreciated. The imperative to finance large amounts of capital-intensive low-carbon generating capacity highlights the advantages of risk-reducing long-term relationships. However, a full-fledged return to the past is not an option. Hybrid electricity markets combining short-term competition for dispatch with long-term incentives for capacity development would argue for similarly balanced approaches also in project management. This could mean that nuclear new build would be undertaken by oligopolistic structures, where a small number of partly, but not totally, vertically integrated competitors would compete. The benefits of vertical integration would thus be combined with the ability to benchmark the performance of an operator against that of its competitors. Political decision makers thus need to set out the contours and level of granularity of such oligopolistic competition at different step of the value chain.

Not every wheel in the complex machinery of a nuclear new build project needs to be reinvented. Project managers of recent reactor construction projects have carefully engaged in advance planning ahead of the first concrete pour. Unfortunately, this did not always extend to detailed design completion, a major factor in the cost explosion of early projects. Advance planning has mainly concentrated on assembling the project supply chain, sometimes under stringent requirements to include domestic suppliers.

The World Nuclear Association (WNA), the trade body of the global nuclear energy industry, argues that sufficient levels of industrial capacity are available at each step of the value chain. While there are arguments for being relatively sanguine about the state of the nuclear supply chain from a technical and commercial point of view, others are less relaxed. Suppliers thus complain about high uncertainty and a lack of long-term perspectives. Perspectives also vary widely from country to country. Attitudes towards supply chain issues vary also with expectations that beyond supporting an industrial project, they should also strengthen industrial development, competitiveness and national security.

Similar observations also pertain to worries about skills and workforce training. Of course, a project as complex and challenging as a new nuclear power plant requires large numbers of skilled welders, electricians and engineers. However, labour markets react, sometimes with time lags, to incentives. When these are attractive and consistent through time, qualified applicants step forward. Certainly, advance planning also in this field, training at both the university and vocational level, and communication are additional pieces of the puzzle.

Ultimately, however, attractive long-term financial incentives, which include not only gross salaries but also health and pension benefits, will be the most important factor in establishing an adequately skilled nuclear workforce.

If the nuclear sector is keenly aware of the challenges posed by design completion, supply chains and skills, there are three additional dimensions – leadership, independent project advisory and incentive structures – that are crucial to project success and require greater attention than they currently receive. Leadership consists of the ability to align the interests of multiple contributors to a project, combined with the ability to deal with unforeseeable and uninsurable risks in an environment in which not all aspects can be fully codified in a contractual manner. The more complex the project, the more important becomes effective, personal leadership in order to ensure a common vision and common rules of engagement between self-interested stakeholders to minimise the inevitable friction, informational asymmetries and rent seeking.

Regarding uninsurable risks, no leader will be able to assume them personally in a project as large as building a new nuclear power plant. His or her task is thus modified to being able to mobilise the necessary private or public resources as well as to draw on a network of financiers, public figures and major suppliers in the case that "tail risk" materialises, i.e. when new, unforeseen and unforeseeable, circumstances risks arise that cannot be covered by commercial hedging arrangements.

Leadership is indispensable, yet good leaders will be aware of the limits of their ability to focus the myriad bilateral transactions so that they contribute to the success of the overall project. They will thus realise that it may be helpful, even necessary, to delegate some authority to a third party that will exercise independent project oversight. This third party could be an experienced project operator with nuclear expertise or a professional mediator. Crucially, this trusted third party should have no stake in the outcome of the project itself but instead work on a fixed commission. Their role is twofold. They will advise the project leadership on overall management issues, e.g. organigrams and incentive structures, and will intervene in dispute resolution between the project leadership and major outside stakeholders such tier one suppliers, the nuclear safety authority or the national government.

Leadership and independent advisory will need to be complemented by efficient incentive structures as a third building block. This is particularly important as transaction costs and asymmetric information do not allow contractual relationships to organise a project as complex as the construction of a new nuclear power plant. Given the technical complexity, iterations with regulators and permanent quality control issues, even very long contracts drawn up by specialised lawyers could not cover all contingencies that inevitably arise between cost-conscious suppliers and demanding project managers.

Managing "moral hazard" between principal and agents arises also in other fields, such as corporate governance, and is the subject of a specialised literature. However, the basic idea is simple: the payoff to every individual agent must be tied not only to their individual performance but also to overall project performance. It may be possible to manage smaller misalignments between individual and project-level outcomes by fostering a culture of openness, honesty and information sharing. Longer-term contracts with a potential for repeat transactions can also be helpful to align incentives.

However, if misalignments are large, i.e. when individuals can gain substantially from deviating from the optimal path towards project success, perhaps even while satisfying formal contractual obligations, financial incentives need to be adapted in a more explicit manner. In other words, the payoff of every individual and every company needs to be a function not only of individual performance but also of the performance of the team or the group of suppliers and of the performance of the overall project. Developing consistent incentive structures and communicating them convincingly is a key task of project leadership.

How to involve the private sector in the financing of nuclear new build

Public or quasi-public actors, which rely on implicit or explicit government guarantees, will always have lower costs of capital than private actors in the financing of new nuclear construction projects. This is due to the fact that when things go wrong governments can always rely on their powers of levying new funds through taxation. This poses a critical question: if public sector financing can be arranged at lower rates than private sector financing, then why bother with the latter? For market economics in general, the answer is that the efficiency gains, cost reductions and utility improvements through innovation due to private competition outweigh any considerations of financing costs. However, this does not yet apply to the nuclear sector, where "merchant investors" have yet to emerge and where the financing of new low-carbon power plants relies on risk sharing with consumers or taxpayers. Despite their inability to apport funding at lower costs, it remains highly desirable to associate private investors in nuclear new build projects and to attract them with an appropriate combination of risk and rewards. There are essentially four reasons for this:

1. The participation of private investors is an important signal that a nuclear new build project has obtained its "social licence" and that nuclear power plants constitute an investable asset class.
2. If public involvement, commitment and oversight remain indispensable, the private sector has much to offer in terms of know-how in project management, contract design and in achieving cost reductions.
3. Private investment in a nuclear new build project during the construction phase is an entry into the gradual transfer of ownership from the public to the private sector as the operational phase with a risk structure well-suited to private investors approaches (see below).
4. Private sector investment allows governments to keep some of the costs of financing new nuclear power plants from its balance sheet. This holds even if it continues to insure private investors against project completion risk.

Private sector participation in the construction of nuclear new build projects is thus essential not because private investors would be able to offer funds at rates lower than public institutions. Instead, its contribution consists in driving forward the social and political validation of a project as well as its industrial delivery. It could also be said that its role is to reduce financing costs not as an input to the project but as an output through successful project management.

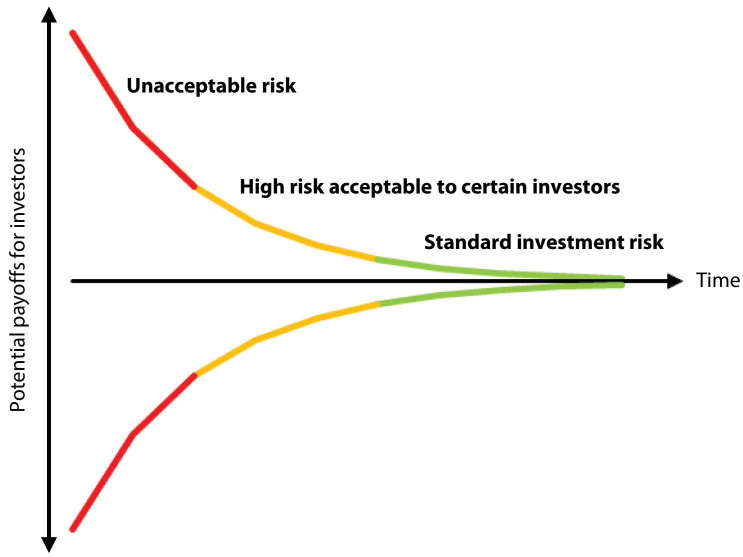
Once there is consensus that private sector participation in a nuclear new build project is desirable, the question is how to best arrange for it. The answer lies in understanding the changing risk structure of a nuclear new build project over its life cycle. The life cycle of a new nuclear power plant has indeed two major phases, construction and operation, with very different risk profiles.

If financial risks exist during both phases, they are considerably higher during construction than during operations. In particular, market risks during operations, while sizeable, can to some extent be measured, anticipated and hedged. Construction risk instead, at least at the current state of industrial development and maturity of reactor construction, cannot be hedged on private markets for risk and insurance and any attempt to do so will be prohibitively expensive. During construction and up to the date of commissioning, building a new nuclear power plant is thus a high-risk project; during operations, from the date of commissioning onward, a working nuclear power plant can be considered a low-risk project. Thus, while there is currently a need to socialise construction risk, this does not hold for operational risk.

The optimal financing of nuclear new build projects needs to reflect the changing level of risk over the life cycle of a nuclear power plant. A *dynamic* approach to the financing of new nuclear plants is thus required. This means that the shares of public and private ownership over the project life cycle will need to change at predetermined intervals. These intervals should be set according to previously agreed project milestones such as first concrete, completion of excavation, completion of the reactor base, installation of the reactor pressure vessel, completion of the coolant system, installation of instrumentation and control systems, fuel loading and commissioning. At each successful passing of a milestone, private actors would progressively assume a greater share of financing and ownership of the project.

It is important to agree on the conditions and timing for this incremental transfer of ownership to private *before* first cement is poured. Only in this manner are private investors fully committed to the project, even while the government remains liable for construction risk. Arrangements anticipating dynamic refinancing would see governments or public entities incrementally transfer their share in project ownership to the private sector, typically up to the date of commissioning, when the handover is completed. Different variants of the timing and conditions for such dynamic refinancing can be developed, reflecting the risk profiles and ability to generate financing of the different stakeholders.

Figure ES.2. **The cone of uncertainty reduces through time as construction progresses**



The concept of dynamic refinancing in function of the decreasing level of completion risk as construction advances and the risk management abilities and risk preferences of public and private investors is now being discussed regularly among project operators and financiers. Chances are that forthcoming nuclear new build projects will begin to integrate elements of an increasing role for private sector finance as the project progresses.

The key point is, of course, that the risk profile of a nuclear new build project changes during the course of construction (see Figure ES.2). This means that the risk appreciations and hence costs calculations of different investor groups will also change during the project cycle. Completion risk that was deemed uninvestable before first concrete had been poured looks very different once the cooling system has been successfully installed. There are few limits to creativity as long as such financial engineering is undertaken with a view towards a fair and sustainable distribution of risks and rewards. Needless to say, assessing and reassessing those risk as well as reallocating them in through time in function of risk preferences and portfolio effects requires specialist skills and has real costs. However, given the very large size of nuclear new build projects, the benefits accruing to those who are able to organise such dynamic financial risk reallocations over the project life cycle can be considerable.

A checklist of ten points requiring discussion before starting a nuclear new build project

This report on "Financing, market design and project management in nuclear new build" concludes with a checklist of ten key points that need to be addressed in the lead-up to the construction of a new nuclear power plant. Obviously, this is not a checklist for project managers during the actual planning and building of a new nuclear reactor. Its purpose is to assist stakeholders far earlier, when societal and political discussion processes prepare the strategic orientations that define the conditions under which nuclear new build takes place. A fundamental transversal question, the answer to which will colour many of the different issues, is to what extent nuclear generating capacity is an industrial asset like any other and to what extent its role as a dispatchable low-carbon provider of last resort, as well as its contribution to the security of energy supplies, gives it the characteristics of a public infrastructure.

On the basis of their culture, experience, generation mix, societal structure and industrial fabric, different OECD and NEA countries will undoubtedly decide on different answers to the questions contained in the following ten points. However, it is indispensable not to avoid the necessarily controversial conversations surrounding them. While it is possible to imagine different degrees of public involvement during the construction process, it is unambiguously the responsibility of governments to ensure that these points are addressed before construction gets under way. Once the relevant strategic orientations have been clarified, however, project managers can concentrate on addressing the technical, industrial and organisational challenges head-on and thus maximise the chances for successful nuclear new build.

1. **Net zero carbon targets:** How important are climate change emissions reduction objectives as a long-term determinant of energy and climate policies? The answer to this question is not only of political and environmental interest but also economic and financial. Under a strict carbon constraint, the returns on investments in low-carbon generators such as nuclear power will act as a financial hedge against investments in other sectors that will be negatively affected by the effort to reduce carbon emissions. This would reduce financing costs and hence the total costs of nuclear new build projects.

2. **Energy transition costs:** Even at the level of a mid-sized country, the costs of the energy transition over the next three decades are measured in hundreds of billions or even trillions of USD or EUR. Costs of this magnitude will accrue independently of specific technology choices. While many find the benefits of nuclear energy as a scalable and dispatchable low-carbon baseload provider obvious, and it will reduce the costs of attaining net zero targets in most OECD and NEA countries, societies have to be aware of the magnitude of the tasks ahead and will need to decide on the pace at which they want to advance and how they want to share the resulting financial burden.

3. **Systems approach adoption:** The net zero electricity systems of the future will be built around a mix of nuclear energy, hydroelectricity, wind and solar PV. Low-carbon hydrogen will be used in niche applications, while electrification will reduce emissions in transport and industry. Each technology has very distinct strengths and weaknesses and will thus fulfil a different function, complementarily to the others. Achieving an efficient least-cost generation mix requires systematic advance modelling of different technology options. Centralised planning of the mix must be coupled with elements of competition in each segment of the system as well as with appropriate technology-specific support measures to achieve the desired levels of capital-intensive, low-carbon generation capacity. Sound analytical work needs to be complemented by a broadly shared long-term vision of the future electricity system at the societal level.

4. **Systematic risk management:** The large-scale build-out of nuclear energy that is part of a clear and achievable path to net zero will require the comprehensive de-risking of the financial risks of nuclear new build. Other than the impact of the financial insurance function of low-carbon generation in economies operating under stringent carbon constraints, this requires measures to insure against political risk, price risk and construction risk. Each of these dimensions requires comprehensive provisions in terms of legal frameworks, market designs and risk allocation. Each time, this will vary the risk

exposure for different stakeholder groups. There thus needs to be transparency, discussion and ultimate consensus that the costs of nuclear power during construction and its benefits during operations are fairly and sustainably shared.

5. **Low-carbon infrastructure:** Even with careful system analysis and advance planning, the low-carbon electricity systems of the future will not be off-the-shelf solutions. Innovation, experimentation and market competition will thus need to be complemented by a sturdy and reliable backbone of the electricity mix providing an insurance function for the system as a whole, even beyond day-to-day generation. There needs to be discussion to what extent nuclear energy fulfils this function of a low-carbon infrastructure that reliably ensures the required minimum levels of security of supply and carbon emission reductions. Political responsibility for such public goods would further strengthen the argument that some socialisation of the costs and risks of nuclear new build is appropriate.
6. **Electricity market design:** To what extent are current designs appropriate for the low-carbon energy transition and conducive to nuclear new build? There is no need to construct intransigent oppositions between deregulated and regulated markets, competition and vertical integration. Pragmatic exemptions from purely market-based financing have regularly been granted for new nuclear projects in North America, Europe and Asia. However, a substantive expansion of nuclear new build will require a more systematic review of the performance of market designs, providing project managers and investors with frameworks that provide adequate degrees of advance financing through ratepayers or taxpayers as well as, in complement or as substitute, a degree of revenue certainty.
7. **Project management framework conditions:** The management of projects as complex as a new nuclear power plant is an enormous industrial undertaking. The task of policymakers in this context is to insist on publicly discussing and implementing the appropriate framework structures. This regards, in particular, the relative strengths in relying on a competitive international supply chain and global labour markets on the one hand and vertically integrated national structures on the other. The right balance needs to be found according to country-specific cultures, histories and industrial strengths. At the same time, nuclear new build projects must not be burdened with additional objectives such as strengthening the industrial fabric or redressing the trade balance, which are extraneous to efficient project execution. In any case, governments as the ultimate project owners, holding the residual risk, will need to commit themselves more systematically than in the past to active management oversight.
8. **Project management and execution:** Organising projects of this magnitude and allocating responsibilities must be matters of transparent, public discussion. As ratepayers and taxpayers are assumed to take on sizeable portions of the financing of construction, they have the right to public oversight in appropriate form. This may or may not be combined with independent technical oversight. Leadership and its link to political power, the ultimate arbiter, must be clearly and publicly defined. Of key importance are the incentive structures at all levels of the value chain. Only if agents have something to lose will they exert themselves to contribute timely and efficiently to overall project success. The nature of those incentive structures should form an explicit and transparently communicated module of the overall project.
9. **Private investor involvement:** The degree of involvement of private investors, even if they will never be able to offer capital at rates lower than those at which sovereign governments can borrow, should be discussed as an economic policy issue. In principle, their involvement remains attractive for four reasons: (1) as a signal that the project has obtained its "social licence"; (2) to benefit from the competence of private investors in project management, cost control and structuring incentives; (3) to enter into the dynamic transfer of ownership as the project progresses; and (4), if required, to keep part of the project costs from public balance sheets and thus limit public borrowing costs. However, these contributions come at somewhat higher overall returns on capital. The costs and benefits must thus be carefully analysed, weighed and communicated.

10. **Private investor involvement modalities:** Organising the participation of private investors in an optimal and cost-minimising manner needs to reflect the changing levels of risk over the life cycle of a nuclear power plant. A nuclear new build project remains a relatively high-risk project until commissioning even if construction risks and financial risks decline with each technical milestone that is passed. It is a relatively low-risk project from that day onwards. This requires a *dynamic* approach to the financing of new nuclear power plants, which means that the shares of public and private ownership over the project life cycle will change at predefined intervals as ownership is incrementally transferred from public to private investors. It is important that the conditions and timing for these transfers are agreed upon *before* first cement is poured. While primarily a technical issue of financial engineering, dynamic refinancing as different project milestones are passed is an important manner to reduce the overall costs of the project for all stakeholders.

Chapter 1. **Introduction**

A demand for sustainable financing solutions for nuclear new build is now being formulated at the highest policy-making levels. The energy ministers assembled at the Roadmaps to New Nuclear conference that was co-hosted by the Nuclear Energy Agency (NEA) and the French Ministry of Energy Transition on 28-29 September 2023 put adequate financing at the centre of their efforts to create the conditions for nuclear energy to realise its potential to reduce greenhouse gas emissions in an economically efficient manner and to ensure the security of energy supply. The financing of new nuclear capacity was also discussed at COP28 from 30 November to 12 December 2023, when over 20 countries called for a tripling of nuclear capacities by 2050. Other key determinants of successful nuclear new build projects, such as supply chains and adequate human capital, are increasingly seen as depending on first having convincing long-term financing arrangements in place.

Replying to the demand for further insight into the conditions for financing successful nuclear new build, this report by the Nuclear Energy Agency (NEA) continues the work undertaken in the earlier NEA report *Financing New Nuclear Power Plants: Minimising the Cost of Capital by Optimising Risk Management* (NEA, 2022) and *Effective Frameworks and Strategies for Financing Nuclear New Build* (NEA, 2024a). It is thus equally part of the programme of work on financing nuclear new build supervised by the NEA Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC).

A key element of the earlier NEA report (NEA, 2022) was to show how optimising the management of different risks that arise during the preparation, construction and operation of a new nuclear power plant impacts its cost of capital. Adapting the well-known CAPM, this NEA report presented a framework to characterise and analyse the different risk dimensions in nuclear new build, in particular policy risk, price risk and construction risk. It also proposed policies and measures to substantially reduce the economic costs of those risks by allocating them to those parties best able to manage or carry them.

An additional key point was that the correlation of the returns on low-carbon assets such as nuclear energy with systemic market risk may be approaching zero or even be negative, as increasingly stringent emission reduction targets impact growth and general returns. Such decorrelation of the returns on nuclear capacity and other investments would offer investors a highly prized opportunity for diversification. A major conclusion of the report was that comprehensively reducing the economic costs of different risks in combination with the attractive portfolio characteristics of low-carbon investment could de-risk investments such that the real cost of capital of nuclear new build projects would approach the cost of sovereign borrowing of national governments.

NEA (2022) and NEA (2024a) provide first responses to the question of how to overcome the challenge of financing the large amount of dispatchable nuclear capacity that is part of a clear path to reaching or approaching net zero emissions by 2050 at a reasonable cost. Such solutions are required not only to build new nuclear power plants, both large Generation III+ reactors and small modular reactors (SMRs), but also for the large projects to refurbish the fleet of existing reactors to enable them for long-term operation, as are currently underway, for instance, in Canada and France.

Financing nuclear new build is part of the enormous challenge to finance the energy transition at both the national and global levels. Switching from fossil fuel-based technologies to low-carbon technologies, whether nuclear, renewable or hydroelectricity, always implies a massive shift from technologies with high variable costs and comparatively low fixed costs to technologies with high fixed investment costs and comparatively low variable costs. Inevitably, questions of financing those fixed costs upfront are at the heart of the energy transition, while the increasingly low prices set by variable costs, driven down by the zero marginal costs of wind and solar PV, make pure market provision more challenging. In this general context of the energy transition, constructing new nuclear power plants of course retains a number of specificities. Both the general and specific challenges of nuclear new build will be discussed below.

A new paradigm of industrial policy to ensure the building of adequate amounts of nuclear capacity

Governments aiming at expanding nuclear capacity are likely to have a key role to play in shaping future financing arrangements for nuclear new build. They will need not only to put into place the necessary regulatory and political frameworks and decide on appropriate electricity market designs (see Chapter 3), but also to ensure that the necessary societal trade-offs required in different allocations of financial risks are made explicitly on the basis of transparent discussion processes. They might also be asked to step in themselves in cases where large-scale failures of private markets are identified. The increasing recognition of the role that nuclear energy can play in efforts to reduce carbon emissions is in the process of leading to new forms of industrial policy after more than two decades of increasing public disengagement from infrastructure provision in general and the energy sector in particular.

Having fallen out of fashion following the wave of market deregulation in the last two decades of the twentieth century, which focused on operational efficiency gains rather than investment in new capacity, industrial policy is coming back due to the increasing recognition of the challenge to ensure a number of public goods that competitive markets are unable to provide. Together with ensuring the security of energy supply, perhaps the most important public good of the present time is the mitigation of greenhouse gas emissions in order to protect the global climate. The challenge for industry and policymakers is twofold here. The first challenge is that the global climate is indeed a public good where freeriding is rife and appropriate policy measures need to internalise the externality of greenhouse gas emissions, in particular carbon emissions. This can be accomplished by standard incentive measures such as carbon emission trading systems or carbon taxes. The latter have, however, engendered in a number of OECD and NEA countries resistance by those primarily affected, in particular fossil fuel-based industries, and their customers. The second challenge is that almost all measures for the generation of low-carbon energy and electricity are highly capital-intensive. This creates added risks for investors, in particular during the construction period to respond to the standard incentive measures mentioned.

A mix of long-standing and new measures is now attempting to solve both challenges together and may be considered as being part of a new paradigm of industrial policy. Industrial policy measures in the climate field can be distinguished by one fundamental criterion: whether the inevitable costs of switching towards low-carbon generation are borne by ratepayers, i.e. consumers, or by taxpayers. European countries and Canada, in accordance with the polluter pays principle (PPP), have by and large favoured allocating these costs to the industrial emitters, who would pass them on to ratepayers. This takes place either directly, by assigning the costs of carbon to emitters through emission trading systems or carbon taxes, or indirectly through feed-in tariffs for renewables or contracts for difference (CFD) for nuclear energy, which provide stable revenues for low-carbon producers, whose costs are then included in electricity bills. The nomenclature is not consistent over all jurisdictions. In the European Union, CFD are thus available for all “transition” energy sources, including carbon capture, utilisation and storage and hydrogen generation.

The United States instead has often favoured allocating the costs to taxpayers, incentivising low-carbon generation through direct subsidies, zero-emission credits, investment tax credits or production tax credits. The 2022 US Inflation Reduction Act (IRA) provides further subsidies and credits to a large range of low-carbon or clean energy technologies, including different nuclear energy technologies (The White House, 2023). All OECD and NEA countries provide support for the research and development of low-carbon technologies, of which support for research on new nuclear energy technologies, in particular SMRs, constitutes a considerable part.

Such measures have been at the disposal of industrial policymakers for decades. However, they might not be sufficient to trigger the low-carbon revolution required in order to durably reduce global carbon emissions and to reach or approach ambitious net zero targets. This is due to the point mentioned above that the high capital intensity of low-carbon generators and accompanying solutions – nuclear energy, wind, solar PV, hydropower, storage, transmission and distribution networks – poses additional challenges for investors, in particular during the construction phase, which translates into higher capital requirements, higher real and perceived risks through time, and thus higher financing costs.

Overcoming these challenges requires at least two additional sets of measures for industrial policymaking. The first is to reinforce the provision of long-term contracts to stabilise the revenues of low-carbon generators in a systematic fashion. PPA and CFD are the watchwords in discussions about the design of low-carbon electricity markets – in particular in Europe. These are excellent measures to insure private investors against price risk. By providing visibility of long-term revenues, they insure capital-intensive low-carbon capacity, including nuclear power plants, against unforeseen longer-term changes in the price level (see NEA, 2015 for an extended discussion). Since electricity remains a non-storable good, even small amounts of excess capacity or subnormal demand can cause such breaks. Providing stable long-term revenues is thus an important measure to reduce the financial risks for investors in low-carbon technologies. It is, however, not sufficient on its own.

This is where the second set of measures, providing capital support and de-risking the construction phase, comes in. Not all low-carbon technologies require such insurance against construction risk in an equal measure. Popular renewable energies such as onshore wind and solar PV, employed at a higher than optimal share of the generation mix, cause added costs to the electricity system due to their variability and suffer from the declining value of their output, which is concentrated during a subset of low-price hours. At the same time, their construction risk is relatively contained. Similarly, the building of a gas or coal plant, while not low-carbon without carbon capture, utilisation and storage (CCUS), is a fairly standard industrial project. For the time being, however, building new nuclear power plants, hydropower plants and also new offshore wind parks is subjected to considerable industrial construction risk, including long delays, that translate into significant financial risks. The latter are currently of such a magnitude that financing the construction of new nuclear power plants on the basis of purely private investors is not a viable option.

In such cases, industrial policy can provide capital support through loan guarantees and investment tax credits and has done so in the past. In cases where this is insufficient, direct public equity investment or systematically de-risking construction for investors through measures such as RAB or CWP may be required. In the case of direct public investment, construction costs are borne by taxpayers. In the case of RAB or CWP, the funds for financing new construction are advanced by ratepayers, who also bear the risks of cost overruns, delays and abandonment of the project. Clearly, this does not make construction risk go away; however, its economic costs are reduced by spreading the risk over a large number of individuals, for each of whom potential losses are comparatively small.

Providing systematic revenue stabilisation, de-risking the construction of new power plants and direct public investment where required therefore complement and complete an array of industrial policymaking tools in order to constitute a new paradigm fit for an age of radical decarbonisation of the energy and electricity sectors. If the energy transition and net zero carbon emission objectives are to be achieved, providing sufficient amounts of dispatchable low-carbon capacity, most likely in the form of new nuclear and hydro power plants, is required as a form of public infrastructure provision. Like in other areas, this does not preclude the participation of the private sector, quite to the contrary. However, the risks of building this highly capital-intensive backbone of future low-carbon electricity systems would be borne either by ratepayers or taxpayers and thus socialised. Reallocating the costs in this manner would also imply new forms of public oversight, participation and sharing in the eventual benefits so that those bearing costs and risks also receive their share of the benefits.

Once this dispatchable low-carbon infrastructure is established and the essential elements of the double objective of the security of electricity supply and carbon emission reductions are ensured, private actors can then graft themselves on it at their own risk and benefit. The long-run vision of an economically sustainable low-carbon electricity system would thus be built on a clear division of labour between a public and a private segment. At the current state of technology, risk, regulation and knowledge, the construction of new nuclear power plants would fall firmly into the first.

While a comprehensive doctrine of this new paradigm of industrial policy has yet to be advanced, this report argues that the direction of travel is clear. In addition to revenue stabilisation and de-risking different dimensions of new nuclear construction, one additional trend merits attention: in an increasing number of countries, the overall higher-than-expected costs of financing the energy transition have led to a gradual change, in which the costs will ultimately be borne by taxpayers through government budgets, rather than by electricity and energy consumers through electricity tariffs. This can be seen as zero-emission credits and investment tax credits rather than carbon taxes, and reflects the status of energy as a merit good as well as a desire to maintain industrial competitiveness. It also affects distributional arrangements. While all taxpayers are also energy consumers, the opposite does not always hold true, such as is the case of pensioners, welfare recipients or low-income consumers. This, however, implies that the low-carbon electricity and energy mixes of the future will increasingly be determined by governments based on a mix of economic and political criteria rather than by markets based on short-term financial performance. If this return of industrial policy in the energy sector is confirmed, it will see the emergence of new forms of competition and co-operation, as well as new distributional arrangements that will be discussed and implemented in the coming years.

Financing costs are outputs, not inputs, of nuclear new build projects

This new NEA report on the financing of nuclear new build situates itself in continuity with NEA (2022) in its intent to contribute with a conceptual framework that can help individual countries clarify, discuss and define their own choices. There is, nevertheless, a key difference between the two reports.

NEA (2022) proceeded on the assumption that the cost of capital as the cost of the risk of building a new nuclear power plant was *exogenous* to the project itself, determined by the financial arrangements determined between governments, private investors, regulators and stakeholders. The framework proposed, based on the CAPM, improved the understanding of the different dimensions of risk that affect nuclear new build and identified options to reduce their economic and financial cost through optimised allocation.

This new report builds on this basis but takes the framework a step further. In particular, it abandons the assumption that there is a fundamental separation between the internal workings of a nuclear new build project on the one hand and an optimised financing arrangement on the other. It could be said that this report opens the "black box" of the new build project itself in order to explore its impact on financing options and on the cost of capital. In particular, it argues that financing arrangements, electricity market design and project management interact in several important ways that cannot be disregarded when developing successful approaches to nuclear new build. Financing costs are thus an *output* of the project itself, its technology, its management, its technical risks, its role in the overall electricity system and a country's carbon emission targets, as much as they are an *input*, determined by outside financing arrangements.

It has been recognised for some time now that electricity market design and the expected level of price volatility affect the risk and cost of capital for investing in nuclear new build (see NEA, 2015, or Peluchon, 2021). This holds much less for project management, which usually enters financing discussions as a fixed overnight cost adjusted by a contingency as an allowance for construction. Conceptual discussions and practical policymaking have thus concentrated in recent years on the management of the volatility of electricity price risk. As the discussion advances and the experience of recent new build projects is being evaluated, it transpires, however, that construction risk and hence project management are the most critical parameters in any nuclear new build project. Completion risk, not long-term electricity price risk, is uppermost on the minds of investors.

While this may seem obvious to practitioners on the ground, it is less obvious to the economists and the political decision makers, who are concerned with framework setting and are quite happy to treat the firm, as the operational entity of the construction process, as a black box. In many circumstances, this is a sensible division of labour. It works due to the selection process of trial and error in competitive markets. Well-managed firms thrive, badly managed firms leave. There is no need to open the black box.

In the case of nuclear new build, however, the size of both the project itself, the length of the timeframes under consideration, the constant interaction with government and regulators as well as the specificity of the non-insurable technical and organisational risks no longer allow for such wilful disregard of project arcana. The self-regulating and efficiency-enhancing forces of the market are simply no longer operative. The nuclear industry is unable to operate under the process famously identified by Schumpeter as "creative destruction". The unit size of a Generation III nuclear power plant is simply too large to allow for trial and error and to iron out inefficiencies in design, supply chain and execution over time. In addition, project sponsors and operators are firmly tied down through long-term relationships with regulators and fuel-suppliers, which not always operate according to a logic of efficiency optimisation. In other words, once the decision for building a nuclear power plant has been taken, the project is essentially condemned to success, no matter the obstacles, no matter the attractiveness of newly arising alternatives and, far too often, no matter the costs.

There is little use in bemoaning this state of affairs, which most direct stakeholders understand at an intuitive level, even if they do not frequently evoke it explicitly. In policy discussions, however, participants frequently assume that the construction of nuclear power plants operates under the same incentive structures as other, more or less competitive, industries.

Project management, leadership and societal commitment are key to successful nuclear new build

In this situation, where closing down a newly initiated nuclear new build project is only possible by sacrificing large amounts of sunken costs with no benefits other than avoiding even greater future costs, and where designs, supply chains and financing arrangements are largely fixed, project management becomes the decisive variable for the success of the project. On the other hand, inefficient project management inevitably raises risks and costs. Chapters 4 and 5 regard the conditions and requirements of successful project management. This includes the allocation of inevitable construction risk between different parties, but also the design of incentive structures that reflect the large potential asymmetries of information that offer scope for gaming, hold-up and the extraction of informational rents.

However, even with highly efficient project management, most nuclear new build projects are likely to remain complex and costly. This poses the additional challenge of "leadership". This is, of course, a highly subjective category that means different things to different people, including personal qualities such as adaptability, resourcefulness or a talent for relationship-building. This report focusses instead on the two most economically relevant qualities of leadership in the context of large industrial projects:

1. The ability to align the network of multiple contractual and hierarchical relationships that evolve around a given project in such a manner that their outputs align with the strategic objective of concluding the project successfully.

2. The ability to mobilise private or public resources when, inevitably, new, unforeseen and unforeseeable risks arise that cannot be dealt with through existing hedging arrangements.

Two well-known slogans may convey something of the nature of leadership here. The first is the insight from industrial economics and game theory that “there is no such thing as a complete contract”. While multiple complex contracts will always be part of large industrial projects, the larger and more complex the project, the more often “leadership” will be required to maintain project discipline and assume additional costs. The second is the oft-invoked line that “the buck stops here”. Again, trading, i.e. “passing the buck”, externalising and slicing and dicing costs, risks and responsibilities have their uses. Yet, if unique and un-codifiable situations or issues arise, a previously designated authority, whether private or public, must assume responsibility, and, in return, be entitled to concomitant rewards. Falling back on standard contracting will in such cases create outsized transaction costs that will, if they do not threaten overall project success, inevitably drive up financial costs.

The very notion of leadership requires a commitment through time by the authority that installs the project leader, which in the case of large nuclear new build projects is frequently the government. Similarly, beyond a certain size, the resources the leader will try to mobilise when unforeseen circumstances arise will frequently be public. This poses the question of the long-term role of nuclear energy in a country’s electricity and energy system. As a dispatchable source of low-carbon electricity that is technically mature and can be scaled at a reasonable cost, nuclear energy is an important part of achieving ambitious net zero targets in many OECD countries. Depending on fundamental societal choices, this can make nuclear new build projects seem to be part of a critical low-carbon infrastructure, much like a transmission network, rather than as a specific technology choice. A broad and stable societal consensus galvanising the commitment to overcome the inevitable challenges of nuclear new build is thus the final basic piece of the project management puzzle.

There is thus an essential role for the governments of countries aiming at increasing nuclear capacity to organise the public discussion that will decide on the breadth and depth of the commitment to nuclear new build, to shape the framework conditions for effective leadership and even to oversee the structures that will govern project management. This does not preclude private sector participation in nuclear new build, quite to the contrary. Governments will also need to decide on the conditions under which private investors can partake in nuclear new build projects. This is essential not only for tapping additional sources of capital but also for the focus on timely and cost-conscious project delivery that experienced private sector investors can bring to large industrial projects.

When it comes to the involvement of private investors, two distinct phases with very different risk profiles must be considered:

1. Up to the date of commissioning, a nuclear new build project will inevitably be a high-risk project due to construction risk. Some form of direct public involvement, either from taxpayers or ratepayers, will be inevitable during this phase. Participating private investors will need to be largely indemnified against the risk that the project will run substantially over time and over budget or may even never be completed.
2. After commissioning and during operations with the generation of electricity or heat, a new nuclear power plant, with its low and stable variable costs, is an asset with comparatively low economic and financial risks. Common sense indicates that operational risk should be borne by operators. While price and quantity risks remain, this is not uncommon in other markets, either. There also exist hedging opportunities, which do not exist for construction risk, partly through private counterparties, partly through public counterparties as in the case of CFD In any case, during the operational phase a nuclear power plant should offer interesting investment opportunities to private actors.

One of the most interesting questions in this constellation is whether it is possible to convene before the beginning of actual construction a progressive handover from the public to the private sector under agreed-upon conditions at major milestones: authorisation to proceed, ATP); first concrete; completion of base; instalment of RPV; hot testing; commercial operations, etc. Chapter 6 will explore this and other questions related to private sector participation in more detail.

These introductory remarks primarily concern issues related to the financing, market design and project management of large-scale Generation III+ reactors, which will continue to provide the bulk of new nuclear capacity during the next decade. While there is palpable dynamism in the field of SMRs, with private venture capital highly interested at least during the design phase, the vast majority of designs have not yet proceeded beyond the preparation of building demonstration plants. The construction of a 300 MW BWR by Ontario Power Generation, wholly owned by the Province of Ontario in Canada, is one of the very few commercial SMR projects underway in NEA countries. This means that potential forms of financing, including risk-sharing arrangements, appropriate market environments and promising project management models for SMR projects intended for commercial operations must currently still be conjectured on the basis of comparable industries, e.g. shipbuilding or aviation, rather than identified on the basis of experience. Nevertheless, future work under the NEA Working Group on SMR Economics may shed some first light on these issues and may become part of more specific work on SMR financing in the future.

Overall, this report thus intends to identify the appropriate forms of financing, market design and project management as well as their interactions for new large-scale nuclear power plants. It will offer concrete proposals in each area that will be brought together in a final checklist. Of course, no project manager nor investor will proceed on the basis of a checklist, however pertinent its contents. The report is instead aimed at policymakers, experts and stakeholders in order to help steer the public debate towards those crucial issues that require the societal and political trade-offs that will define the frameworks in which nuclear new build could take place.

Chapter 2. Optimising financial risk management remains essential for successful nuclear new build

Compared to earlier NEA work, in particular *Financing New Nuclear Power Plants: Minimising the Cost of Capital by Optimising Risk Management* (NEA, 2022), the premise holding added value in this report is that the financing costs of new nuclear power plants cannot be separated from considerations of market design and project management. While subsequent chapters will show the intrinsic links between these three dimensions, classic financial considerations remain essential. Optimising the allocation and the financial management of different risks in order to achieve the lowest possible costs of capital remains essential in order to make a capital-intensive technology such as nuclear power a viable proposition. Only in a wider perspective can it then be considered how extra-financial considerations such as market design and project management have a bearing on particular risk parameters.

In order to reduce the cost of financing of a nuclear new build project there exist, broadly speaking, four different pathways: (1) choosing investors that have lower financing costs, (2) allocating risks to the parties that are best able to manage and to carry them, (3) electricity market designs that reduce price risk and (4) better project management.[1]

The first pathway is to choose investors that have lower financing costs. The one investor with the lowest funding costs is the national government, which can borrow at rates reflecting its sovereign risk. While the latter varies between countries, it is, at least in NEA countries, systematically lower than that of private institutions. That said, for budgetary reasons as well as for reasons of economic efficiency, not all industrial projects can be, nor should be, financed by government. While an argument can be made that public investment is indispensable for building a low-carbon infrastructure for electricity and energy, there are of course also benefits to attracting private sectors investors, even if they have somewhat higher financing costs. Private investors can provide a vital vote of confidence in a project. Having private investors experienced in cost minimisation and efficient project delivery on board can also focus attention on better project management (see Chapter 6 for more details on the role of private sector investors and the options to attract them).

The second pathway is to allocate different risks to the parties that either have (a) the best ability to manage them, or (b) have the lowest economic costs of carrying them. Concerning the first point, it makes sense, for instance to allocate operational risk to operators. Concerning the second point, the transfer of construction risk to ratepayers, such as under RAB or CWP provisions, can lower economic costs through risk spreading over large numbers of consumers (see Box 3.1 in Chapter 3 for more detail). Part of this pathway to reduce the economic costs of risks is also acting on the insight that investments in low-carbon projects, including nuclear energy projects, are uncorrelated or even inversely related to systemic market risk (see Trinks et al., 2022 for some empirical evidence). Including low-carbon projects in an investment portfolio can thus offer an improved risk-reward ratio to a wide class of investors. If informational asymmetries would

1. Of course, things like better technical designs or more accommodating regulatory frameworks would also reduce financing risks, primarily by way of reducing the challenges of project management. However, the following remarks, even if reflecting on the role of governments, take the point of view of the project manager or the financier. Designs and safety regulation thus need to be considered as exogenously given. That does not mean that they are not important. In particular, nuclear safety regulations and the two-way relationships between project managers and regulators can make a significant difference in the chances of success of a given project. Considering this is, however, outside the scope of the current study.

prevent the realisation of such opportunities, there would be a case for government either to intervene directly or nudge investors into the appropriate direction (see also below).

Pathways one and two essentially treat the project itself as a black box with a given cost and revenue structure, in particular a known overnight cost of construction and a stable long-term electricity price. These pathways thus indicate ways to reduce financing costs through financial engineering or the reallocation, of risk to parties with lower economic costs. Pathways three and four towards lowering risk and the cost of capital are "opening the black box". They are geared towards unpacking the framework conditions and internal workings of nuclear new build projects during construction and operations.

The third pathway towards lowering the costs and risk of the financing of nuclear new build thus consists in improving the economic and political framework conditions of a project. This includes, in particular, price and quantity risk in electricity markets as well as political risk. This is where appropriate market designs can make an important difference. Electricity market designs affect the allocation and the magnitude of both price risk and construction risk. In this perspective, electricity sector experts and regulators increasingly recognise that the energy-only markets that operate in Europe, Australia, Canada and parts of the United States are not providing the appropriate framework for the large amounts of capital-intensive low-carbon investments required to realise the ambitious net zero carbon emission targets of OECD and NEA countries. While their ability to organise efficient short-term dispatch around prices equalling marginal costs is recognised, this same pricing mechanism provides poor long-term investment signals. The latter would require a stable revenue signal for average costs, which would need to include the capital costs of investment for all technologies.

Such a more predictable price signal could come in the form of either FIT, PPA or CFD. An alternative would be constituted by measure providing price support such as FIP or carbon prices. While useful, such design features that shift price risk away from operators and investors to ratepayers and taxpayers (governments) might ultimately not be sufficient. This is due to the fact that price risk is unlikely to be the most relevant risk dimension that is holding back investment in low-carbon generating capacity such as new nuclear power plants. The key risk, here as in other low-carbon generators such as hydroelectricity or offshore wind, is construction risk. The latter is not addressed by providing price support, which, by definition, would accrue only when the plant is up and running. More recent proposals for electricity market reform thus concentrate either on measures such as RAB or CWP that allow to include the construction costs for ongoing projects into electricity tariffs from the start of construction rather than the start of operations or direct government involvement through loan guarantees, equity stakes or outright nationalisation. The first set of measures would shift construction risk to ratepayers and the second set to taxpayers. Chapter 3 will discuss these issues in greater detail.

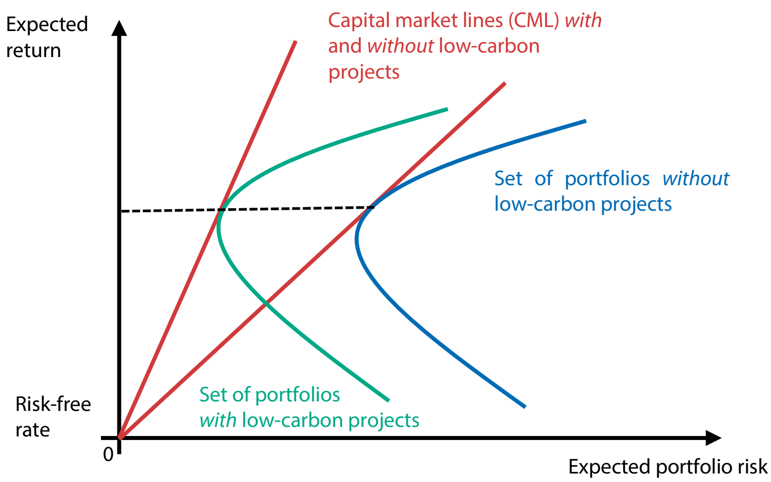
The fourth pathway is, of course, improved project management, which is the essence of the effort to reduce construction risk. There is growing awareness that construction risk, i.e. the risk that projects will not be delivered on time and on budget, is the key barrier to successful nuclear new build today. Improving project management will include every aspect of new construction projects from procurement to the structuring of the supply chain, contracts and hierarchies, the implementation of effective incentive measures as well as leadership. The issues will be carefully discussed in Chapters 4 and 5.

Decisively improving the cost and performance of nuclear new build projects will, of course, require all four pathways to be pursued in parallel. In addition, neither financing nor project management take place in a vacuum. Nuclear safety regulations and relationships between regulators and project managers, the availability of a qualified workforce and public trust all affect the project outcomes and the ability to deliver new nuclear capacity on time and on budget. Both public and private actors play a part in these matters. The following remarks, nevertheless, consider them as primarily being dealt with in other contexts, which does not exclude commenting on them when they should be directly impacted by financing issues, market design or project management. Before delving into the role of appropriate frameworks for electricity market design and the importance of robust project management with credible incentive structures, the key points of the first two pathways, choosing investors with lower costs of capital and allocating risk to the parties best able to carry them, shall be briefly recalled as set out in NEA, 2022.

A new approach to risk management in the financing of nuclear new build

Financing New Nuclear Power Plants: Minimising the Cost of Capital by Optimising Risk Management (NEA, 2022) established a new structure of thinking about the different components of financial risks for investors in nuclear new build projects. This structure was based on the CAPM, which is the most widely applied model in financial economics to determine the cost of capital and 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.

Figure 2.1. **Including low-carbon projects improves the risk-reward ratio of financial portfolios**



Source: NEA, 2022.

For any given investment project, the CAPM distinguishes the following components of risk: (1) the risk-free rate, which is defined by the rate at which countries with the highest credit rating 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.[2]

2. In principle, the finance literature considers idiosyncratic risks diversifiable, in the sense that they can be offset against comparable risks in other projects with the average being zero. However, in essentially unique, large-scale nuclear power plant projects these risks could not be offset by way of including them in larger portfolios of investment. Already, the sheer size of the investment required would make it difficult to build portfolios capable of offsetting multi-billion outlays. Furthermore, what would nuclear policy risk be offset with? Electricity price risk would affect most alternative investment in the energy sector and in industry to the extent that some experts argue that price risk is already included in systemic risk (Weymuller, 2023). While this report's author does not subscribe to this view, the argument highlights how difficult it would be to offset electricity price risk through diversification. Last but not least, the construction risk of nuclear power plants is idiosyncratic not only in the sense of financial theory, i.e. project-specific and hence diversifiable, but idiosyncratic in the wider sense that it is not part of any known probability distribution that would make it commensurable with the successes and failures of industrial construction projects throughout an economy and could thus be used to offset them against each other.

The premise of NEA (2022) was 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.

   In the case of **systemic market risk,** the key parameter is a project's **correlation** with market risk, often indicated as β (beta). Investors will always strive to include projects in their portfolios whose financial risks will offset each other in order to have a stable flow of returns. If a project is uncorrelated or negatively correlated with general market risk, then overall risk is lowered by adding such a project to a portfolio.

   In a net zero world, such negative correlation with systemic market risk 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. As carbon constraints begin to bite this will be felt in all corners of the economy as a reduction in profitability and rates of return on capital. The one exception to this tendency will be low-carbon investments themselves whose stock, profitability and rate-of-return are likely to rise. Such a countermovement of the risk-adjusted rates of return of low-carbon investments such as nuclear energy *vis-à-vis* the rest of the market would offer attractive opportunities for offsetting risks and increasing overall portfolio performance (see Trinks et al., 2022, for first empirical evidence).

   In this case, including low-carbon investments will reduce the risk and improve the risk-reward ratio, also called the Sharpe ratio, which measures the risk-adjusted returns of financial portfolios (see Figure 2.1). 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.

2. As far as the **project-specific risks** of a nuclear new build project, policy risk, price risk and construction risk, are concerned, NEA (2022) did not provide new insights into the true magnitude of those risks. Instead, it proposed for each risk category effective measures to allocate the risks to those parties that would be best placed to either manage them or to best withstand the economic costs of the underlying risks. For the three main idiosyncratic risks, it thus holds that:

   a) 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 sponsors and investors against changes in energy policy that would limit the use of nuclear power and allocate that risk to national governments.

   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 FIT or 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) For the large, complex and highly capital-intensive projects in nuclear new build, **construction risk** is almost certainly 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 RAB in the United Kingdom or 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.

In summary, the real costs of capital for nuclear new build projects are both lower than is usually assumed and can be further reduced through appropriate policy measures. They are lower than usually assumed, because the returns of low-carbon generation investments are de-correlated from systemic market risk in an environment where net zero targets are pursued with vigour and consistency. In addition, governments and electricity market regulators have at their disposal measures to reduce, if not the physical or structural risks themselves, the overall economic cost of construction risk, electricity price risk and political risk. The systematic de-risking of the project-specific risks, i.e. policy risk, price risk and construction risk, does imply a shift of risk from investors to taxpayers or ratepayers. However, such measures will also reduce the overall economic cost of the risks. Both effects together result in a radically reduced cost of capital. Effectively, such measures make it possible to bring close to zero the financial costs of the three project-specific risks for investors.

This has a straightforward implication: if nuclear new build projects are thoroughly de-risked in the manner outlined above, investors, whether private or public, will offer capital at very low rates of return to acquire the right to large amounts of low-carbon electricity delivered predictably around the clock for decades.

The NEA approach to analysing the risks and the costs of capital of nuclear new build has been welcomed by financing experts as a useful way to classify and understand the different sources of risk and the potential measures to de-risk them. Subsequent discussions nevertheless gave rise to complementary considerations that modify, limit or extend the basic model outlined above.

In a comprehensive discussion, Weymuller (2023) thus questioned whether construction, price risk and policy risk could be as neatly separated as indicated in the model. After all, policy discussions concerning market design impact both construction and price risk. Furthermore, the current financing model does not consider system costs, a fact that again feeds into questions about electricity market design and decisions about how to internalise these added costs related to the intermittency, uncertainty and higher grid outlays of variable renewables (see also NEA, 2019). Finally, to what extent is electricity price risk correlated with systemic risk? In other words, can the decorrelation of low-carbon generators from systemic risk be maintained if economic growth pushes up electricity prices for all generators?

Clearly, different risk dimensions interact and the segmentation proposed in NEA (2022) has to be understood as pragmatic choices that reflect particular areas of policymaking or sets of stakeholders as much as distinct analytical categories. Their purpose is primarily to allow for a coherent discussion of different key dimensions of nuclear new build. The question of the correlation of the rates of return of low-carbon generators with systemic risk and macroeconomic developments is ultimately an empirical one (see also Cherbonnier and Gollier, 2022). Such an empirical study, while useful, exceeds the scope of this NEA report.

Two conceptual points are nevertheless offered for consideration. First, recent high-price episodes in electricity markets such as the double crisis of European gas supply and the availability of French nuclear electricity generating capacity were linked to technical, regulatory and geopolitical factors and not to unusually high economic growth and electricity demand. While higher prices benefitted all generators, including low-carbon generators, they do not suggest a particularly close correlation between macroeconomic developments and electricity prices in general, quite to the contrary. Second, a robust pursuit of net zero carbon objectives would require considerably higher carbon prices than those currently practiced, especially in OECD countries in North America and the Asia Pacific region. This would inevitably drive a wedge between low-carbon and fossil fuel-based generators at the level of prices, profits and rates of return. At the same time, carbon pricing inevitably constitutes a constraint on economic activity though higher electricity prices, especially in systems relying heavily on fossil fuels. These higher prices, however, will increase the inframarginal rents of low-carbon generators. In short, recent experience does not imply a particularly close relationship between systemic developments and electricity prices in general and an inverse relationship between systemic developments and the returns of low-carbon generators. The assumption of a correlation of zero proposed in NEA (2022) seems well justified as a starting point for a broader empirical inquiry.

Deciding on the funding and financing of nuclear new build projects to ensure their social and political sustainability

The ability to answer distributional questions of the nature "who bears the financial risk?" in a fair, convincing and politically sustainable manner is at the heart of successful nuclear new build. It ultimately relates to the difference between the "funding" of a project and the "financing" of the project. While an economy is always a circular flow, so that ultimately everything is connected, it makes sense to clearly delineate the difference between the two notions, as they relate to distinct constituencies close to the project with different functions.

Funding relates to the party that ultimately, perhaps with a significant time-lag, provides the funds that will pay for the project. This party is constituted either by taxpayers, represented by the government, or by ratepayers, i.e. in the case of a nuclear new build project, electricity consumers. Financing instead relates to the party that engages in the intertemporal and horizontal minimisation of the costs of risks and that advances the necessary funds over time when they are required for disbursement. Quite obviously, this party is constituted by the institutions in finance and banking that provide upfront the funds required for paying for a very large construction projects with the intent to be reimbursed, at carefully negotiated conditions at a later stage.

Before engaging in developing the financing structure, the funding question needs to be clarified. The idea that "investors" will "fund" a project is mistaken. This can only happen if investors are not fully reimbursed, i.e. lose money on a project. Of course, this can happen due to overly optimistic expectations, the materialisation of large, low-probability risks or the advent of entirely unanticipated events. Philanthropy, where very rich individuals are willing to invest in possible solutions for urgent challenges such as climate change, or venture capitalists prepared to bet and lose large amounts of money on exciting "moonshot projects" may constitute further exceptions. But it is obvious that this is not a sustainable manner to finance any investment project, let alone large and highly capital-intensive projects such as new nuclear plants. In addition, once bitten, twice shy. Capital, whether from public or private sources, is the most mobile of factors of production. Even unspoken hopes to have financing investors on the hook for funding will translate into higher perceived risk, reduced investment appetite and ultimately higher financing costs to be borne by the ultimate funding parties.

Thus, before the question of financing is approached, the question of funding needs to be addressed and answered. This relates not only to the creation of a solid basis for subsequent financing negotiations. Answering the funding question in a convincing manner goes to the heart of the social and political sustainability of nuclear new build projects. These projects imply unusually long timeframes and unusually large amounts of capital. The time between the decision to invest and commissioning can take anything from five to ten years, with individual projects taking much longer. A new Generation III plant is then expected to operate for up to 80 years and, of course, decommissioning and waste disposal commit a country, fortunately at rapidly decreasing financial intensity, for decades to come after that. The investment volume for a plant with two reactors to benefit from increasing returns to scale will be above USD 20 billion.

Of course, society in return will receive a vital part of low-carbon infrastructure, providing large amounts carbon-free baseload electricity around the clock. Yes, the scales are such that a government needs to manage the discussion on the allocation of funding costs carefully and with large lead times. It may be argued that in recent years such funding questions were not always decided in the most transparent manner, not necessarily out of an explicit preference for opacity in this matter, but due to the misunderstanding that the construction of one or several new nuclear power plants is not a run-of-the-mill industrial project whose funding and financing is best left to the experts. The sets of citizens, electricity consumers, taxpayers and voters may ultimately largely overlap. Nevertheless, individuals and their representatives will likely have clear views on whether they prefer a 10% increase in their electricity bills or a 1% increase in their tax rate.

In the end, when it comes to funding the decarbonisation of the economy, something will have to give, a simple truth that is often overlooked and for which societies are so far unprepared. This is because the funding of nuclear new build, or low-carbon investment in general, between ratepayers and taxpayers is complicated by two additional considerations that make organising the relevant societal consultation and decision-making processes indispensable. First, it has been shown consistently that nuclear energy is a key element of achieving ambitious emission targets such as net zero carbon emissions by 2050, an objective to which many OECD and NEA countries have subscribed (see NEA 2012, 2019 and 2022b) at least cost. Nevertheless, achieving such targets will always constitute a constraint on energy and electricity systems, as well as on the overall economy. Logic imposes that a constrained system can never have lower costs to reach a given level of output, whether this is measured in energy consumed or GDP produced, than an unconstrained system. This also means that the costs for providing the high levels of electricity security that citizens of NEA countries have rightly become accustomed to will rise. As shown in the studies cited, these costs will rise less if nuclear energy is included in the decarbonised mix – but rise they will.

Second, the discussion of how to fund the increased and increasing costs of the energy transition, of which the electricity sector is expected to carry a large burden, is wound up with a parallel debate, at least in some OECD countries, on how to ensure attractive framework conditions for energy-intensive heavy industries and manufacturing industries. Different countries or regions choose different pathways in this field. The United States has decided, as signalled for instance by the headline measures of its 2022 Inflation Reduction Act (IRA), that it is taxpayers that should fund the energy transition. In the European Union, intense discussions were conducted in 2023 on the extent to which providing low-carbon electricity generated based on nuclear power at or below full costs could be a considered a subsidy to energy-intensive industry. In this case, the debate was not only about allocating the costs between taxpayers and ratepayers, but also about allocating between different groups of consumers, in this case industry and households. Overall, the considerable costs of the energy transition have so far not been adequately articulated to voters and decision makers. This has led to unrealistic expectations and is fast becoming a serious strategic impasse for OECD and NEA policymakers in the energy and climate field. While many voters and decision makers call for more climate action, they often recoil from the costs when these measures are set to become concrete.

Once funding has been clarified, and arguably this is the more important issue, the next essential step is to arrange for financing at the lowest possible cost, which means working with partners who are capable to arrange for the intertemporal allocation of funds in an efficient manner. Financing is about intertemporal smoothing of the funding needs. This is where public or private investors come in with the upfront provision of capital in the form of debt or equity. Those funds will be required to match the costs of the project during the construction period.

These costs are constituted by the overnight cost, i.e. the expenditure on materials, labour and management during construction, without accounting for the dimension of time, and the funding costs, i.e. the cost of capital during the lifetime of the project, including the duration of the construction project. In all conceptual approaches, including that of the NEA/IEA *Projected Costs of Generating Electricity* series, these two items are considered distinct, in the sense that financing costs are considered to be exogenous, and there is no obvious methodological alternative to doing so.

Keeping overnight construction costs and the cost of capital distinct is a well-established practice and part of the standard analysis of cost accounting. However, one of the key points of the present report is to highlight the link between the two. As emphasised repeatedly in NEA (2022), the cost of capital is the cost of risk, which determines the time value of money. Wellmanaged projects that can deliver new nuclear capacity at cost and on time signal lower risks to investors than projects with cost overruns and can thus expect investors to ask for lower rates of return from those who ultimately fund the project (see also Chapter 5).

Major determinants of overnight construction costs are the choice of design for the reactor and the nuclear power plant, which determines the amount of resources required for construction, and the efficiency of project management. The latter may be interlinked with financing arrangements, in particular through the feedback loop of incentive structures, and the level of oversight by public and private investors. Reducing overnight costs and reliable project execution are the two most important issues in nuclear new build to an even larger extent than usually understood. They not only define the overnight costs as such but also ultimately determine, to a large extent, the financing costs. Due to the decorrelation from system macroeconomic risk (see above), construction risk really does determine the largest part of the cost of capital in a nuclear new build project. With construction risk as the key driver, ultimately the cost of capital is endogenous to the project itself. This holds for both the current generation of Generation III reactors in the gigawatt-range and for new designs of SMRs.

Socialising the economic cost risks of low-carbon generators is a good idea – up to a point!

In keeping with a general trend in climate finance, project-specific risks such as policy risk, price risk and construction risk are increasingly socialised through government and regulatory framework setting and intervention. Financial theory holds that this is unnecessary. Assuming efficient markets with perfect information, project sponsors would diversify the costs of a project, including risks, among a broad swath of investors who would advance the necessary funds and then make ratepayers return the money as part of their electricity bills. This classical mechanism, however, has broken down in the case of financing low-carbon generation in general and new nuclear power plants in particular.

The reason for this is twofold. First, the deregulation of electricity markets has made medium- and long-term price risk all but unpredictable. The very low prices for many years before 2020 alternated with the extreme peak prices of 2021 and 2022. The only thing that is certain about the future is that in deregulated markets violent price swings will continue and are likely to increase as decarbonisation takes hold. They will continue because electricity cannot be stored cost-effectively for more than a few hours, which means even small changes in demand and supply lead to large changes in the respective equilibria. Such price swings are likely to increase because of the increasing share of low-carbon technologies with low (nuclear, hydro) or zero (wind and solar PV) marginal costs. This will push operators towards reducing capacity to generate as many hours as possible of the (very) high prices when electricity is no longer available for all. The result is more price volatility, both in the short and, even more importantly, in the long run. If short-term volatility can partly be compensated by storage and demand response, the long-run average price is what investors are really concerned about.

Second, there is the complexity and scale of nuclear new build projects, which increases investor risk, in particular during the construction phase. Construction is by far the greatest concern in assessing investor risk. Moving from standard PWR and BWR Generation III+ designs towards SMRs promises a welcome reduction in scale. However, depending on their design, new generation SMRs may have to overcome additional challenges in technology, materials fuel supply and waste management. While private venture capital has been willing to finance the development of new designs and, in some cases, even prototype development, the key financing question will regard scaling up industrial production. Factory building rather than stick building individual power plants is a much-vaunted option for SMRs. Hence, the financing and building of the required SMR factories will become a major issue, involving new questions of market demand, increasing returns to scale and investor risk.

Yet, these challenges are hardly unique to nuclear energy. Across the board, the energy transition is characterised by highly capital-intensive technologies, some of which are even exposed to additional challenges. Hydroelectricity, especially, in the form of large reservoirs or run-of-the-river plants, is perhaps the technology with a financial risk profile closest to that of nuclear energy. A dispatchable low-carbon technology of large size, high fixed costs and considerable construction risk, it has to carefully engage with stakeholders to convince them of its social and environmental acceptability. Onshore wind and solar PV are today mature technologies with limited construction risk. Their challenge is, of course, their intermittency and declining value factor, i.e. the fact that as their share in the electricity system increases, the electricity that they produce yields progressively lower prices. This is due to the fact that their output is concentrated during a small number of hours, when all plants of a given technology produce, thus generating oversupply and driving prices down. Offshore wind, with its higher load factors, was supposed to change this. However, the hypothetical economics of ever-larger turbines to be installed in unforgiving marine environments have led to serious industrial challenges, compounded by connection problems both from the wind parks to the coast and from often thinly populated coastal regions to the centres of demand. A race for scale and overconfidence has also led to the conclusion of underpriced contracts, which engendered a series of costly, high-profile cancellations in the second half of 2023.

A key issue for future nuclear new build is the extent to which construction risk shall be borne by taxpayers or by ratepayers before or after the date of commissioning of the new power plant. Bearing the costs of construction by ratepayers *after commissioning* takes place, of course, in merchant power plants but also in arrangements such as CFD. Taxpayers bear the cost of construction *before commissioning* in the cases of direct public investment, while ratepayers do so under arrangements such RAB or (CWP). The question is far from theoretical. Without socialising, at the very least, a sizeable share of the risks of construction before commissioning, no private investors could be enticed to participate in nuclear new build projects.

In the electricity sector, socialising certain risks, such as the value risks of variable renewables has, of course, been ongoing for decades. The feed-in tariffs received by wind and solar PV generators have isolated operators both from standard price risk but also from the specific loss-of-value-of-output risk to which they are exposed. To the extent that the latter is a direct function of political decisions about the energy mix, such insurance constitutes a justifiable form of internalisation by transferring it to the public sector. The problem has rather been that the very real costs of this risk have been very inadequately assessed and communicated to those who ultimately bear it as taxpayers. These costs and the opacity surrounding them are now beginning to show up with a lag as a main driver of the "transition fatigue" that is palpable in many OECD and NEA countries and is beginning to erode popular support for ambitious carbon emission targets. Independent of the ultimate magnitude, it is reasonable to have the loss-of-value risk of variable renewables borne by taxpayers, as electricity consumers have less influence over the generation mix than voters and their political representatives.

In conclusion, two important points add further perspective on the distribution of the risks and costs in nuclear new build. Investors and, even more so, electricity consumers are highly risk-averse. This means that downside risks are perceived as far more damaging than equivalent upside risks are perceived as beneficial. The greater the magnitude of the risks, the more forcefully this consideration applies. In other words, increasing constant payments, such as electricity bills, by a small constant amount in order to avoid large future uncertainties such as price spikes, or, even worse, supply interruptions, usually is a bargain that most electricity consumers will be open to consider (see, for instance, Deloitte Access Economics, 2023). Everything depends, of course, on the magnitude of the different items. Other things being equal, however, risk aversion increases the appeal of market designs that allow for provisions such as RAB or CWP that rely on ratepayers advancing the funds for new nuclear construction. The Arrow-Lind theorem (see Chapter 4 for a comprehensive discussion) is based on a similar premise.

Of course, the concept of socialising the risks of nuclear new build, and in particular the risks of construction, cannot be applied too broadly. Being exposed to some risk is good, even necessary, in order to motivate all stakeholders in the construction process to perform at their best. Cost control and execution will be lax if those responsible are completely immune to the consequences of their actions. In practice, the right balance needs to be found empirically as theory is of limited help. Notions such as enterprise culture and leadership apply here. Even if protected against most financial risk, stakeholders need to be made aware that their careers depend on successful outcomes. Even in fully nationalised industries, there exist explicit and implicit performance awards or penalties.

At the same time, neither ratepayers nor taxpayers can be held to ransom indefinitely. Financing arrangements in which large parts of the financial risks are socialised need to be perceived as fair in order to be politically sustainable. This implies a high degree of transparency as well as conflict resolution mechanisms. Currently, the purely private financing of new nuclear capacity is for the reasons detailed above not a viable option. The alternative, financing by ratepayers or taxpayers, needs to be implemented with care, a view towards the long-term and a sense of fairness that includes all stakeholders in order to realise the potential contribution of new nuclear generation capacity to low-carbon electricity systems.

Chapter 3. A new realism to consider market designs reducing financing cost and supporting investment in low-carbon generation technologies

Markets provide highly efficient frameworks for optimising resource allocation, minimising costs and incentivising individuals to perform to the best of their abilities. In a dynamic perspective, markets also allow for a process of trial and error, in which less-performing technologies and firms are gradually substituted by better-performing ones in a process sometimes referred to as "creative destruction". The conceptual benchmark for market design is constituted by competitive markets that set prices at the marginal cost of production. It can be shown that under a standard set of assumptions such markets minimise costs, including financing costs, and maximise total welfare.

It is always a rather simple exercise to point out the lack of realism of standard assumptions such as competition, perfect information or rationality. This has not stopped largely unregulated real-word markets from performing quite well in a wide range of sectors, especially when compared to alternative forms of allocation such as regulation or public administration. When motivating "electricity market designs" that complement or supersede the working of decentralised short-term competition based on variable costs, it is thus necessary to develop more convincing arguments. Of course, these markets were designed with technologies in mind that had comparatively high variable costs such as gas plants before the advent of shale gas and not for low-carbon technologies with low or even zero variable costs. Theory maintains, however, that competitive markets should nevertheless also work for low-carbon technologies. Yet there exist in the electricity sector a number of reasons why deregulated markets are unlikely to provide the appropriate framework for optimal levels of investment in low-carbon generation capacity in order to realise the energy transition and move towards net zero carbon energy systems. The most important of these reasons can be grouped under five headings:

1. **Political and social choices**: Many experts will argue that electricity markets have never been entirely free. Electricity is considered too important a good to be able to operate outside of the political and social sphere. On the demand side, electricity is often considered a merit good. In other words, all consumers should be provided electricity at high levels of security of supply that may exceed their willingness to pay for the units providing the last MWh during a situation of supply stress. On the supply side, climate objectives and, in particular, the support for variable renewable energies (VRE) such as wind and solar PV have moved electricity markets far from simple economic or social optima. Reconciling security of supply and carbon concerns requires additional measures. The choice is thus not primarily between deregulated markets and regulated markets but between markets disturbed by unco-ordinated ad hoc policy interventions and market designs aiming at sensible systematic linkages between public and private concerns.

2. **The difficult storability of electricity**: This may seem a moot point in the age of demand side response and battery storage, but the fact remains that the bulk of electricity must be produced the same second it is consumed. While the intermittency of wind and solar PV poses a particularly thorny challenge in this context, it is not the only one. The inability to store electricity in great quantities and over longer periods at a reasonable cost is also responsible for the complicated organisation of the "merit order" of different technologies stacked according to their variable costs, and the inelasticity of short-term demand, which during periods of extreme peak demand can lead to the temporary disconnection of consumers ("rolling blackouts"). The merit order of different

technologies, whose shares are determined according to highly uncertain anticipations of the future, and the inelasticity of short-term demand are also responsible for highly volatile prices in both the short and long run. Interventions to ensure the security of supply, either through capacity mechanisms or long-term contracts out of the market, are thus frequently necessary with inevitable repercussion on price formation, which no longer functions as predicted by theory.

3. **"Too big to fail" creating irreversibilities**: As indicated above, a highly useful characteristic of competitive markets is that they allow for efficiency-enhancing trial and error. If, however, single investments, for instance the costs of a Generation III nuclear power plant, a large hydropower installation or a major grid extension, are measured in the billions or tens of billions of dollars or euros, trying and failing is no longer an option for investors. Since success can never be guaranteed in advance, the latter will simply refuse to bet the bank or the company on a single project without wide-ranging financial guarantees supported by ratepayers and taxpayers. The latter constitute, inevitably major market interventions. In such cases, when a project is essentially condemned to succeed, as abandonment would be considered an enormous waste of resources, far beyond the value of the lessons that could be learnt through trial and error, good project management and independent oversight assume an even more critical role than usual. Indeed, the irreversibility implied by the "too big to fail" argument not only applies to individual projects, but also to programmes or policy commitments, such carbon emission targets or shares of renewables. In all cases, foregoing the option value of being able to pull the plug on a project, programme or policy commitment requires careful preparation, accompaniment and management in order to ensure broad long term support even if unforeseen difficulties should arise.

4. **The capital intensity of the energy transition**: Since the industrial revolution, global economic growth has been favoured by the widespread availability of fossil fuels such as coal, oil and gas. The economic advantage they provided was not primarily their price, which could be volatile and high at times, but their ease of handling and the comparatively low capital costs of the transformation technologies turning them into electricity, heat or motive power. The energy transition and the imperative to reduce carbon emissions does away with this. The cost of low-carbon sources of electricity and energy, whether nuclear, hydroelectricity or renewables, and even storage and fossil fuels with carbon capture, utilisation and storage, lies predominantly in the fixed costs of the generation capacity, which are substantially higher per kW than the costs of equivalent fossil fuel-based capacity. Their short-term variable costs instead are low or, in the case of wind and solar PV, even zero. This has fundamental implications for electricity market design. With the low fixed and comparatively high variable costs of fossil fuels, the latter setting the price, competitive markets with marginal cost pricing were a proposition that most OECD and NEA countries found attractive. With low-carbon technologies with low variable costs increasingly setting the price, financing the capital costs of their fixed investment on the basis of market prices alone is becoming increasingly difficult if not impossible. Instances of *negative* prices have been a widely visible indicator of the more general challenge to generate sufficient returns in electricity markets with marginal cost pricing. [1] Market designs thus need to be adapted to provide investors with sufficiently high and predictable returns to allow for the financing of the large capital costs of the energy transition.

1. Negative electricity prices are a function of a temporary oversupply from VRE power plants such as wind and solar PV and the relative inflexibility of some, usually older, dispatchable thermal power plants such as nuclear and coal. The autocorrelation of VREs, whose entire production is compressed into a subset of hours, explains not only the temporary oversupply during certain hours but also the fact that VREs during the hours that they generate earn, on average, less than the average prices over the complete set of hours. Due to their capital intensity, all low-carbon technologies face huge challenges in deregulated electricity markets; the challenges of VRE, however, are of a magnitude greater still.

5. **The high costs of the energy transition:** The fact that the energy transition towards net zero will imply real and significant costs for economies and societies of OECD and NEA countries and beyond is now slowly being realised by energy policymakers and stakeholders. In principle it is obvious: any exogenous constraint, such as limiting carbon emissions, imposes economic costs on a system that otherwise would have been free to minimise costs and maximise profits. This holds for market-based systems as much as for planned systems. However, due to a mix of economic naïveté, short-term political opportunism and blue-eyed technological optimism, the costs of the energy transition have been undersold since its beginning, which can be placed, for lack of a more precise date, at the time of the 1987 Brundtland Declaration. In parallel, conceptual approaches such as the "Porter Hypothesis" (Porter and van der Linde, 1995) or "Race to the Top" (Murphy, 2004) suggested that more stringent environmental regulations would yield not only ecological benefits, but would also spur growth-enhancing technological improvements.

   There were interesting considerations contained in those contribution, for instance relating to the information-enhancing role of regulation. However, it did not take long for the realities of basic economics to reaffirm themselves. A constraint on economic activity, however well-meant and well designed, will have an economic cost and reduce output and growth below what it could have been otherwise. Even those who understood the working of economic systems were willing to assume, implicitly more often than explicitly, that the costs of the energy transition could be hidden in the form of a small reduction of economic growth rates. Policymakers, keen to strengthen politically attractive renewable targets, were also led to believe in opportunities for industrial development and technology exports that never materialised. Others for many years confused low electricity prices, due to low marginal costs, with low total costs of low-carbon systems, conveniently forgetting to mention the high fixed costs of low-carbon systems. As the full economic costs of energy (and of low-carbon energy in particular) become apparent, societal debates about their necessity, and their distribution are imposing themselves. This necessity remains undiminished, due to the need to contain accelerating climate change. New measures and market designs accompanying the financing of nuclear new build are thus part of broader debates on how to allocate the costs and financial risks of the energy transition.

Energy policymakers are just starting to respond fully to the implications of these five sets of reasons, which are unmistakably being felt in society. After 25 years of deregulation, progressively introducing markets based on short-term marginal cost pricing, there is a new willingness in OECD and NEA countries to consider alternative market designs that offer better frameworks for investing in low-carbon technologies. There exist essentially two complementary strategies that are being pursed, often in parallel. The first addresses price risk, the second construction risk.

The limits of energy-only markets with marginal cost pricing and the move towards average cost pricing

Working with the constraints and requirements of the energy transition thus requires a fundamental rethink of how electricity markets should work. This is not primarily about "competition" versus "regulation". Also, electricity markets fit for the energy transition can contain competitive elements, even if they may at times take the form of competing "for the market" rather than competing "in the market". The fundamental change that electricity markets need to operate is to switch from marginal cost pricing to average cost pricing, i.e. reflecting fixed capital costs in addition to variable costs. Setting the price of electricity equal to the variable costs of the marginal technology was always based on the leap of faith that the "missing money" corresponding to the fixed capital costs of the marginal technology could somehow be recuperated through a limited number of "scarcity hours" with very high prices.

Although even the idea, let alone the reality, of scarcity hours with rolling blackouts was always deeply unpopular with politicians and consumers, the leap of faith could be defended in an environment that allowed for carbon emissions as natural gas plants have comparatively low capital costs. Electricity market deregulation only became conceivable with the increasing competitiveness of combined cycle gas turbines in the 1970s. The system would thus require only a limited number of scarcity hours to balance costs and revenues. The relevant target for system planning in France, for instance, foresees 30 hours every ten years, for instance during an unusually severe cold spell. That is equivalent to three hours per year on average. In a net zero context, however, this approach becomes entirely unworkable due to the comparatively high capital costs of low-carbon technologies requiring a larger number of scarcity hours. To this must be added the large unit sizes, associated with non-diversifiable financial risks, of dispatchable low-carbon technologies such as nuclear energy and hydroelectricity. No private party could ever invest several billions of USD or EUR based on the statistical hope of a string of harsh winters in order to recuperate their investment.

The idea that energy-only markets with marginal cost pricing could bring forth the investments in the large amounts of low-carbon generation capacity required by the net zero energy transition is fanciful. No nuclear power plant has ever been built based on expected revenues from a deregulated energy-only market.[2] The same holds probably for tightly regulated hydroelectric plants although the data situation is less complete. Finally, in OECD countries at least, the investment in variable renewables such as wind and solar PV has been universally supported by investment tax credits or FIT.

A consensus is thus emerging that it is necessary to turn to average cost pricing. The challenge, of course, is that deregulated spot markets, in which individual traders buy and sell in a decentralised fashion, do not do average cost pricing. This incontrovertible fact is hard to swallow for many observers, as life would be so much easier if markets did do average cost pricing.[3] Even future markets offering delivery of electricity for up to three years will not include fixed costs, as buyers can always return to the spot market. While technologies such as nuclear energy, whose variable costs are usually lower than the price, do earn “inframarginal rents”, these are not sufficient, absent the requisite number of scarcity hours, to finance the full amount of fixed investment costs, even abstracting from the inherent uncertainty surrounding the evolution of electricity prices.

If markets do not do average cost pricing, what is then the solution? A return to electricity systems planned by regulators, who will also be setting consumer tariffs? The ability to set tariffs at average costs and thus to ensure sufficient funds for investment is perhaps the greatest advantage of regulated energy systems. Centralised, or, more appealingly, integrated, long-term planning of the generation mix has the advantage of developing a coherent vision of the system, including the inevitable political preferences for certain technologies in the process. While this may seem a dubious advantage, proceeding on the basis of an explicit planning process is probably preferable to an incoherent muddle of theoretical high-handedness insisting on market-based investment, massive yet selective support of technologies currying favour with the public but with a limited system contribution and a mix of ad hoc patches to keep the lights on.

Does this mean a return to old ways? Not necessarily. The movement towards deregulation that began in the 1980s and gathered its full force in the 1990s had some valid arguments to make that were only partly related to system planning as such. There was the suspicion of widespread “regulatory capture”, i.e. that energy regulators and utility managers were both part of the same tight-knit community that was, consciously or unwittingly, exploiting consumers

2 The closest the construction of a nuclear power plant has ever come to taking place in a deregulated market is the about-to-be-completed EPR in Flamanville, which is at least formally taking place in the deregulated European electricity market. France, however, maintains a regulated tariff for residential consumers (*tarif bleu*) and EDF, which was recently fully renationalised, has always benefitted from explicit and implicit public financing guarantees.

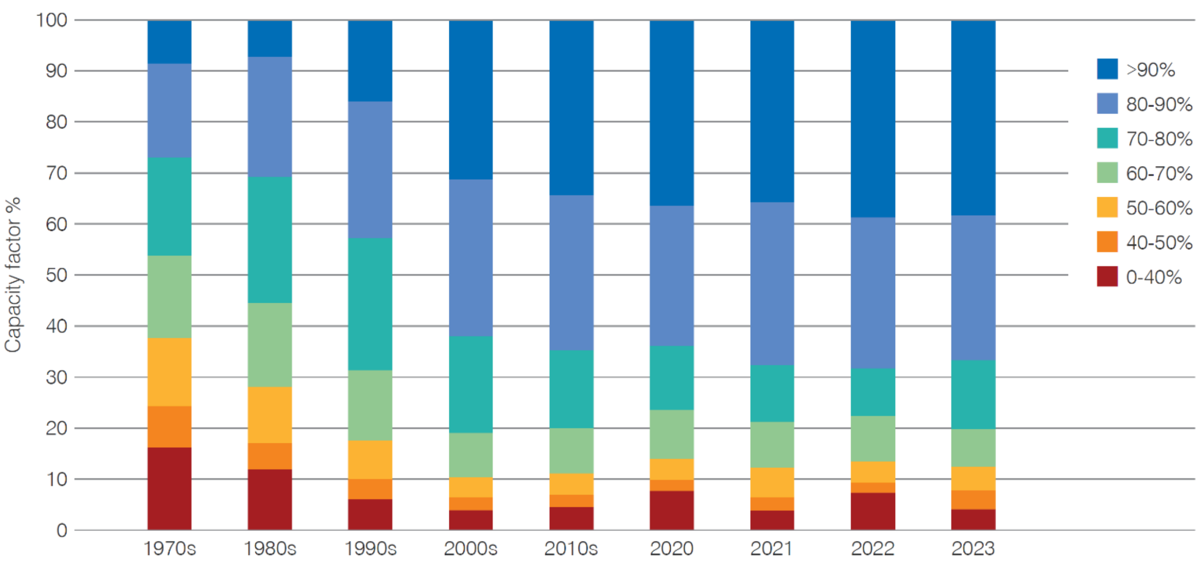
3 In the field of nuclear energy, the issue arises not only in electricity generation but also in the production of medical radioisotopes (MRI). “Full cost pricing”, implying average cost pricing including a unit share of capital costs, has long been the declared objective of producers, policymakers and stakeholders. While *any* conceptualisation of a coherent pricing mechanism is difficult in an area riven by sometimes willful, opacity, explicit and implicit cross-subsidisation at different levels and a need for operational reserve capacity (ORC), one thing is sure: despite a decade of exhortations by policymakers, the market for MRI is further away from full cost pricing than ever.

with overblown rates while at the same time living comfortable and riskless corporate lives. Other issues were "gold-plating" and corporate slack, the tendencies to overinvest either in the quality or the quantity of generation and transmission capacity. Finally, regulated industries were found to lack in technological dynamism and efficiency, precisely because there was no need to break with the existing way of doing things.

Deregulation in combination with widespread privatisation of previously publicly held utilities managed indeed to eliminate or moderate a number of these drawbacks. The relationship between utilities and regulators has certainly grown more adversarial. Competitive pressures have all but done away with gold-plating and corporate slack, operations have become far more efficient and capacity factors have increased markedly. Figure 3.1, which provides a global picture of the increases in capacity factors, does not report the even stronger improvements in the deregulated electricity markets of the United States and Europe.

While deregulated markets have proven to work less well than expected regarding the ability to incentivise investment, in particular investment in low-carbon generation capacity, they have worked at least as well as expected in terms of improving the efficiency of hourly dispatch. According to industry consensus, competitive dispatch is doing remarkably well in squeezing out good performance from generation plants ("sweating assets"), once the latter have been constructed and are up and running. The future will thus likely consist of "hybrid markets" combining competitive dispatch with targeted incentive measures for investment in different low-carbon technologies (see below). A centralised process of integrated system planning will then again determine the relative share of those technologies, while allowing new technologies willing to come forward without added investment incentives to enter the market. This does not mean foregoing competitive processes altogether. In many instances, the now standard procedure to incentivise capital investment is to hold competitive tenders or auctions, which selects the utility or consortium willing to go ahead with the lowest amount of support. Experts speak of competition *for* the market substituting for competition *in* the market.

Figure 3.1. **Capacity factors of nuclear power plants have increased markedly also due to deregulation**



Source: World Nuclear Association (2023), *World Nuclear Performance Report 2023*, WNA, London, p. 8.

During several months at the beginning of the 2020s, the advocates of deregulated energy-only electricity markets, who had maintained that they would eventually generate revenues sufficiently high to allow for investment in low-carbon capacity, were vindicated. The very high

European electricity prices for electricity of 2021 and 2022, when monthly forward contracts in France exceeded a previously unthinkable EUR 1 000 per MWh, induced some producers to consider that market-based pricing electricity finally might be sufficient to provide sufficient margins also for covering their investments. The return to more normal prices of well below EUR 100 per MWh in 2023 and 2024, however, quickly deflated such lofty expectations. Financing investment in new low-carbon capacity solely out of the revenues of the energy-only market is as elusive today as it was before the energy and electricity crisis induced by Russia's war against Ukraine.

Measures to address price risk aim primarily at offering long-term contracts that provide a stable remuneration per MWh of electricity priced at average costs. PPA, CFD or even regulated electricity tariffs all provide generators and their investors with a stable remuneration, independent of short-term market developments. If the counterparty is a public entity, such long-term contracts may include a subsidy element in the sense that the negotiated price may lie above market expectations. Typically, this has been the case for wind and solar PV generators receiving FIT or FIP, a fixed top-up above market prices that guarantee a minimum revenue. Also, capacity remuneration mechanisms aim at making investment decisions independent of "energy-only" short-term markets. However, they usually only provide capacity support for up to three or four years, which makes them attractive for plants with relatively short construction times, frequently pure capacity providers such as open-cycle gas turbines (OCGT) or offers of demand response. Sometimes even shorter periods are the only ones being offered – for instance when the challenge is to keep existing plants from closing down. An exception is the UK capacity market, which offers contracts for newly built plants for up to 15 years.[4]

Independent of specific capacity mechanisms to support the financing of fixed investment cost, understanding and managing electricity price risk remains a major topic. NEA (2015) thus advocated a shift towards long-term contracts for existing and nuclear power plants. While this remains an essential complement, additional research revealed that fixed-price long-term contracts may not be sufficient to incentivise nuclear new build. Even when price risk is neutralised, construction risk is thus that the subsidy element in a long-term contract, typically a CFD, would be very strong to allow investors to go ahead.

Finally, fixed-price contracts come with their own risk for both parties. It is the risk of being locked in a contract that is no longer consistent with market conditions. Imagine being a gas-fired power producer with a long-term contract for electricity delivery but having to face the extremely high gas prices of 2022. At the same time, while ensuring against downside risk, long-term contracts imply foregoing upside risk. During 2022, once more, electricity generators selling on the short-term spot market clearly had the advantage over those stuck in long-term contracts. And, of course, those who wanted to conclude longer-term supply agreements on organised markets have always been able to do so, either on organised exchanges or through bilateral "over the counter" contracts. However, data from European electricity markets show that there are literally no buyers and sellers for long-term contracts beyond two years, even though the products exist (EEX, n.d.). There is a reason for this: neither buyers nor sellers see a particular advantage in switching towards competitively priced long-term contracts.

Hence, long-term contracts are attractive for electricity suppliers only to the extent that they contain an implicit subsidy element, i.e. a promise of a remuneration above expected market prices. FITs and CFD contain such premiums in an implicit manner and FIP in an explicit manner.[5]

4. A primer (Clifford Chance, 2015) usefully provides additional information.
5. Precisely because they do not contain such a premium over expected market prices, bilateral PPAs between private partners are unlikely to be able to incentivise large amounts of low-carbon investment. Electricity buyers, who are usually supplied through one-year forward contracts, will prefer to sit out medium-term price changes in a market with structurally declining prices rather than pay a long-term premium for stability. The market for long-term PPAs is likely to remain very thin, except if governments will resort to supporting it through tax incentives. The "Mankala model", for instance, which constitutes a form of long-term PPA and is popular in Finland for a variety reasons, benefits from the fact that both revenues from electricity sales as well as gains due to receiving electricity below market prices remain untaxed.

It should be noted that such long-term contracts provided by governments directly or by government-mandated public or quasi-public entities such as regulators or regulated system operators always imply a certain degree of system planning. This comes back to the issue of the revival of industrial policy in the context of the energy transitions, mentioned in Chapter 1. Although the notion of industrial policy needs to become more precise and more detailed in the years to come, the governments of OECD and NEA countries increasingly understand that they need to take responsibility for shaping the low-carbon electricity systems of the future, since markets designed to optimise dispatch on the basis of variable costs will not be able to bring forth the required amounts of capital-intensive low-carbon capacity. Ultimately, government "owns" the risks to the stability of electricity prices and the security of supply. Taking explicit responsibility for the long-term framework of the electricity system also provides investors and project operators with a form of insurance against policy risk.

The generation mix is thus increasingly a function of the number of FIT, FIP and CFD that are offered, frequently in the form of auctions in order to remain close to the level of support actually required by generators. This is not necessarily a bad thing; countries and societies have often clearly articulated objectives in terms of the generation mix. Targets to achieve this or that level of technology are commonplace. Aiming at the targets directly is preferable to paying lip-service to the mantra that "free electricity markets decide the generation mix", while trying to steer the generation mix indirectly. Moving towards electricity market designs allowing for the provision of long-term contracts with implicit subsidies, public preferences for certain generation mixes are being made explicit allows for increased transparency, certainty and, ultimately, efficiency. The problem is that much of this development is still taking place in a selective and haphazard manner. Long-term price support was thus for the better part of the past decades limited in many OECD and NEA countries to onshore wind and solar PV.

Nevertheless, providing long-term contracts, including contracts that contain an implicit premium over expected average electricity prices, is a legitimate manner to incentivise investment in low-carbon generation. Indeed, they might not only be legitimate but necessary to the extent that the average costs of low-carbon generation are likely to be permanently higher than electricity prices, which, in competitive markets, correspond to the variable costs of the marginal technology. The variable costs of all low-carbon generators, whether nuclear, variable nuclear energies (VRE) or hydroelectricity, however, are very low. To the extent that fossil fuel generators are pushed out of the market, possibly due to carbon prices, an increasing number of hours will have low or zero prices, thus dragging down also average prices. Abstract theory maintains that low electricity prices will be offset by increasing numbers of scarcity hours with very high prices. However, the implication that during scarcity hours not all customers will be served is difficult to accept for consumers and policymakers in a security of supply perspective and thus the structural revenue shortfall in low-carbon electricity markets remains.

There have been several attempts to reconcile the points of the view of the theorists, who maintain that deregulated markets with enough scarcity hours should be able to incentivise investment, and of the practitioners, who refuse to build in the absence of out-of-market guarantees. After all, the theorists maintain, a very small number of scarcity hours will be compensated with an overall least-cost provision of electricity during all other hours. However, what the theorists are often overlooking is that the electricity sector has a number of particularities that impede the optimal provision of capacity, which corresponds to the optimal level of the security of supply, based solely on the revenues from electricity sales on the energy-only markets. Among the two most important ones are security of supply externalities and asymmetric incentives given the granularity of capacity investments (see Keppler, 2017). The first particularity of electricity systems is that they work as networks, not only in a physical but also in an economic and social sense. A supply interruption during scarcity hours affecting one person will not only have individual costs but will produce spillovers on his or her customers, contacts and friends. However, these external costs are not accounted for by energy-only markets. The second particularity of electricity systems is that short-run demand is very inelastic, which is related to the fact that electricity is difficult to store in large quantities at reasonable cost. In addition, cost-effective capacity comes in certain minimum sizes. Any given investment is thus likely to either overshoot or undershoot the optimal level. As overshooting inelastic demand gives rise to large penalties in terms of very low prices, risk-averse investors will always aim at staying slightly *below* the optimal level of capacity.

The impact of electricity market design on ownership, project management and technology choice

Electricity market design, the rules under which generators and consumers trade, buy and sell electricity, directly impacts the profitability, financial risk and cost of capital of generators by way of the level and volatility of electricity prices. But market design can also have an indirect impact on the cost of capital by influencing the ownership and financial structures of generators as well as on project management. In three different manners the choice between the two paradigmatic forms of markets design – rate-of-return regulation with tariffs set at long-term average cost and deregulated electricity markets where competition establishes prices at short-term marginal cost – thus determines ownership, project management, and technology choice. All three dimensions, in return, have an impact on financial risk and the cost of capital of generation capacity such as a new nuclear power plant:

- **Company structure and ownership:** Historically, electric utilities in regulated markets were publicly owned. Conversely, the wave of electricity market deregulation in OECD and NEA countries in the 1990s and early 2000s was accompanied by large-scale privatisation. The link can be explained by the changing objectives pursued by policymakers: the primary task intended for regulated utilities, usually headed by engineers, was to complete electrification and to ensure adequate capacity and security of supply; the task intended for the private operators in deregulated markets, headed by financiers and corporate managers, is to achieve cost reductions, efficiency gains and technological dynamism. The link is not inevitable but goes very deep, nevertheless. The incentive regulation primarily applied to publicly owned monopolies such as network operators, for instance, is considered in the United Kingdom also for private generators. However, the objective is also in this case to wring out maximum effort to reduce costs.

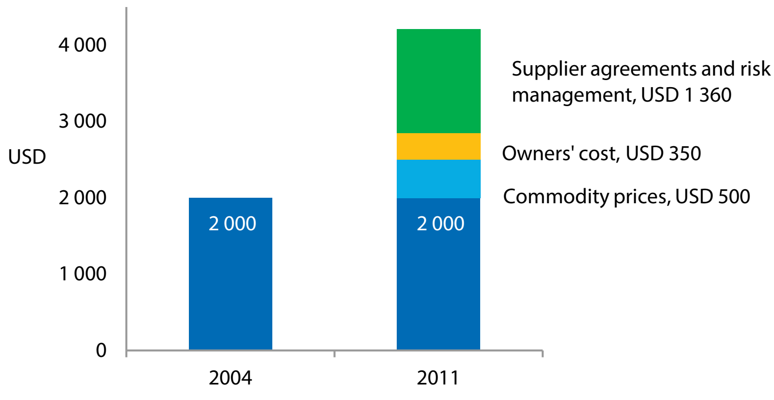
- **Project structure, management and supply chains:** The typical project under rate-of-return regulation was vertically integrated, with the utility assuming the roles of investor, contracting authority, project manager, operator transporter, distributor and output vendor. This reduced transaction costs on the one hand but excluded entities, which may have had superior knowledge and capacity in any one of the different steps of the value chain. In deregulated markets, already competition authorities insist on the separation of generation from the natural monopolies of transport and distribution. In construction, the dominant idea was to work with engineering, procurement and construction (EPC) contracts. Previous supply chains were designed around long-term contracts with a small number of preferred suppliers, not unlike the Japanese *keiretsu* system. Competition, if any, was not about price (costs could be passed on to the regulator), but about reliability. An EPC contractor as an expert in logistics and co-ordination instead was supposed to contract competitively and globally all elements necessary for completing construction. Since they were not supposed to know their counterparts, the primary variable of competition was price. The advantages and disadvantages of the two models are quite obvious. In nuclear new build, however, current evidence seems to suggest that vertical integration at least in construction is again the default model.

- **Technology and design choice:** As shown, for instance, in NEA (2015), the volatility of electricity prices, especially over the medium and long term, affects different technologies differently. This is due to their relative ratios of fixed costs to variable costs. Exposed to the possibility of a prolonged slump in prices, investors in a technology with high fixed costs such as nuclear energy face higher financial risks than investors in a technology with comparatively lower fixed cost such as a gas turbine. In fact, some argue that electricity market liberalisation could have never happened without the advent of the combined cycle gas turbine (CCGT), capable of providing baseload at reasonable fixed costs. Its problem is the price of gas. Yet, in a competitive market the producer with the highest variable costs sets the price, so to some extent, CCGTs possessed an automatic hedge against price risk. At equal average costs, investors will thus invest in CCGTs rather than in a new nuclear power plant (the story is different for long-term operation of existing plants). The decarbonisation of electricity supply to attain ambitious net zero targets changes the game again, however. All low-carbon technologies – nuclear, hydro, wind and solar PV, even geothermal and batteries – are highly capital-intensive, i.e. have a high ratio of capital costs to total costs. Deploying them in volatile markets implies very high costs to compensate investor risk. If decarbonisation is the overarching policy objective, market design will need to come back to updated forms of regulation at fixed costs (see also section on hybrid markets below).

These different processes set into motion by changes in market design strongly affect the cost of capital, even if indirectly, and, in particular, the cost of constructing capital-intensive nuclear power plants. Figure 3.2 provides an interesting breakdown of the increases in nuclear power overnight costs between 2004 and 2011 as estimated by researchers at the Energy Policy Institute at Chicago (EPIC, 2011). The comparison reflects not only the state of play at two different points in time but also two different models of project structure, the 2004 reactor presumably being built by a vertically integrated utility and the 2011 reactor resulting from a contractual structure in which the different layers of the supply chain are separated between different suppliers and contributors.

The result is instructive. Abstracting from commodity price inflation and an increase in the owner's cost, the major part of cost inflation is due to what the authors call "Design maturation: vendor and supplier agreements; risk management". These are added costs to hedge against financial risks such as charges to cover risks resulting from de-verticalisation and externalisation, the high costs of insuring against low-probability/high-impact events and the absence of any party willing to take on residual, essentially uninsurable, risks.

Figure 3.2. **How changes in project structure affect capital costs**



Source: Adapted from NEA, 2015, p. 159 and EPIC, 2011, p. 5.

The authors themselves explain their findings in the following manner:

> The study team found that overnight capital cost estimates increased as project sponsors moved from vendor "budget" estimates to contractual agreements containing fixed or firm pricing together with warranty provisions. Outside experts consulted by the study team indicated that that these prices may be conservative because of the possibility of "pancaking" of contingencies (EPIC, 2011: p. 33).

There are two forces at work here. First, costs will increase as soon as vendors have to commit to a firm contract as the vendors hedge their risk. Second, the de-verticalisation of the supply chain leads to a "pancaking" of contingencies. In both cases, a complete and costly contractual hedge is sought, where previously financial risks were hedged implicitly by the regulated utility as the investor of last resort and ultimately by electricity consumers. The difficulties and costs of doing so grow as risks become rarer and more difficult to assess until they blend over into an area of essentially non-codifiable and not diversifiable risks. In the absence of an investor of last resort, looking for even partial cover for those risks, say geopolitical risk, becomes very costly indeed.

It has therefore yet to be determined whether the cost savings promised by a switch towards deregulated markets and competition driving efficiency gains were in such cases not superseded by added contractual transaction costs as well as asymmetries of information, offering opportunities for gaming and rent extraction, all along the de-verticalised value chain. In other words, it is unclear even for consumers, who were supposed to be the ultimate beneficiaries of the changes in market design and ownership, whether the regulated utility model was not only the simpler and less stressful but, in the end, also the more cost-efficient framework for delivering adequate amounts of electricity generating capacity. Given the capital intensity of the low-carbon transition called for by policymakers, these considerations assume an even greater importance.

Addressing construction risk for nuclear, hydroelectricity and offshore wind

While paying an implicit or explicit premium for low-carbon generation through contracts with a publicly funded or insured third party can thus be justified, there are doubts whether this constitutes the most efficient manner to incentivise investment in new low-carbon capacity in all cases. Due to differences between low-carbon technologies regarding their unit size, length of construction period, magnitude of construction risk and intensity of the interface with political and social actors, there also exist differences with regard to the extent that long-term supply contracts, even at favourable terms, are capable of spurring investment.

Essentially, there exist two groups of low-carbon technologies on this regard – onshore wind and solar PV on the one hand and nuclear energy, offshore wind and hydroelectricity on the other. The inability of onshore wind and solar PV, due to their intermittency, to provide electricity during a sufficient number of hours and their low spatial density are now understood as a major cost to electricity provision at the system level, not least due to the NEA studies on this topic (2012, 2019, 2022 and 2024). That said, VRE are technically mature, their construction poses only moderate technical challenges, and they have small or, in the case of solar PV, very small, unit sizes. Even for an onshore wind farm, construction times are measured in months rather than in years. In other words, onshore wind and solar PV pose only limited construction risk. Once a favourable supply contract is in place, construction can go ahead with risks that can be reasonably supported by even mid-sized private parties.[6]

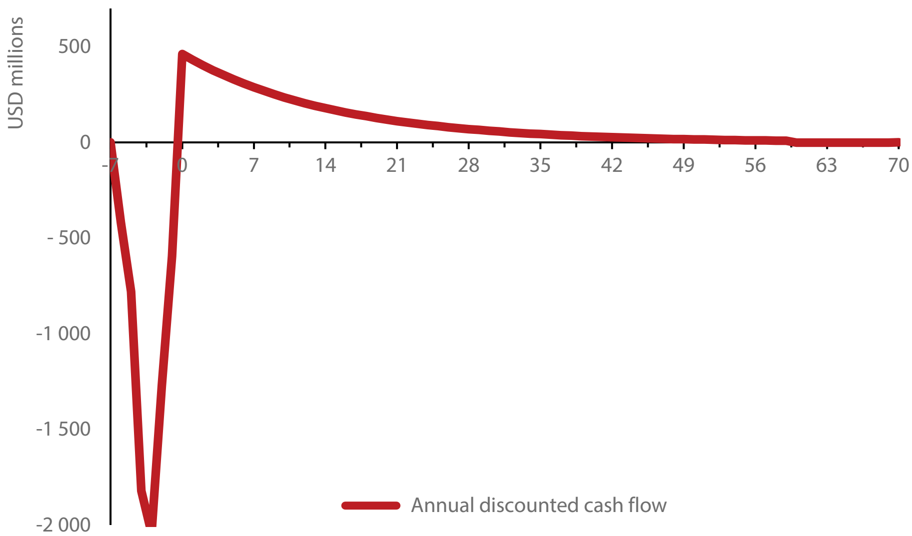
This is not the case for nuclear energy, hydroelectricity and offshore wind. While their contribution to the sustainability of low-carbon systems is by now well recognised as completely or largely dispatchable baseload providers (nuclear and run-of-the-river hydro), flexibility providers (reservoir hydro) and mid-load providers (offshore wind), they all pose distinct challenges during the construction period. These challenges are due to a mix of large or

6. It should be noted that the premium over market prices required to break even would need to be *higher* for wind and solar PV than for other low-carbon technologies, even if lifetime costs and construction risks are identical. This is due to the auto-correlation effect, the fact that all wind plants and all solar PV will produce together during a limited number of hours, when, consequently, prices will be lower than average market prices. This effect already asserts itself at relatively low rates of VRE penetration but increases sharply at higher rates of penetration. In other words, onshore wind and solar PV, due to their low load factors, produce electricity when it is least needed, which is another manner of characterising their low contribution to the security of electricity supply as well as their profile costs.

very large unit sizes, sheer technical complexity, the need to stabilise new designs, and, in some cases, an insufficiently experienced labour force and the need to reconfigure the supply.

Whatever the precise reasons (see also the chapters on project management), the fact is that the period between the first concrete pour and the date of commissioning is highly risky for project promoters and investors. This holds in particular for nuclear power plants (see Figure 3.3). High capital intensity, i.e. the fact that the vast majority of costs accrue before the first electron is delivered, is not unique to nuclear energy but is shared by all low-carbon technologies, including onshore wind and solar PV. However, high capital intensity combined with very large project sizes, long lead times and intrinsic uncertainty about project success leads to risks that are difficult to diversify also for large financial actors, even if they possess an advantageous CFD for the electricity output of the plant once it is operational.

Figure 3.3. **In the life cycle of a nuclear power plant all financial risks are frontloaded**



Annual discounted cashflow for a 1 350 MW nuclear power plant with a 7-year construction period, an operating lifetime of 60 years and 10 years of decommissioning, assuming a fixed capital cost of 5 000 USD/kW and a cost of capital of 7% per year.

The announcement of France's EDF in February 2024 to take an accounting impairment of EUR 12.9 billion because of cost overruns in the construction of two new European Pressurised reactors (EPR) at Hinkley Point (United Kingdom), taking the total costs for 3.2 GW of nuclear to GPB 46 billion is a case in point. Similar reasonings hold for hydroelectricity and offshore winds. While hydroelectricity projects are few and far between, the construction of several high-profile offshore wind parks was cancelled in late 2023, requiring billions of USD of write-offs, although the projects had obtained CFD that had originally been considered attractive.

This state of affairs requires rethinking the proposition that energy-only market designs with marginal costs can be mended by introducing long-term price guarantees (FIT, FIP, CFD, PPA, etc.) without implicit subsidy elements. Incentivising sufficient amounts of low-carbon generation capacity and, in particular, nuclear baseload capacity will require forms of public support not during the operational phase through price-based measures but directly during the construction phase.

Box 3.1. **Elements of the RAB model being considered for the nuclear power plant at Sizewell C**

The regulated asset base (RAB) model is a financing model that is currently in preparation under the leadership of the UK Department for Energy Security and Net Zero (ESNZ) for the construction and operation by EDF of two EPRs at Sizewell, Suffolk (Ofgem, n.d.). The RAB model is to be applied for the first time in the context of the construction of a new nuclear power plant, but has been used before, notably for the construction of the Thames Tideway Tunnel, expected to be completed in 2025. Its application to fund nuclear capacity springs from unhappiness with the CFD concluded to fund the construction, also by EDF, of two EPRs at Hinkley Point (Somerset), expected to be completed by 2031. The British public considered the strike price of the CFD (GPB 92.50 per MWh in 2012 prices) excessively high compared to average electricity prices during the past decade. EDF had misgivings about having to take on highly expensive construction risk in an economic and political environment that it did not control. This point of view was shared by other potential promoters, as both Hitachi at Wylfa (Wales) and Toshiba at Moorside (Cumbria) cancelled their nuclear new build projects.

The key change in switching from a CFD to the RAB model is to impute the greater part of the construction risk to British ratepayers and taxpayers, while subjecting EDF during the operational phase to an incentive regulation. The idea is that the reallocation of the respective risks will lower the economic costs of the risks and thus reduce overall financing costs (see also Chapter 4). The RAB model clearly distinguishes the construction phase and the operational phase, or the pre-PCR (for Post Construction Review) and the post-PCR phase in the language of the regulator. During the pre-PCR phase, an Independent Technical Advisor (ITA) will determine the capital expenditures that are eligible for a guaranteed return under the RAB. This return will be financed by a payment from electricity suppliers *pro rata* to the electricity they distribute. Obviously, suppliers will impute that payment to the electricity bills of their customers.

These payments are calculated on the basis of the estimated construction cost of the Sizewell C project, which over time is thus financed by ratepayers. This still requires capital to be advanced, albeit at a guaranteed range of returns, by private parties, EDF, as the project operator, and the UK government. Negotiations with interested investors were initiated by the UK government in September 2023. A key point is what happens if construction costs exceed the initially projected costs. On current indications, excess costs will be shared between investors and ratepayers according to a formula yet to be published up to 130% of the initial cost estimate. Cost increases beyond 130% will be covered by the UK taxpayer through a government support package (GSP).

Post-PCR, Sizewell C will be subjected to incentive regulation implemented by the UK Office of Gas and Electricity Markets (Ofgem), the independent regulator. Incentive regulation implies that Ofgem will set a fixed rate of return, the initial weighted average cost of capital (IWACC), on capital expended during the generation phase. This rate will be adjusted for any operational over-underperformance compared to a yet to be defined benchmark (Ofgem, 2023). If required due to a prolonged period of low electricity prices, the IWACC could be guaranteed by a CFD-like compensation payment. While Ofgem has decades of experience with incentive regulation in the electricity sector, crucial questions to be decided are what the IWACC for a company such as EDF could be and which operational benchmark could possibly be chosen for operating a Generation III nuclear power plant in the United Kingdom. In addition, the UK government assumes the costs for decommissioning and the disposal of spent nuclear fuel.

In summary, the RAB model is a promising but also highly complex approach to new nuclear new build through the sharing of construction and operational risk between ratepayers, private investors, project operators and taxpayers. The financing and construction of the two EPRs at Sizewell C will be closely watched by nuclear financing experts to see whether the RAB model holds lessons also for European countries and beyond.

See: Nuclear Energy Financing Act, 2022, www.legislation.gov.uk/ukpga/2022/15/contents/enacted.

Earlier, it was indicated that project funding would ultimately have to come from one of two parties, ratepayers (electricity consumers) or taxpayers (governments). While this is quite obvious in the abstract, the assumption usually was that while ratepayers would fund investment in the long run, private investors would shoulder risks during the construction period, eventually passing them on through electricity prices. This assumption is no longer tenable in low-carbon electricity markets in general and in nuclear investments in particular. The reason is that both price and construction risks have become incalculable. Risk has mutated into uncertainty in the classic dichotomy of Knight. The passthrough of risks and costs through the market mechanism only works as long as risks can be assessed, codified and, at least in some reasonable approximation, measured and monetised. In nuclear energy construction today, technical, regulatory and political uncertainties are such that private investors will shy away without commensurate guarantees. In other words, construction risk is too high for any single private party to take on.

If nuclear energy, nevertheless, constitutes an essential element of least-cost net zero systems, it becomes indispensable to implement market designs that allow some degree of "socialising" construction risk right from the beginning in addition to socialising price risk through the subsidy element inherent in many long-term pricing arrangements. There are essentially two ways of proceeding. First, there is the option that national governments directly finance nuclear new build, possibly with the intermediation of a national champion, such as a national electricity company. This would transfer construction risk to taxpayers. Second, there is the option to that ratepayers pre-finance construction through an added charge to electricity bills, before and during the construction of a new nuclear power plants. This is the essence of financing mechanisms such RAB in the United Kingdom or CWP in the United States.

The choice between direct public finance or prefinance through ratepayers must, of course, depend on broader fiscal, economic and social arbitrages. In general, ratepayers have in the past been considered the primary party for funding new investment in low-carbon generation capacity. This assumption has been challenged by taxpayer-financed provisions such as zero-emission credits in the United States or the renationalisation of EDF in France. The transfer of the renewable energy levy from electricity bills to the federal budget in Germany reflects the same basic trend. Instead, much-discussed mechanisms such as RAB and CWP pivot back to ratepayers. This is clearly a process that has not yet been concluded. What is already certain, however, is that this process will become politically much more charged to the extent that the high, and until now underestimated, costs of the energy transitions will become increasingly apparent.

In either case, such financial risk-transfer mechanisms from private to public stakeholders cannot on their own reduce the pure technical risk of constructing and completing a nuclear power plant. They will, however, substantially reduce the risks for project operator, may reduce the overall economic cost of the risk (see Chapter 4 on the Arrow-Lind theorem), may be able to attract private capital to complement the risk transfer and may, finally, impact the incentive structure and the project management (see Chapter 5). In other words, for complex, highly capital-intensive technologies such as nuclear energy, hydroelectricity and offshore wind, the socialisation of construction risk is an indispensable element of electricity market designs capable of delivering enough low-carbon capacity to reach net zero emissions.

Of course, such a drastic reallocation of large-scale economic risks requires careful preparation and discussion with a broad range of stakeholders in order to guarantee social and political sustainability. Technical and financial feasibility is indispensable, but so is the perception that such arrangements are fair and part of a broader allocation of the benefits and costs of the energy transition and economic output in general. The costs of the transition in a mid-sized country will run into many hundreds of billions of dollars or euros. Such sums will not be mobilised by sleight-of-hand arrangements, clever accounting or off-balance sheet financing. As indicated above, countries are only at the beginning or realising the true costs of the transition in the energy and electricity sector. The socialisation of construction risks for certain technologies must now be included in the discussions that will emerge from this realisation.

Putting it all together: Hybrid markets for the deep decarbonisation of electricity systems

Do the preceding paragraphs imply that in the low-carbon markets of the future all electricity will be produced by *de facto* nationalised generators with governments and the public taking all risks, responsibilities and rewards? Certainly not. Future low-carbon electricity markets will be characterised by a mix of pricing arrangements and incentive measures for different technologies. While the latter will steer long-term investment in a manner specific to each technology, all technologies together will continue to bid for customers in competitive spot markets in order to co-ordinate their dispatch. They will also consciously and explicitly assume their specific roles as part players in an exogenously set and political decided generation mix. This mix of out-of-market measures, competitive dispatch and a centrally planned generation mix is frequently referred to as constituting a "hybrid market".

As indicated in Figure 3.4, it is possible to distinguish three categories of technologies in the decarbonised electricity systems of the future. Each category faces distinct challenges to attain economic and commercial sustainability for capacity investments in an environment of low-carbon markets needed to attain net zero carbon emissions by 2050. In such markets, prices will be volatile and structurally on a downward trend, given the public and societal aversion to allowing for a sufficient number of scarcity hours to offset the large amounts of VRE-only hours, during which prices will be zero or negative. Each category will also require specific solutions for its challenges.

This is a key feature of hybrid electricity markets: different technologies provide different services to the overall system, but while doing so they face different challenges and require specific policy measures that complement market outcomes. As already indicated, they will continue to be united through a common system of competitive short-term dispatch and the long-term planning of the generation mix. Given these constraints, it is however perfectly conceivable that there is competition between private generators for market share inside the capacity levels determined for each category as part of the long-term system planning process.

The first category is constituted by **low-carbon baseload providers** such as nuclear energy and hydroelectricity. Offshore wind can also be included in this category. While it is not a baseload provider in the strict sense, its average capacity of above 40% attenuates the intermittency challenge and it also faces high construction risk. These technologies face high fixed costs, serious construction risk and low variable costs. Once up and running, they thus face low to moderate risks in the context of a competitive dispatch based on variable costs. Their capital intensity and complexity, however, poses the double challenge of (a) construction and completion risk and (b) whether average prices will be sufficiently high in order to ensure that the fixed costs are recuperated over time. The second challenge is now well understood and policymakers and regulators are viewing with increasing favour the ability to ensure project success through long-term pricing arrangements such as CFDs or PPA.

The first challenge, construction and completion risk, is as of yet insufficiently conceptualised although in practical terms it is quite obvious that no private entity is willing to take on the risk of constructing a new nuclear power plant without pervasive de-risking by public bodies. Socialising the major share of construction and completion risk, by transferring it completely or partially to the public, thus seems the only viable perspective under which to realise large, complex and capital-intensive contributions to the infrastructure of the low-carbon systems of the future. In this context there are essentially two options as outlined above: either transfer construction risk to ratepayers through advance integration of construction costs into electricity bills or have public actors involved directly in the financing and construction of major low-carbon generation projects such as nuclear energy or hydroelectricity. In both cases, attention must be paid to questions of fairness and distribution as well as to the question of maintaining appropriate incentives for project operators (see Chapter 4 for a comprehensive discussion).

The second category of technologies consist of **variable renewable energies (VRE)** such as onshore wind and solar PV. Their principal challenge, for themselves as well as for the system as a whole, is their intermittency. While their capital intensity is very high, even higher than for nuclear energy, construction risk is not a major issue. Administrative approvals and local resistance may constitute risks and barriers in certain locations; however, this is not a make-or-break issue, primarily because these challenges will be resolved one way or another *before* the bulk of capital investment is committed. The great challenge of VRE is their autocorrelation, i.e. the fact that all VRE capacity produces during a small subset of hours at zero marginal costs, which drives down prices during those hours. Geographic variations only marginally attenuate this challenge. It is empirically easy to verify that onshore wind and solar PV therefore earn less than average electricity prices, an effect that increases with their share in the system. In a truly deregulated electricity market, without interventions and free exit and entry, VRE capacity would indeed be intrinsically limited to a level where their by and large favourable investment costs would just about be covered by the remaining revenues of an additional plant. The trouble is that in many OECD and NEA countries policymakers and the general public have set their minds on VRE targets that far exceed that level. In other words, at the projected levels of future VRE shares in the generation mix, their market revenues would be wholly insufficient to finance their costs.

VRE such as onshore wind and solar PV thus depend on long-term price support. By accident or by design, the FIT that supported the first generation of VRE were the appropriate instruments to ensure long-term price stability and revenues, even though at the time their shares were still too low to make the price and revenue decline due to the autocorrelation effect felt. Today, price support is usually provided through long-term contracts for FIT or FIP that are allocated through competitive auctions. This is the appropriate instrument, under the condition of course that decision makers insist on levels of VRE capacity that are uneconomically high.

The third category of **flexibility providing technologies** in the low-carbon electricity systems of the future consists of dispatchable technologies with comparatively low fixed costs and high variable costs. This constellation allows these technologies to be operated at very low load factors. They would be called upon to provide additional capacity only during times of high demand, low VRE generation and consequently high prices. They include gas-fired power plants, both with combined cycle gas turbines (CCGT) and open-cycle gas turbines (OCGT), the latter having even lower fixed costs and higher variable costs. While today the vast majority of gas plants are fired by natural gas (CH_4), future plants may be fired by hydrogen or biogas. Thermal plants based on solid biomass would also belong to this category. Of course, under a net zero constraint carbon emissions from plants still fired by natural gas would need to be offset. Finally, demand response and storage would also belong into this category. While they are not electricity generation technologies in the narrow sense of the concept, they provide needed capacity during times of system stress. An important point here is that investment in demand response and storage, even at possibly lower costs in the future, will require precise economic conditions to be fulfilled and will not automatically materialise as a free resource to solve the co-ordination of supply and demand.

As these technologies will only produce during hours with high residual demand and high prices, their key risk is quantity risk, in the sense of not being called upon sufficiently often to finance their fixed costs, even though the latter are comparatively low. In order to ensure the profitability of a sufficient level of flexibility providing technologies, capacity mechanisms, which remunerate availability rather than production, constitute the appropriate instruments. This is due to the fact that their system contribution consists in the capacity rather than in the energy they would provide only during a limited number of hours. CRMs can be operated in a centralised or a decentralised manner. An example of the former are the capacity auctions in the United Kingdom paid for through a levy on consumption during the winter months. An example of the latter are the tradable capacity obligations in France.

Since during peak demand hours *all* available generators will be called upon, dispatchable baseload generators such as nuclear energy and hydroelectricity are also entitled to the availability payments. However, these will not nearly be sufficient to cover the outlays for the fixed investment costs and construction risk. CRMs are only a complement in these cases. Nevertheless, quantity risk is becoming a concern also for nuclear and hydroelectricity with low variable costs as the number of hours that are entirely covered by VRE increases. VRE themselves are remunerated according to their "capacity credit", that is the fraction of their capacity that is reliably available. However, the latter is very low and approaches a zero in many cases.

Figure 3.4 summarises the different key elements that will characterise efficient low-carbon hybrid markets. As the premise that the energy-only markets introduced in the wave of market deregulation in the late 1990s and early 2000s can generate adequate levels of generation investment is no longer tenable, the low-carbon hybrid markets that are emerging are characterised by a mix of competitive short-term dispatch and coherent long-term planning. The long-term planning modules will provide incentives for adequate financing of low-carbon technologies and their complements through different instruments, each one focusing on the key risk of each technology category – construction risk for nuclear energy, hydroelectricity and offshore wind, price risk for variable renewables and quantity risk for flexibility providers.

Figure 3.4. **Future electricity markets will require a mix of incentive measures for different technologies**

Time horizon and purpose	Allocation mechanism	Contract type	Technology	Challenge	Why should we care?
Short term for dispatch	Competitive spot markets	Pay-as-clear at variable cost of marginal technology (EUR/MWh)	All technologies	Missing money, no investment in LC technologies	Efficient dispatch, "sweating assets"
In conjunction with targeted top-up payments to incentivise investment					
Long-term investment with centralised decision-making on the electricity mix	Competitive auctions for long-term contracts	Capacity payments at fixed cost of marginal technology (EUR/MW)	CCGT, dispatchable REN, storage, demand response	Quantity risk due to high variable costs	Reliable capacity at reasonable cost
		Feed-in tariffs (FIT) or feed-in premia (FIP) (EUR/MWh)	Variable renewables (wind, solar PV)	High price risk due to auto-cannibalisation	Low-carbon electricity, high social preferences
	Case-specific long-term agreements	CFD, RAB, CWP, local concessions at avg. costs (EUR/MWh)	Nuclear energy, hydroelectricity	Construction risk, political risk	Reliable low-carbon baseload electricity

Hybrid market designs need to be complemented by carbon pricing and long-term system planning

If the preceding sections have identified the main parameters of a sustainable market design capable of delivering for least-cost constellations for low-carbon electricity systems, such market designs require two additional framework conditions. These are a robust carbon price and long-term electricity system planning based on advanced system cost modelling. Both conditions need to be understood in a specific sense. Carbon pricing was, of course, once thought to be capable of delivering low-carbon electricity generation in a least-cost manner on its own.

The idea was that by making the variable costs of technologies based on fossil fuels such as coal and gas more expensive, their reduced dispatch would favour the short-term profitability of renewables and nuclear energy and ultimately also trigger corresponding capacity investments. Carbon pricing indeed works similarly to a FIP for low-carbon technologies, which receive an add-on to electricity prices each time that a coal- or a gas-fired generator as the marginal producer with the highest variable costs sets the price. Economists also appreciated the idea of a carbon price as a straightforward internalisation of the climate externality caused by greenhouse gas emissions, equivalent to a Pigouvian tax.

However, for several reasons, things did not turn out that way. The fact that despite emphatic commitments to climate protection politicians of OECD and NEA countries could never get themselves to introduce carbon taxes that were sufficiently robust and, more importantly, inspired sufficient confidence that they would remain in place for the foreseeable future to steer long-term behaviour of investors is only part of the story. Economists also had to go through a learning process: ultimately the link between relative short-term variable costs, long-term profitability and investment in generation capacity, in particular low-carbon capacity, was more complex and more tenuous than was originally thought. Three sub-ordinated considerations play a role here:

- **First**, if the key challenge of nuclear new build is construction risk, the support of short-term profitability based on variable costs would need to be exceedingly high to sway investors. One may call this the "Hinkley Point-fallacy", in the sense that decision-makers attempted to mitigate construction risk by offering highly favourable electricity prices through a CFD. Achieving such prices through carbon prices alone, the latter would need to be unacceptably high.

- **Second**, what has been said under the first point is all the truer as the purpose of carbon prices is to drive fossil fuel-based generators out of the market. However, without coal- or gas-fired plants setting prices, the latter will be very low or zero during long periods, punctuated only by hours with scarcity pricing in the thousands of USD, EUR or GBP. The resulting price volatility, highly dependent on specific system constellations as well as demand and weather patterns, would imply even higher carbon prices, progressively less and less relevant for steering investment decisions.
- **Third**, even with generous carbon prices, VRE such as wind and solar PV, would not escape the predicament that their revenues would decrease as their capacity increases due to their autocorrelation, regardless of the surrounding market conditions. Of course, high carbon prices could somewhat mitigate that effect during hours in which coal and gas-fired generation are still marginal. However, and this is the very real economic quandary of VRE, a wind or a solar PV plant is far more likely to produce during hours when all other wind or solar PV plant are producing and prices are zero, than during hours when coal- and gas-fired plants are called upon due to a lack of low-carbon sources.

In short, carbon prices, even at high levels, are unlikely to be able to ensure the investment in low-carbon capacity required for ambitious net zero objectives on their own. So why bother? Carbon prices are a necessary but not a sufficient instrument in spurring investment in low-carbon capacity. They are required to complement the measures outlined above as a pedagogic device and as a signal of a long-term political commitment. Market designs and support measures come and go under various guises. However, it needs to be clear to investors, as well as to the decision-makers themselves, that whatever happens, the commitment to low-carbon electricity generation and, beyond electricity, the commitment to a low-carbon energy transition is irreversible. A robust carbon price, possibly constitutionally enshrined to make it difficult to rescind, is such a commitment that would subsequently concentrate the minds of all stakeholders and orient the complementary measures that will ultimately achieve the desired outcomes.

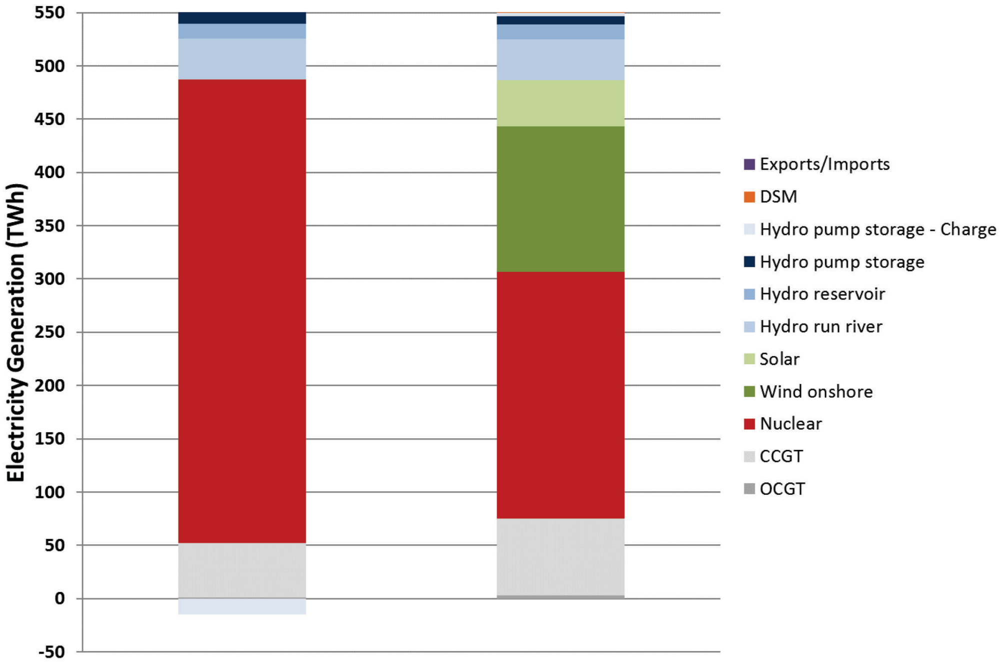
Spelling out the desired least-cost constellations to achieve ambitious carbon targets is precisely the second key complement to efficient electricity market designs. This effort to make a government's vision of the electricity system explicit is inherent in hybrid market designs that separate competitive markets for day-ahead and infra-day dispatch from complementary modules to incentivise investment into generating capacity. This is because the design of the investment modules needs to be based on exogenously determined capacity targets.

The determination of such targets requires a combination of energy system modelling establishing least-cost capacity mixes for low-carbon electricity and the integration of political and social preferences for certain generation choices. Hybrid markets thus systematically supersede or complement the capacity choices that would have been made by investors based on expected prices in energy-only markets.[7] This may include support for otherwise not or not yet competitive technologies such as certain renewables, hydrogen as an energy vector, batteries, or SMRs. Integrating least-cost modelling outcomes with choices determined by social or political preferences is not necessarily an incoherent manner to define the main constituent parts of the desired long-term outcome for the energy system. Not all choices in the energy field can be reduced to economics. If certain environmental impacts can, in principle, be monetised and

7 The true relationship between the outcomes of large-scale electricity system modelling informing policy decisions and market outcomes is complex. Large-scale electricity system optimisation models, such as the NEA's POSY model, are designed to identify least cost outcomes under a series of technical constraints. Such least cost outcomes correspond, in theory, equally to the result of the work of a benevolent and fully informed electricity system regulator and the result of a perfectly working competitive market. So why then try to second guess the market in the first place? Because, as discussed during this chapter there exist unsurmountable hurdles for private investors in competitive markets to realise socially optimal outcomes. The construction of new Generation III+ nuclear plants is the most important example in this context. Electricity sector modelling can thus identify socially optimal outcomes that competitive markets could never realise due to issues ranging from transaction costs, investor myopia as well as the ability of the public sector to spread risks and thus reduce the welfare cost of large and risky investments.

internalised by way of environmental taxes added to the price of electricity or certain of its components, no such instruments to neatly complement the market mechanism exist for issues such as security of supply or technological innovation. This is indeed why energy-only electricity markets with marginal cost pricing have never been left to their own devices. For the theorists this is the primary reason why these markets have not worked as predicted. For the policymakers, these interventions were necessary precisely because the markets did not work as desired.

Figure 3.5. **Combining nuclear energy and renewables constitutes the least-cost generation mix***



* Figure 3.5 shows two least-cost generation mixes for different technology cost assumptions calculated by the NEA's POSY linear optimisation model. The left-hand column indicates a least-cost generation mix in a case when the levelised cost of electricity (LCOE) of nuclear energy are lower than those of wind and solar PV. The right-hand column shows the least-cost generation mix in a case where the LCOE costs of wind and solar PV are lower than those of nuclear energy. In this case, the lower LCOE costs of wind and solar PV are balanced by the declining value of their output, which limits their entry at the privately and socially optimal point. Nuclear energy, which earns average prices, comes in once the revenues of wind and solar PV no longer cover their costs.

Source: Based on NEA 2019.

On the other hand, economics, efficiency and cost control define an indispensable dimension of energy system planning. Least-cost optimisation thus remains an essential tool in defining economically and politically sustainable choices. An important extension of the assessment of the economic costs of different energy choices and scenarios was pioneered in the work by the NEA and others on system effects of different technologies (NEA, 2012, 2019, 2022 and 2023). One of the important insights coming out of this work was that both markets, as long as they are free from outside intervention, as well as energy system models, arbitrage the plant-level costs of different technologies against their costs at the system level (see Figure 3.5). This is due to the fact that the variability of wind and solar PV generation implies two intrinsically linked effects at the private and at the system level. First, variability and correlation lower the revenues of wind and solar PV, as all plants produce together during a limited number of hours with consequently lower prices. Second, precisely the same variability causes a need for dispatchable backup capacity that increases the overall costs of the system.

A precise understanding of these interactions can be acquired through the modelling of different low-carbon scenarios with different shares of nuclear and renewable capacity as performed by the NEA on the basis of its mixed integer linear programming (MILP) POSY-model. Such economic analysis can then be overlaid with extra-economic considerations. In a complementary fashion, these two strands then form the basis for the development of a coherent long-term view of an economically, socially and politically low-carbon electricity and energy system. This long-term target scenario will then provide the basis for the implementation of the hybrid market designs required to achieve it.

Successfully financing the construction of new nuclear power plants thus requires mastering the double challenge of, first, understanding and defining the specific role of nuclear energy in the low-carbon electricity systems of the future in complement with other technology categories in a hybrid electricity market and, second, focusing on managing nuclear energy's critical risk in construction and completion. This double challenge will be framed by a coherent long-term view of the generation mix and a robust carbon price, both determined by policymakers in a strategic fashion. For the time being, spreading the financial risks of construction among large numbers of ratepayers and taxpayers will remain also indispensable in this context. However, decision makers in policy, regulation and industry must also be mindful of the fact that announcing firm targets for specific technology categories and organising public financing for their construction can induce rent seeking and complacency. As will be shown in Chapters 4 and 5, tight oversight and the introduction of competitive elements at different submodules of the system must thus complement the hybrid market designs required to achieve net zero carbon emissions by 2050.

Chapter 4. The role of the public sector in assuming risks in the construction of nuclear new build projects

The previous chapter argued that in the construction of large, capital-intensive low-carbon baseload providers such as nuclear energy or hydroelectricity some form of public sector involvement is indispensable to obtain the capacity levels required for clean energy transitions aiming at net zero carbon emissions while safeguarding the high levels of the security of supply that residential, commercial and industrial stakeholders in OECD and NEA countries have become accustomed to. This chapter will now look at (1) the conceptual argument justifying public involvement in large and risky investment projects as well as its limits, (2) historical evidence from the successful large-scale nuclear new build programme in France and (3) the continuing relevance of public sector participation in the energy sector and the forms that a public role in the construction of nuclear new build could take in the coming years and decades.

The conceptual justification of public commitment when investing in nuclear new build, its limits and its continuing relevance

The formal analytical justification for public engagement in investment projects is based on the conclusions of the article by Kenneth Arrow and Robert Lind "Uncertainty and the evaluation of public investment decisions" (1970), sometimes also referred to as the Arrow-Lind theorem.[1] Their argument relies heavily on the perfectly intuitive notion of risk aversion, which implies that individuals prefer a constant income to an uncertain one, even if the latter has the same mathematical expectation. This is due to the declining marginal utility of income, which means that the increase in well-being due to an additional income of, say, USD 1 000, is *smaller* than the decrease in well-being due to a loss of USD 1 000. Consequently, also the well-being (utility) of an individual on a small income will increase more due to an additional income of USD 1 000 than a rich individual's well-being.

When applying this logic to large investment projects such as a new nuclear power plant, it is particularly relevant for the costs of intrinsic risks, such as construction risk, that cannot be easily reduced otherwise. Of course, good project management will try to reduce such construction risk. This is, however, not an issue that is directly affected by the decision of whether the financing of investment should be undertaken by private or public parties.[2] The work of Arrow and Lind concerns the reduction of the economic welfare costs of a financial risk of a given size. Their insight exploits the property that risk-averse individuals assign relatively lower costs to smaller risks (see Figures 4.1 and 4.2). In order to reduce the cost of risk, Arrow and Lind thus propose to share the risk over the greatest possible number of individuals, such that for each individual only a very small portion of their income is at stake.[3] Public investment

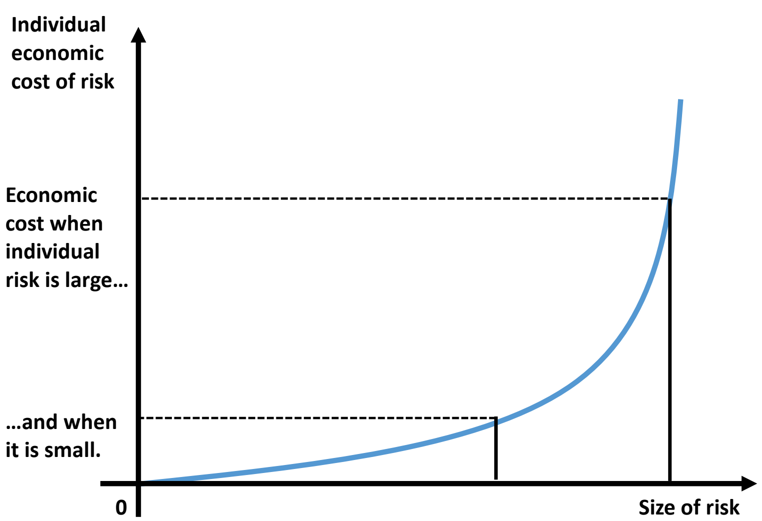
1. Some of the material used in this presentation of the relevance of risk sharing to nuclear new build in the spirit of the work by Arrow and Lind was first presented in NEA, 2022.
2. As will be discussed below and in Chapter 5, the question of public sector involvement might well have an indirect bearing also on the efficiency of project management. However, this indirect bearing does not take the general form of "public involvement either increases or decreases management efficiency". It is rather a question of dividing and linking the respective responsibilities of private and public sector in the areas of procurement, on-site organisation, incentive measures and regulation.
3. Risk sharing is, occasionally, referred to as risk diffusion or, also, as risk spreading. The latter terms should be used with care though, as it may also infer risk diversification, where individuals spread their investments over several assets, thus reducing the variance of the average risk. This is an alternative strategy to reduce the costs of risk working through a different channel.

can indeed share the costs of risk in this manner, as it ultimately parcels them out among taxpayers. If the number of individuals goes towards infinity, the economic costs of the project-specific risk, construction risk in this context, approach zero. The correct cost of capital in this case is the long-run risk-free rate that only reflects systemic market risk (see also Chapter 2 and NEA, 2022). In the words of Baumstark and Gollier:

> When an investment project yields socio-economic net benefits that are uncertain but independent of the systematic risk of the economy, these benefits should be discounted at the risk-free rate if they are disseminated among a large population of stakeholders. This may be the case of a public project whose benefits are distributed within the large population of taxpayers (Baumstark and Gollier, 2014: p. 45).

Given the form of risk sharing for nuclear new build projects that are currently being discussed, in particular in the regulated asset base (RAB) model (see Chapter 3), it would be necessary to amend the citation from Baumstark and Gollier by writing "…within large populations of either taxpayers or ratepayers".

Figure 4.1. **The economic cost of risk increases over-proportionately with the size of the risk**



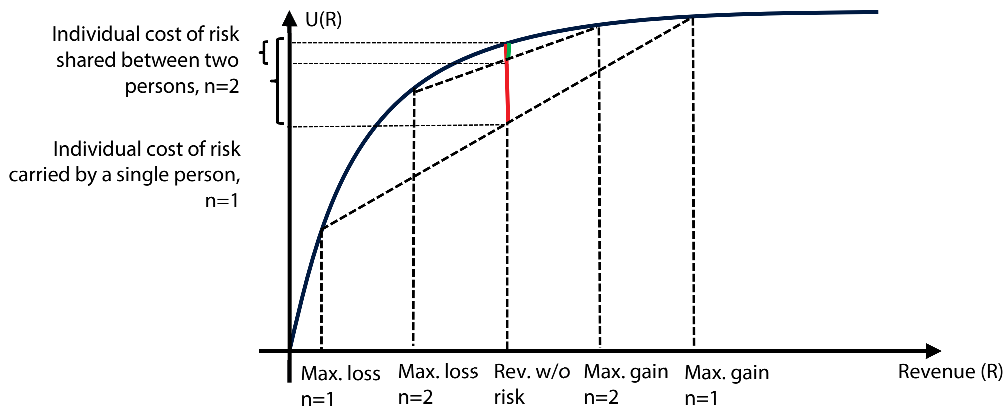
Source: Adapted from Baumstark and Gollier (2014), p. 46.

However, the central message remains unchanged: sharing the costs of risk over as many individuals as possible will reduce the economic costs of that risk. It should be noted again that this only holds for project-specific or idiosyncratic risks. The latter are also referred to as diversifiable risks. Risk sharing does not work for systemic, economy-wide risks nor, importantly, for that portion of the diversifiable risk that is correlated with the former. In other words, in order to evaluate a public investment project at the risk-free rate, its β (beta), its correlation with systemic risk must be zero (see Chapter 2).

In extension of this argument, also the returns of different investment projects must be uncorrelated. Otherwise, different small risks would again add up to larger risks, with their economic costs again increasing exponentially. Standard investments aiming at maximising market revenues would also fall foul of the criterion to be uncorrelated to systemic risk. This is why the fact that the returns of low-carbon investments are uncorrelated to broader macroeconomic developments is so important. In any case, the Arrow-Lind argument certainly provides no justification for a wholesale transfer of economic activity from the private to the public sector.

Regardless, the message of Arrow and Lind was interpreted in the 1970s as a conceptual justification for a large-scale expansion of public investment. Of course, this expansion did not continue unchecked and was followed by the broad movement of privatisation and sectoral deregulation, theorised in the 1980s and implemented in the 1990s. This movement was economy-wide but was particularly pronounced in the electricity sector, where many OECD and NEA countries switched from the decades-old model of utilities operating under rate-of-return regulation to competitive electricity markets.

Figure 4.2. **Reducing the economic cost of risk when sharing it between two agents***



* The bold red line indicates the economic cost for an individual of the 50/50 risk of either obtaining (Max. loss, n=1) or (Max. gain, n=1) instead of having a stable income at (Rev. w/o risk). The bold green line indicates the economic cost for an individual of sharing the same risk with another individual. Graphically speaking, the total cost of the risk after sharing is thus twice the length of the green line, which is still substantially shorter than the red line. The logarithmic shape of the curve indicates risk aversion.

Source: NEA (2022), p. 45.

The principal conceptual criticisms of the Arrow-Lind argument can be summarised in the following four points that concern (1) the fact that the outcomes of public investment projects are finally closely correlated with GDP and systemic developments, (2) a wilful misinterpretation of the Arrow-Lind argument in order to justify private investment at public sector rates, (3) inefficiencies in investment decisions and project management by the public sector and (4) the fact that risk sharing can be accomplished by financial markets better than through public investment. The four arguments are evaluated one by one below:

1. **The correlation of the returns of public investment projects with those of the general market is not zero:** The argument says that any economic activity is to some extent related to other economic activities. Therefore, all economic projects evolve to some extent together. A rising tide lifts all boats and a receding one will bring them down again. The Keynesian investment multiplier is the analytic expression of such spillovers of economic activity. The question is whether individual projects, and particularly large-scale investments in power generation, can be different. They may, for instance, be undertaken in a long-term perspective or counter-cyclically. The key point in the present context, however, is not answering this question in a general fashion but for nuclear new build projects. And here, NEA (2022) showed that low-carbon energy projects are either negatively correlated or uncorrelated with system-wide economic activity. Like any constraint imposed on economic activity, achieving net zero carbon emissions will reduce economic activity as measured in financial and economic terms. Net zero will even constitute a significant constraint. In the same environment, however, low-carbon energy and electricity generation will thrive. Low-carbon investments are not independent of the general economy. However, their rate of return will ultimately be defined by two counteracting forces, the impact of carbon

constraints on general economic activity and their own increasing competitiveness. An assumption of absence of correlation, i.e. a zero β (beta) is thus the most appropriate one.[4]

2. **The Arrow-Lind argument can be misunderstood or misappropriated:** Consider a private company or even a public company investing in an ordinary commercial project that is competing with existing private suppliers. In principle, they would have to borrow at market rates. However, by arguing for the public interest of its investment and attracting public investment at or, at the very least, borrowing much closer to the risk-free rate, they could lower their cost of capital and hence the competitiveness and profitability of their project. For a private enterprise, teaming up with a public entity could produce similarly favourable outcomes, benefitting from a cost of capital corresponding to the public sector but retaining an ability to invest in higher-risk private projects and pay private sector salaries and benefits. Baumstark and Gollier are quite explicit in their warnings about these possibilities of abusing public guarantees:

   > We also believe that many public-private partnerships exist just because of the discrepancies in the way the two sectors evaluate the cost of risk. This potentially generated a massive transfer of risk from the private sector to the public one (Baumstark and Gollier, 2014: p. 47).

   Of course, such criticisms do not imply that public-private partnerships should be proscribed *per se*. Harnessing the efficiency of private sector suppliers also for publicly financed projects remains a highly attractive objective for national governments and policymakers at all levels. This includes nuclear new build projects benefitting from direct public investment or public guarantees. Chapter 5 indicates ways to improve the efficiency of nuclear new build projects, precisely by better understanding the workings and incentive structures of the private sector in the management of large-scale project.

   However, policymakers committing public funds to given projects must understand the differences between the public and private sectors in operating the trade-offs between risks and rewards and must remain vigilant to forestall abuses. It also means that their role cannot be confined to financing, but that they must retain some degree of oversight throughout the construction phase until commissioning.

3. **Inefficiencies in public investment decisions:** A common remark by detractors of the Arrow-Lind argument has been that "if public investment is really so great, why not make all investment public?" First, the question is based on an erroneous premise. If all investments were undertaken by governments, they would, by definition, in the aggregate be correlated with systemic developments such as economic growth and the business cycle. As indicated earlier, in this case, the Arrow-Lind argument, which is based on the decorrelation of a given investment project from systemic developments, would no longer hold and market rates for the return on capital would need to be applied.

4. Baumstark and Gollier (2014) provide a very useful and highly readable synthesis of several key arguments around the Arrow Lind theorem. However, they and also Gollier (2012) questionably argue that projects aiming at climate change mitigation and carbon emission reductions are positively correlated with increases in future consumption:

   > It is likely that the climate beta is positive, so that the Arrow-Lind Theorem cannot be applied for climate change (*Ibid*., p. 48).

   Their underlying assumption is that climate change mitigation projects increase economic output. This erroneous assumption is common among researchers, policymakers and the general public. Instead, the benefits of climate change mitigation and carbon emissions reductions accrue in terms of otherwise unrealised non-market (public) benefits such as lives saved, quality of life improved and biodiversity protected. Effective climate change mitigation and carbon emission reductions will thus be financially and economically very costly, both in terms of current annual costs and in terms of total discounted costs evaluated at any non-zero discount rate. The truth that climate change mitigation imposes a major constraint on economic activity as measured in GDP-terms is slowly being recognised (Trinks et al., 2022). Low-carbon investment projects, including nuclear new build, are thus uncorrelated or even *negatively* correlated with economic growth and consumption. This justifies taking a zero β (beta) as an upper bound for climate-related investments (see also NEA, 2022).

However, the rhetorical challenge of the detractors of the Arrow-Lind argument ultimately aims at a more fundamental point: how exactly should the trade-off between the financial benefits of public investment, in terms of reducing the costs of investment risk, and its economic inefficiencies, in terms of sub-optimal investment choices and management, be evaluated? In the market economies of OECD and NEA countries , this question seems a relevant one. Yet, even understood in this sense the question is misplaced. The Arrow-Lind argument does not make the case for a planned economy but shows that risk sharing under precisely defined circumstances can lower the welfare costs of the risks of a particular project, especially if the market disdains from undertaking it. At no point do Arrow and Lind provide any justification for a planned or even a systematically mixed economy.[5]

The main strength of a competitive market economy is its dynamic to reduce costs, to develop new products and markets, and to introduce better-performing technologies. This strength is never questioned by the Arrow-Lind argument. At the same time, it is important to avoid the simplistic opposition between "inefficient bureaucrats" and "smart entrepreneurs". There have been expertly executed large public investment projects. Much of the European nuclear sector is a case in point. There is clearly also slack and substandard work in private enterprise. One of the abiding differences between the two sectors, however, is constituted by their different attitudes towards risk. Clearly, in some cases the comparatively low risk, low reward attitude of the public sector and in others the high risk, high reward attitude of the private sector is preferable. Getting right the interface between the two worlds is again a crucial element of success.

4. **The role of financial markets:** This is perhaps the criticism of the Arrow-Lind argument that is being presented in the most succinct manner: risk spreading is indeed a good idea, but it is already performed systematically by financial markets. Even retail investors do not need to invest the totality of their savings into a single project or company but can diversify them through mutual funds and exchange traded funds (ETF). There is thus no need to share risks either for governments among taxpayers or for regulators among ratepayers. This criticism points towards an important role of financial markets in risk management, but ultimately does not affect the Arrow-Lind argument. Pointing towards the role of financial markets confuses risk sharing and risk diversification. Financial markets are the principal instrument for risk diversification. However, the latter only pertains to diversifiable risks, i.e. non-systematic or idiosyncratic risks that are specific to a given company or project. Diversification does not reduce systemic market risk. The best one can do through diversification is to replicate the market. Risk sharing in the spirit of Arrow and Lind instead goes beyond standard financial market diversification to the extent that the risks of the underlying project are decorrelated from systemic market risk. As indicated, there is good reason to assume that the returns on low-carbon generation capacity are decorrelated from general market developments in this manner.

   There is an additional argument that in the context of nuclear new build, and to some extent in the context of the low-carbon energy transition, financial markets are not very good even at the task of diversifying project-specific risks. This is due to the fact that risks such as electricity price risk or construction risk are too complex and too opaque to be priced in the unequivocal way required by financial markets. Frank Knight, one of the founders of the Chicago School of Economics, introduced the distinction between measurable risk with a known probability distribution and unmeasurable uncertainty. In this categorisation, declining electricity prices or construction problems are subject to uncertainty and not risk. Rather than dealing with "known unknowns", investors are facing "unknown unknowns". That means that the cost of the latter cannot be traded. When looking for reasons, it is possible to cite informational asymmetries, transaction costs or missing markets. However, regardless

5. Kenneth Arrow is even considered one of the most important supporters of a generalised market economy by way of his 1954 article, co-written with Gérard Debreu, which proves the existence of a pareto-efficient general equilibrium for a set of competitive markets. Subsequent commentators have taken their work as "showing that the invisible hand really does work" (Arrow and Debreu, 1954).

of the particular conceptual prism applied, the fact is that when financing the construction of nuclear new build, the diversification function of financial markets frequently breaks down.[6]

The reason that items related to the energy transition are so difficult to price is that they are closely intertwined with the unpriced public goods of climate change and security of supply. Only governments can assess their determination to reduce greenhouse gas emissions or to ensure the security of supply and which risks they would like their voters to share in. Governments "own" the public goods of climate change and the security of energy supply beyond all monetisable risk assessments. Socialising the related costs in the spirit of Arrow and Lind is a logical consequence.

Box 4.1. **Complementary arguments: Social discount rates and public goods**

Risk sharing, which exploits the fact that risk aversion reduces the overall economic costs if they are spread very broadly, is a strong argument for public investment in projects and infrastructures uncorrelated to the business cycle. A complementary argument for public investment, unrelated to risk aversion, is the fact that governments and societies may have different time preferences of consumption. This is the idea behind the establishment of social discount rates, which would be lower than market rates. Although the concept of social discount rates has been less relevant during a period of ultra-low and even negative market rates from 2008 to 2022, it might become more relevant again if global interest rates stay as high as they currently are.

The basic intuition is still valid. Governments and societies can wait far longer than private entities or individual companies for returns on an investment to materialise. Two considerations support this statement. First, governments have the exclusive privilege to levy taxes. Their bankruptcy risk is thus much lower, which is reflected in their cost capital. Governments can thus borrow at the risk-free rate plus an appropriate country risk premium, which is lower than the systemic market risk that individual borrowers have to consider. Second, governments are frequently mandated by their voters to act according to ethical imperatives such as to ensure that favourable framework conditions for the well-being of future generations are maintained. Keeping global warming below critical thresholds and reducing carbon emissions thus would typically justify the application of lower discount rates and public intervention in the cost-benefit calculations for low-carbon projects. While the general argument holds for all low-carbon technologies, it is particularly relevant for nuclear new build projects. Not so much because of their large size and capital intensity, as *all* low-carbon technologies are highly capital-intensive, but due to their very long lead times both during the construction phase and the operational phase.

Finally, there is the issue of external effects and public goods. Competitive private markets are an excellent mechanism to organise the production and distribution of marketable goods. To be marketable, however, requires a degree of codification and an absence of significant transaction costs. This holds for the many goods that can be found in shops and on the Internet. It obviously does not hold for the far more complex public goods such as the environment or energy security. By definition, private, decentralised decision-making is unable to take these goods adequately into account and either disregards them or degrades them by producing negative external effects. In these cases, public efforts can not only be justified but are indispensable to maintain the public goods in question.

In the energy field, reducing carbon emissions and guaranteeing the security of energy supplies are today the two most policy-relevant public goods. If the reduction of carbon emissions could theoretically be achieved by way of a robust and credible carbon tax, ensuring the security of energy supplies is a more complex task due to the multi-dimensional nature of the issue. In the absence of credible alternatives, public efforts to build a low-carbon infrastructure around nuclear power as the backbone of the domestic energy system would thus be the principal path towards safeguarding the public good of the long-term security of supply.

6. The fact that the risks of the construction of new Generation III+ nuclear power plants are not sufficiently codified to be monetised and traded by private markets is not an intrinsic feature of all things related to nuclear energy but is related to the large size and small number of such projects. Only repetition makes it possible to establish the probability distributions that underlie market risk assessments. If every new plant is a first-of-its kind, its costs will reflect a double penalty of cost-overruns due to objective technical difficulties and an unwillingness of private investors to consider financing without far-reaching public guarantees. In contrast, the repeat deployment of small modular reactors would seem to offer new possibilities for the benchmarking, codification, measurement and monetisation of construction. However, the challenges of elevating a whole new class of industrial assets or even a single new technology to marketability and investability may be just as great or even greater than those for an individual Generation III+ plant.

The preceding discussion of the four criticisms of the Arrow-Lind argument – the correlation of publicly funded projects with systemic risk, the implicit risk transfer to the public sector operated in public-private partnerships, the inefficiencies in public investment decisions and project management and the role of financial markets in risk management – provides a broader perspective, highlights potential pitfalls and limits the applicability of the theorem to a small number of genuinely unique projects. Building an infrastructure for low-carbon electricity capacity, including an indispensable share of nuclear baseload, would fall into that category. An indiscriminate expansion of the public sector shadowing broader market developments would not. The same four critical arguments, however, are unable to invalidate the central tenet of the Arrow-Lind argument that sharing risks over large numbers of taxpayers or ratepayers can radically reduce the cost of capital for projects uncorrelated with systemic market risk.

Implementing risk sharing and maintaining incentives in the construction of nuclear new build

Once implemented, the welfare impacts of adopting the Arrow-Lind approach, for instance through a regulated asset base mechanism, can be considerable. A good example of this is provided by the assessment of different financing options for the Sizewell C nuclear plant in the United Kingdom by Newbery et al. (2019). They thus calculate in a first case that purely private financing, i.e. financing by an individual company such as EDF, would result in a weighted average cost of capital (WACC) of 8% and an LCOE of GBP 96 per MWh (all numbers are real). Second, public investment at a level of 60% of the capital costs would reduce the WACC to 3.5% and the LCOE to GBP 52 per MWh. Third, supported by a RAB-mechanism and assuming a social discount rate of 2%, the LCOE would even drop to GBP 50 per MWh. The additional cost of pre-financing construction costs for each of the 27 million UK households would amount to GBP 4 per year (Newbery et al., 2019: p. 48). The total costs of the project for each household would be about GBP 10 per year (The Times, 8 July 2021). The benefits of spreading the risks among taxpayers (case two) or ratepayers (case three) are clearly visible. The limited increases in individuals tax burdens or electricity bills should have a limited impact on well-being, in particular when set against the benefits of an additional 3.2 GW of capacity for dispatchable low-carbon electricity.

Once the general argument in favour of public risk sharing is accepted, the question is how to implement it. Any such discussion is well served by recalling that the Arrow-Lind argument applies only to individual projects uncorrelated with GDP or economic growth. It does not encourage a general expansion of the role of the public sector on efficiency grounds. Precisely because there is competition for access to low-cost funds, whether provided by taxpayers via direct government intervention or by ratepayers via an inclusion of current costs in their bills, careful screening of eligible projects is required. The inevitable political nature of such selection processes, which may be explicit or implicit, requires clearly identifying the benefits and considering distributional considerations from the start.

A second fact to recall is that risks and costs, even if allocated in an economically optimal manner, do not go away. Somebody will have to bear them. Under current circumstances, the costs of building new nuclear power plants would be considerable even if there was no construction and completion risk and capital could be mobilised at zero interest rates. Of course, NEA system cost analysis has shown consistently that the low-carbon transition would be even more expensive without nuclear energy. However, independently of relative costs, the large sums necessary for investments will need to be allocated coherently and transparently to different stakeholders as part of a political economy of the energy transition that still requires to be fully conceptualised and legitimised through democratic processes. The sums at stake are simply too high to be dealt with as part of established investment plans.

Distributional issues and cost allocations will become as important as considerations of economic efficiency. Other than inflation and the consequent rise of interest rates, the principal macroeconomic consideration in the post-COVID-19 economies of OECD and NEA countries is the allocation of the cost of the energy transition. The fact that this is not always obvious is due to the fact that policymakers, for obvious reasons, have stuck far too long with the idea that one can achieve sizeable, even radical, carbon emission reductions without additional costs. Yet the symptoms of the underlying distributional struggle are widely visible such as in the waxing and waning of the promotion of environmental, social, and governance criteria in finance (United States), the fact that a law on domestic heating almost led to a fall in the government (Germany) or that environmental regulations, including obligations to reduce greenhouse gas emissions, are singled out as the single most important cause of the plight of farmers (France).

Of course, distribution and economic efficiency are closely intertwined as evidenced by the Arrow-Lind argument showing that the socialisation of costs can reduce their welfare impact. However, accepting the argument does not resolve two important underlying issues. First, in which manner should costs and risks be shared, and second, how can incentives for corporate entities for efficient project delivery be maintained if they are no longer subjected to any financial penalties in the case of cost overruns?

On the first point, it seems that there is a growing consensus that taxpayers should progressively take on a larger share of the financial burden of the energy transition and thus also of the cost of the construction of nuclear new build. Measures such as investment tax credits, zero-emission credits or even the support measures for green technology investment under the 2022 US Inflation Reduction Act (IRA) point in this direction. This seems to be in direct contradiction with the RAB model, which is currently the most high-profile measure to fund the construction of new nuclear power plants. In a pure RAB model, ratepayers fully finance construction through their electricity bills as the costs come due. That said, also in pure private market finance, ratepayers ultimately pay all costs of electricity generation. It is only that in this case private investors, as project owners, *advance* the funds. If they misjudge costs or market conditions, they will be liable for these risks. In a RAB model, the project owners do not run these risks, which, as shown, are spread across ratepayers.

Yet, in the real world, the RAB model proposed for Sizewell C is somewhat more complex (see also Box 3.1). Ratepayers advance the funds required for construction. In the Arrow-Lind-logic, this (a) reduces financing costs by circumventing system market risk, a fact grasped by policymakers but not yet by private investors, and (b) reduces the welfare costs through risk spreading. However, RAB-financing only extends up to 100% of the estimated project costs plus a 60% share of cost overruns of 30% of the estimated costs. If the numbers detailed in Newbery et al. (2019) are still valid, the maximum amount of cost overruns for which ratepayers would be liable would be 18% of the estimated cost overruns. While this is by no means a negligible amount, it pales against the magnitude of cost overruns observed in a number of recent nuclear construction projects in OECD countries. Indeed, other than these 18% of the original cost estimate, ratepayers do not bear any construction cost risk short of bankruptcy of the project owner and the abandonment of the project.

Part of the remaining risks of cost overruns is borne by private investors, who are supposed to pick up the remaining 40% of the cost overruns capped at 30% of the original cost estimate. Again, this is no doubt a sizeable amount but it is almost negligible compared to what fully merchant investors would have to account for. This is, of course, intended and consistent with the spirit of the Arrow-Lind-model. The fact that private investors are held liable even for a minor share of cost overruns has to do more with incentivising efficient project management (see below) than with allocating financing risks. The oft-overlooked element in the RAB proposed for Sizewell C is that all cost overruns beyond 30% of the original cost estimate will be borne through the government support package (GSP) by the British taxpayer. This is where the real financial risk lies. If ratepayers prefinance an essentially capped amount, taxpayers assume the potentially open-ended tail-risk.

Of course, this may be an entirely sensible proposition. First, it is again fully consistent with the spirit of the Arrow-Lind argument that public financing can reduce economic welfare costs. Second, because the Sizewell C project consists of a pair of second-of-a-kind reactors that are more or less identical to the ones being built at Hinkley Point, is in the same country and under the same regulatory authority, there is reasonable hope that construction risks will be limited also for the British taxpayers. However, to clarify further how the real and large costs of the energy transition are allocated, it would be helpful to foster a broad and transparent debate about the true allocation of the financial costs of nuclear construction risk. Facts, including financial facts, are persistent and will have to be reckoned with at some point. Building true consensus at the level of the political economy of the energy transition is doubtless the best manner to ensure the viability of nuclear new build in the United Kingdom, which is an influential forerunner and emulated by others in this context and beyond.

Box 4.2. **The role of government in nuclear new build: Lessons from the French reactor programme**

Bouttes (2023) provides a synthesis of the development of the French nuclear reactor programme from its beginnings in 1945 to 1975, the time of the start of the "Plan Messmer", which took the French nuclear energy fleet to 58 reactors in 25 years. During the most intensive phase of the programme, France connected during ten years between four and six reactors of 900 and 1 300 MW to the grid, each year. This large-scale deployment of new nuclear capacity is widely hailed as a success. The report is instructive as it contrasts the well-known standard storyline with a more complex picture. It shows that in particular the role of government went far beyond a single, momentous decision and the arrangement of financing. It thus confirms the premise also of this report that in the nuclear energy field, financing cannot be separated from questions of market design, project management and, indeed, industrial policy.

The standard storyline goes somewhat like this: The successful French nuclear energy programme resulted from an inspired policy decision in 1974 by then Prime Minister Messmer in response to the first oil shock, benefitting from strong political support, the choice of a robust reactor design, standardisation, an industrial fabric of high quality and a clear institutional set-up under the strong leadership of EDF and its CEO, Marcel Boiteux. While this story is not wrong, it is incomplete. In particular, it omits the crucial preparatory phase in the three preceding decades during which a surprisingly large community of capable and ambitious risk-takers explored almost all available nuclear energy technologies – fast, heavy water, gas-cooled graphite, pressurised and boiling light water reactors – in a process of trial and error. In this process, the will to advance with successful solutions was as important as the capacity to rebound after failures. The sub-groups of this community were also in fierce technical, institutional and political competition with each other. A key moment was the high-level political decision, made ultimately by President de Gaulle in 1969, to abandon the "national" natural uranium graphite gas (NUGG) technology primarily in favour of the pressurised water reactor (PWR) technology licensed by the US company Westinghouse and working with enriched uranium.

Bouttes convincingly develops a broader narrative around the players and the processes that had established in the preceding years the elements on which the 1974 decision rebounded. In doing so, he develops an intuition for just how long the cycles are for technology development, decision-making and capacity building in the nuclear industry. The political consensus to rely on a civilian nuclear programme as the backbone of the French electricity system thus dates from the late 1950s; the Frech nuclear research programme had been started already in 1946. The existence of a broad and, despite its internal conflicts, rather homogenous technocratic elite with shared backgrounds, codes and, importantly, incentives, was instrumental in realising the French nuclear reactor programme. Partly by default, partly by design, key figures also progressively acquired the necessary management skills to bridge the worlds of theoretical physics and industrial construction.

And yet, the decision in favour of the Westinghouse PWR design was ultimately an economic one. While the decision to abandon a domestically developed technology was painful, a first programme of 8 GW had been decided upon already in 1970 and work had begun in 1971. The construction of a French enrichment plant at Tricastin was decided in 1973. The "Plan Messmer", with its decision to construct between six and seven reactors per year, was thus primarily accelerating an existing programme that had been two decades in the making. Design standardisation, a marked difference to the US reactor programme taking place during the same period, was completed with the abandonment of the boiling water reactor (BWR) design in 1975.

In hindsight, an important element of the success of the French nuclear programme was the long-term commitment at the highest political level, progressively translated into reality by a community of committed and competent engineers, scientists and industrial leaders. A key element was the ability to absorb almost three decades of trial, error and partial success, including sometimes considerable technical and economic setbacks, before a technological and institutional selection process produced a sustainable techno-economic solution.

The new French nuclear power programme reflects this necessity of long-term political commitments, albeit in a profoundly changed political and industrial landscape. Somewhat surprisingly, the history of the French nuclear reactor programme also underlines the value of well-executed and well-timed design competition. Keeping the options of the three most-promising technologies, NUGG, PWR and BWR, open for many years, ultimately allowed to come down on the side of the industrially most advantageous solution. This early concentration on a small number of potential winners may hold lessons also for today's challenge to focus efforts on the best performing technologies. Rebuilding a managerial class supported by long-term financial and symbolic incentives remains a complementary challenge. In the context of the French nuclear energy programme of the 1970s and 1980s, the motivation and emulation of these industry leaders ultimately limited the drawbacks in terms of managerial efficiency that public financing can create.

These considerations are also relevant to the current policy framework for small modular reactors (SMRs). The current phase is one of technological competition. Beyond engaging themselves in financing, market design and project oversight, a key task for the governments of OECD and NEA countries will be to decide how and when to provide incentives for the national and international standardisation that is required to make success also of a future wave of nuclear new build.

Other than cost allocation, the second crucial point pertaining to the implementation of risk-sharing arrangements is closely linked to the general discussion on project management in Chapter 5. However, a general insight in this context is that if society and its agent, government, assume a greater share of the risk of the project as owners and investors, then they will also need to acquire a greater role in the explicit oversight of project management, with the power to incentivise and to sanction. This holds particularly true in an era when the importance of implicit incentives, such as belonging to a certain managerial class, a wide array of secure career opportunities, pension arrangements, access to otherwise exclusive clubs or associations, social standing and so forth, have greatly lost value. Such implicit social contracts, which ensure managerial efficiency even in the absence of permanent explicit oversight, were important for instance in the context of the successful French nuclear programme of the 1970s and 1980s (see Box 4.2 on "The role of government in nuclear new build: Lessons from the French reactor programme").

However, in an era less beholden to symbolic forms of recognition and webs of interdependence established over time, the incentives of different stakeholder groups need to be organised in a more explicit manner. This raises an additional issue in the context of the spreading of the financial costs of risk in the spirit of Arrow and Lind. The preceding sections have outlined why such risk spreading, and the reduction of the welfare costs of risk that go with it, is desirable and necessary to enable the new build of nuclear power plants with large construction. However, an unintended consequence of such socialisation of costs, in particular the costs of risk, is that it stunts incentives for efficient performance and cost reduction for the project owner and project manager. If cost overruns can be passed on to rate payers, why work hard to avoid them?

This is implicitly recognised also in the current discussions about the RAB model for the Sizewell C project in the United Kingdom. During operations, the operator, presumably EDF Energy, will be subjected to the form of incentive regulation routinely practised by the British electricity market regulator Ofgem. Such incentive regulation, theorised by Baron and Myerson (1982) as well as by Laffont and Tirole (1986 and 1993) in the 1980s and 1990s, precisely intends to solicit the maximum effort from operators to provide truthful cost estimates, manage efficiently and reduce costs. Discussing the wisdom of this choice - incentive regulation, for instance, requires the availability of recognised cost benchmarks - must be left to another occasion. However, the key point is that at the time of publication of this report no specific structures were foreseen to incentivise efficient management and cost reductions during the all-important construction phase.

One may argue that the project operator overseeing construction is also an investor. The operator therefore has a stake in the project's cost and an incentive to manage efficiently to remain within the original estimate, as the RAB only covers 100% of that estimate. However, the participation in the cost increase is capped at 130% of the original cost, beyond which the government support package kicks in. Investors in recent nuclear new build projects in OECD countries would have been quite pleased with a cap at 30% of cost overruns. In nuclear construction cost, the long tail risk, the risk of low-probability but high-impact events that lead to far higher excess costs, is decisive.

Beyond, the construction of Sizewell C, socialising financing risks through risk spreading among ratepayers or taxpayers poses the important question of how to maintain incentives for efficient project management in the absence of implicit constraints such as maintaining reputational standing. There are essentially three general answers to the challenge of maintaining efficient project management under public financing of nuclear new build projects:

- **First and foremost**, government as the ultimate project sponsor needs to take responsibility for efficient project delivery at the highest political level with the power to sanction inefficiencies and to reward superior performance, including the ability to dismiss underperforming suppliers, even outside prior contractual agreements.
- **Second**, contractual agreements spelling out incentives for obtaining project milestones on time and on budget have of course a complementary role to play. Nested bonuses, well-known in finance, rewarding performance at the level of the individual, the team and the project would be the appropriate model also in this context.
- **Third**, it is important to commit to a programme of a series of reactors all the while maintaining contestability of access to these multibillion-dollar projects. While vendors will always push for multi-reactor commitments to foreclose access of competitors, governments should strive to avoid such agreements. Competitive pressures, well understood as competition among partially vertically integrated entities, are the principal source also in nuclear new build of efficient project management, cost reductions and project-relevant innovation.

Respecting these conditions, a nuclear new build programme with essentially socialised financing risks can maintain efficient project management (see also Chapter 5). In parallel, governments need to recall that the reduction of welfare costs due to risk spreading following the work by Arrow and Lind only applies if the profitability of low-carbon investments is uncorrelated to generic market risk. This requires two conditions. First, effective policies to attain credible long-term objectives to reduce carbon emissions must be maintained. Second, investments in new nuclear power plants must remain a modest portion of overall public investment. This will be the case in most OECD and NEA countries, but perhaps not in all and is a point that should be watched carefully.

In conclusion, it would be irresponsible to use the Arrow-Lind argument in a manner suggesting that costs do not matter since they can always be conveniently spread over large numbers of individuals. The opposite is the case. Using public financing for nuclear new build implies entering a long-term political and economic compact with ratepayers and taxpayers. Thus, while risk sharing remains an important argument for different forms of public or regulatory intervention in the financing of nuclear power plants, it requires as incontrovertible complement the justification of such arrangement through broad political and institutional processes. The governments of OECD and NEA countries would thus be well advised to spell out the nature of the compact they are proposing to ratepayers and taxpayers, in particular its implications for the distribution of costs and financial risks as well as the conditions for efficient project delivery, as early as possible in a systematic and transparent manner.

Chapter 5. The role of project management: How to better manage

The key insight structuring this chapter is captured by the statement that "financing costs are an output of and not an input into nuclear new build projects". Of course, the previous chapter has systematically developed the case for the spreading of the financial costs and risks in the spirit of Arrow and Lind, precisely to hold financing costs close to the risk-free rate plus the appropriate country risk premium. Without such an "input" of public financing that is engineered *before* the start of construction by governments or their representatives, the building of new nuclear power plants would, at least for currently available technology designs in today's industrial context, become prohibitively expensive for private investors in most OECD countries. However, this fact results precisely from the financially painful experiences with a number of new build projects in OECD countries, many of which were due, at least partly, to sub-optimal project management.

The essence of the above statement is the fact that there exists an intrinsic link between the quality of project management and financing costs, even if that link affirms itself as much in the long term and at the industry level as in the short term and at the level of the individual project. Simply put, sub-optimal project management decreases industrial performance and increases risks, both real and perceived, which raises financing costs. Causalities also run in the other direction as financing structures impact incentives for individuals and institutions and hence management performance. Chapters 3 and 4 have already commented on the risks created by socialising all financial risks through risk spreading. If managers and their employers do not face consequences for project delays and budget overruns, it is inevitable that their commitment to tight and cost-efficient project delivery will weaken. Developing an appropriate incentive structure for all stakeholders is key for successful project delivery. If taxpayers or ratepayers directly finance projects and assume risks, governments or institutions designated and empowered by them must assume the ultimate responsibility also for construction and project management. This does not imply micro-management on a day-to-day level. However, completely separating responsibilities for financing and management will lead to strongly skewed incentives.

This chapter thus has a threefold structure. First, it will briefly develop the link between market designs, project structures and management. Overall, the hybrid market designs presented in Chapter 3 provide an appropriate framework for sustainable project structures and well-performing project management. Second, it will concentrate on several practical elements that are key in nuclear construction such as design completion, relationships with regulators, supply chains and the availability of suitable skills. Third, the chapter will conclude by insisting on the issues of leadership, independent project oversight and appropriate incentive structures that are decisive for the successful construction of new nuclear power plants.

Market design, project structure and project management

Nuclear financing structures, electricity market design and project management are interdependent and must be approached in an integrated manner in order to maximise the chances of success for nuclear new build. As outlined in Chapter 3, the price uncertainty introduced by deregulated energy-only electricity markets raises financing costs and skews investor choices towards less capital-intensive, and frequently more carbon-intensive, technologies. There is indeed an intrinsic link between market design, corporate structures and technology choices. Electricity market deregulation, utility privatisation and the "dash for gas" went hand in hand. The low-carbon energy transition, with the push for net zero carbon emissions, has not yet found a stable paradigm for electricity and energy market design even though several indispensable elements are emerging.

So far, however, the sector is still struggling with the legacy of the past three decades. The impacts of the strategic reorganisation of the electricity sector that happened with market deregulation in most OECD and NEA countries clearly extended also to project management. The previous owner-builder-operator model of the vertically integrated utility under regulation was thus substituted by webs of contractual relationship with external service providers. Outsourcing of project management to providers of engineering, procurement and construction (EPC) services became the dominant model. This extended, at least in theory, also to nuclear new build. In the meantime, the pendulum is beginning to swing back. The progressive introduction of stable, long-term pricing arrangements in electricity markets and the benefits of the integrated owner-builder-operator model are being newly appreciated.

A key question is, of course, to what extent the provision of capital can be separated from "project ownership" and the responsibility for cost overruns and project delays. The already mentioned regulated asset base (RAB) model for the Sizewell C reactor in the United Kingdom is precisely characterised by the attempt to separate the three functions with UK ratepayers providing the capital to remunerate private investors, EDF holding project oversight and UK taxpayers taking on a substantial part of the cost risk.

As pointed out in Chapter 4, such risk spreading over large numbers of individuals reduces the welfare costs of high risks and will need to be an intrinsic part of nuclear finance and hence of electricity market design. Only such risk spreading keeps financing costs sufficiently low to be able to undertake projects with such intrinsic technological risk. The question is to what extent the implication of taxpayers and ratepayers is accomplished in a transparent and socially sustainable manner and to what extent it is accompanied by a role in project oversight and control through delegated experts (see also below the section on independent oversight). Thus again, market design, finance structures and project management evolve together.

As has been underlined all along, a causal relationship runs also from project management towards financing. Efficient project management reduces construction risk and financing costs. Delivering even a limited number of projects to budget and on time would reassure investors enormously that Generation III+ projects have finally stabilised and the technological challenges have been mastered. Yet what is the overall principle that could organise successful project design? Simply put, the key challenge is to get the balance between vertical integration and competition right. The vertically integrated and regulated monopolies of old managed to deliver successful nuclear new build. However, they did so only after long and costly periods of trial and error, all the while benefitting from at least implicit government support as well as from an industry ethos built around lifetime employment that ensured a level of efficient performance. Market deregulation and de-verticalisation explicitly ended this model.

While easy to criticise from certain angles, it is important to recall that deregulation delivered sizeable efficiency gains in operations and dispatch. Deregulation instead failed almost completely in fostering low-carbon investment based on electricity market prices alone. The capital intensity of such investments in combination with high long-term price volatility had most investors retreat. While the fact was recognised by experts relatively quickly, it was veiled for long periods of time by the out-of-market financing of wind and solar PV capacity and the rapid introduction of capacity mechanisms, which tend to favour the most carbon-intensive generators such open-cycle gas turbines or diesel generators with the lowest fixed costs. So, deregulation finished off an industry model that was far from perfect but that did manage to deliver the Generation II nuclear reactors that are the still the mainstay of today's nuclear industry.

The alternative, the EPC model that could, at least in principle, be built around a logistics provider as the operator of the construction project, never got that far. There are several reasons and not all of them are intrinsic to the EPC model itself. A major reason is clearly the shift from Generation II to Generation III+ designs. Uncompleted designs and new technological challenges that are only now being routinely mastered would have tested any model of industrial organisation. A highly formalised and legalised regulatory process, which in some cases masked a breakdown of any constructive solution-oriented dialogue between industry and safety authorities, may or may not be associated with a management model based on explicit codification rather than implicit knowledge, long-standing relationships and trust. The key reason, however, lies with the EPC model itself: in an industry as complex and as sensitive as nuclear energy, market transaction costs are just too high to allow for a high degree of externalisation with competitive market procurement and layered value chains. The market transaction costs extend less to the costs of collecting information about different offers or negotiating contracts but rather to the costs of ensuring quality and delivery as well as supervising, enforcing and potentially adapting contracts.

This is due to the fact that informational asymmetries (the fact that one party knows something, such as the quality of a particular component, that the other part does not) are more pervasive and more critical to project success, primarily due to close regulatory oversight, than in other industries. The adage from transaction costs economics that "there is no such thing as a complete contract" due to bounded rationality, the possibility for creative interpretations and unpredictable contingencies, applies thus particularly strongly to the nuclear industry. There exists thus in the nuclear industry a particularly large scope for applying the kind of opportunism that has been referred to as "self-interest…with guile" (Williamson, 1993: p. 97).

Competitive market procurement also does away with longer-term interdependencies. Individual suppliers thus have no stake in the success of the overall project, which makes for a misalignment of incentives. Together with the large possibilities of gaming offered by the complexity of the nuclear value chain, this will lead for each contract to two different narrow interpretations of one hugely complex and yet incomplete contract. This is not only fertile ground for legal disputes and a source of ill will and frustration. Even in the most dispassionate and rational environment, the informational asymmetries and misalignments of incentives will require additional risk insurance provisions. This is precisely what is behind the term "supplier agreements and risk management", as evoked in Figure 3.2, that were responsible for three quarters of the increase in the costs of nuclear new build between 2004 and 2011. As the supply chain is decomposed ever more finely, each of its links will need to ensure fully against the financial risks emanating from its contracts with the preceding and the subsequent link – at additional costs.

What results from this argument? Does the nuclear industry need to revert to nationalised monopolies in the hope that managerial hierarchies and the watchful eye of government oversight are able to resolve the conflicts of interest that markets and legal codification are unable to settle in an efficient manner? To some extent, yes. The most important point is to give all participants in large and complex projects a stake in the successful outcome of the overall project, even if the latter is still years away. This is the key point. To some extent decision makers seem to understand this. More often than not, reactor vendors will advance as part of a national "team". Yet, even where such national industry networks benefit from a shared language and culture, carefully designed financial incentives must complement the institution-building effort to carefully balance the not automatically converging commercial interests of different team members (see also the next section on incentives).

Another point is, of course, that both market competition and the division of labour have been recognised at least since Adam Smith as having their advantages. Market competition weeds out underperformers, rewards good performers and provides incentives for efficiency and innovation. The division of labour allows reaping the benefits of specialisation and economies of scale. In their absence, decisions are increasingly made on non-economic grounds. The complacency and collusion with sectoral regulators at the vertically integrated utilities to which deregulation had responded were real. The problem in nuclear new build is that project cycles are too long to fully engage in this process of Darwinian selection. As projects run for at least five years, some many more, with preceding planning and contracting periods at least as long, suppliers may no longer exist and may have moved on for reasons unrelated to their project performance or even nuclear construction in general. Others are too big or considered as too strategic to fail and will thus be forgiven even major failures.

In this admittedly complex situation, the pragmatic solution would be to aim for an intermediate position between the two extremes of an almighty monopoly and perfect competition. This would mean that nuclear new build would be undertaken by oligopolistic structures, where a small number of partly, but not totally, vertically integrated competitors would compete against each other both domestically and globally. The economies of scale that a monopolist would claim will have to be offset against the ability benchmark, the performance of a project operator against that of its competitors. A key task for decisions makers would thus be to define the extent of vertical and horizontal integration of each major supplier. Exclusive contracts should be avoided wherever possible.

There is no doubt that experience in organising and executing nuclear new build projects reduces costs. At the same time, the benefits of economies of scale, i.e. the move from first-of-a-kind (FOAK) to nth-of-a-kind (NOAK) plants should not be overestimated. Indeed, they are very small even when assessed by researchers who are sympathetic to the benefits of standardisation, when compared with the cost overruns in recent Generation III+ projects:

> We find that, everything being equal, one can expect on average a 12.4% reduction in construction costs for the second unit of a reactor model built by the same A-E firm (Berthélemy and Escobar Rangel, 2013: p. 16. A-E stands for "architect-engineer").

Ultimately, there is strictly no substitute for high quality project management. "Series effects" will remain elusive if execution is substandard. In addition, very few reactors are exactly alike. Even for reactors with the same basic design, local specificities in geography, regulation, financing and management matter. Taking them into account is not *per se* negative. The decisive factor is, again, efficient project management. Governments have an obligation to create the appropriate framework conditions in terms of market design and industrial policy. Once this is done, industrial project managers, whether in publicly or privately owned structures, need to take over. Fortunately, as set out in the subsequent section, there is a growing awareness of what they must bring to the task in order to foster efficient project management.

Elements of better project management I: Advance planning, supply chains and skills

No clever market design, no optimised risk allocation, no organisational model can substitute competent project management in fostering successful nuclear new build. Construction and completion risk is not exclusively a nuclear energy issue. Already a dedicated chapter in NEA (2015) asked "The divergence between actual and estimated costs in large industrial and infrastructure projects: Is nuclear special?" The answer is "no" and "yes". The 2015 NEA study had pointed out that in all sectors megaprojects such as a new Generation III+ nuclear power plant are frequently over time and over budget with little improvement over the decades. A certain amount of optimism bias is indispensable to get anything moving. However, it also concluded:

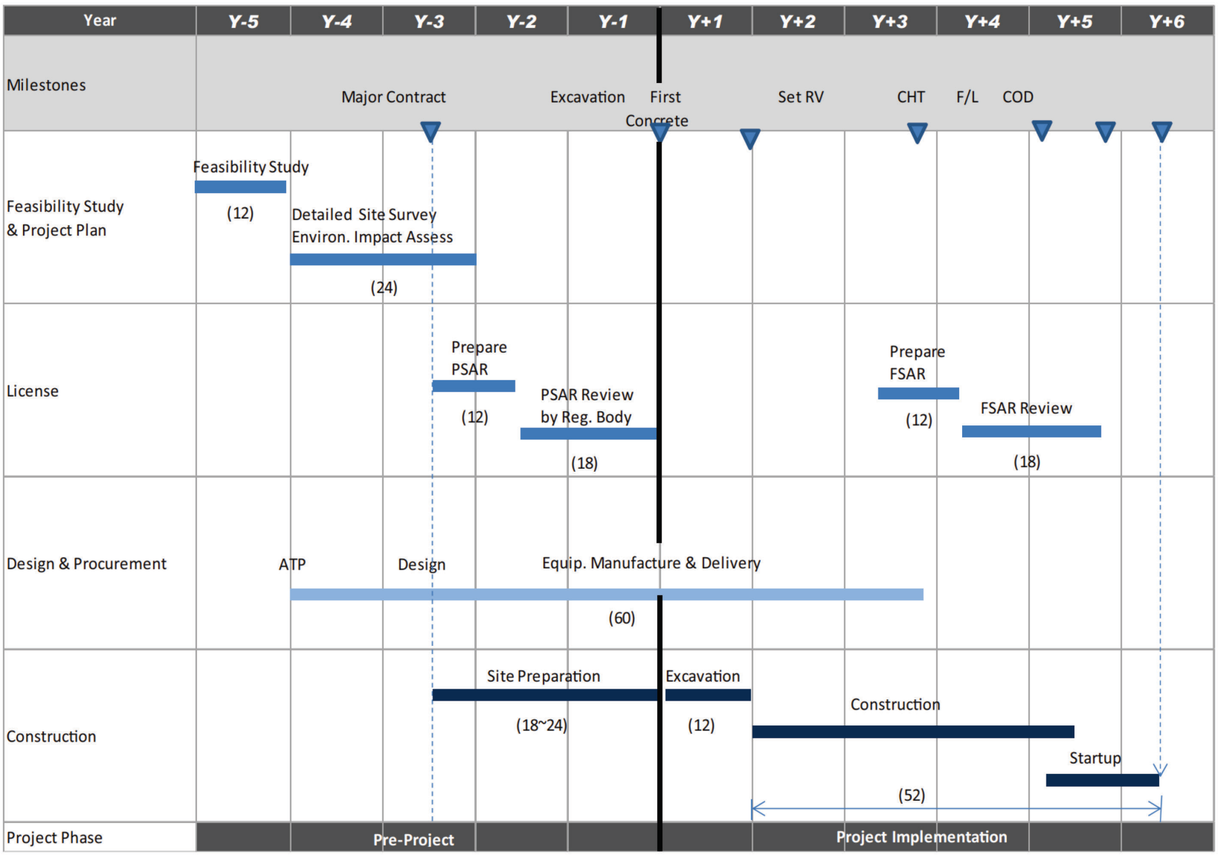
> The nuclear sector presents the highest level of technical complexity compared to other industrial sectors…, which makes paying attention to managerial topics particularly important. When analysing both the past performance of nuclear projects and nuclear incidents, most of them can be traced back to managerial mistakes, not to technical ones. In the past, these considerations were addressed by giving managerial positions in the nuclear delivery chain to very good managers coming from other sectors… The managerial evolution of the military and aerospace supply chain can be considered as a benchmark, since they are from an organisational point of view comparable to the nuclear industry… [a] promising way forward may [also] be to start learning from other high technological sectors such as aerospace or oil and gas, where a number of major companies have evolved from national champions to global competitors (NEA, 2015: p. 186-7).

It also concluded that there were "no silver bullets", which certainly still holds true today. Neither military supply chains nor the aerospace or oil and gas industries have been exempted from criticisms for management failures. In all fairness, criticism levelled at oil and gas majors have most frequently concerned strategic failures, notably dealing with their responsibility for abetting large amounts of greenhouse gas emissions, rather than project execution. Could hiring experienced project managers in oil and gas thus be the answer to the management challenge in nuclear new build? At the very least, it would require two major changes in the nuclear industry: matching the salaries of the oil and gas industry and adopting its culture of awarding direct managerial responsibility with immediate consequences for success or failure.

Advance planning

However, there exist also more consensual elements that are now generally acknowledged as being part of successful nuclear new build. The three most important ones concern advance planning, supply chains and skills. Regarding advance planning, experts agree that long lead times of at least five years, possibly more, are required before first concrete (see Figure 5.1). Early contractor involvement (ECI) before the conclusion of final supply contracts is an absolute necessity. Overall, successful projects require extensive planning and the development of strong and transparent metrics, including planning and accounting for contingencies when, inevitably, some things do not go according to plan.

Figure 5.1. **A simplified timeline for a successful nuclear new build project***



* ATP refers to authorisation to proceed, PSAR to Preliminary Safety Analysis Report and FSAR to Final Safety Analysis Report.

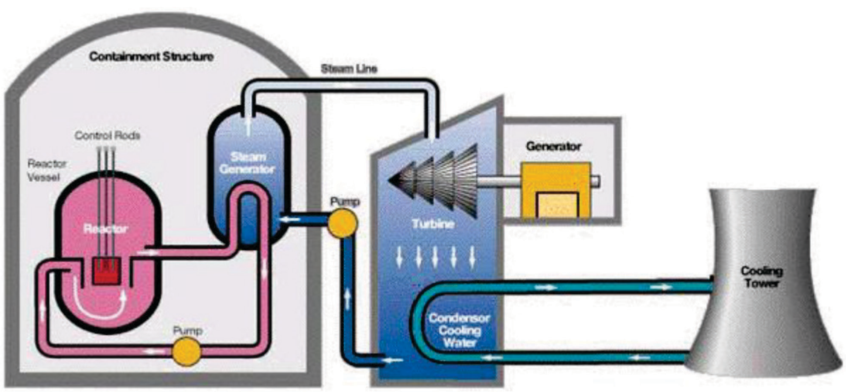
Source: IAEA (2012), p. 24.

Importantly, advance planning includes the completion of technological designs. Not respecting this point has been a major factor in the cost explosion of early Generation III+ projects. This is part of what is habitually referred to as owner's cost. No authorisation to proceed should be given to projects whose detailed designs are not 100% complete. Of course, the desire to move ahead quickly when time is money is understandable. However, the risk to the projects that were initiated without complete designs and, more importantly, the reputational risk to the industry at large, are just too large to allow project operators without fully complete designs to go ahead. Design completion inevitably implies regulatory approval. This is the other side of the coin.

The relationship with nuclear regulators is unquestionably crucial. The good safety performance of nuclear energy, the indispensable basis of the sector's social and political acceptance, is in their hands. At the same time, the precise relationship between regulators and project operators remains to some extent a mystery, which recent NEA work reported in *The Mutual Impact of Nuclear Regulatory Bodies and License Holders from a Safety Culture* has begun to unpack (NEA, 2024c). Among other things, it appears that the ability of reciprocal learning is crucial for a relationship conducive to project success and cost reductions. If project operators regularly and forcefully profess their acceptance of the absolute primacy of nuclear safety and hence of regulatory decisions, they cite with equal regularity "design adjustments" as the reason for cost overruns and delays. More work is needed to understand fully the complex and contradictory relationship between regulators and project operators in order to formulate proposals that would improve it in a manner to become a stable basis for nuclear new build in OECD and NEA countries. A number of general recommendations can nevertheless be formulated in this context:

- Governments must ensure that regulators fully internalise their strategic role of being part of the solution in ensuring successful nuclear new build.
- Regulatory co-operation such as takes place at the NEA Regulators' Forum is necessary in the effort to harmonise designs for specific reactor types over different jurisdictions and to keep local and national design adjustments to a minimum.
- A review can be carried out of the components, large or small, that are "nuclear safety-related" and must conform to exacting regulatory requirements and complex review processes. In Generation III+ projects, the structures outside the containment structure that houses the nuclear island with the nuclear steam supply system (NSSS), i.e. the conventional island and the balance of plant (see Figure 5.2), are responsible for roughly two thirds of the costs of a project. This certainly does not mean that none of these structures are safety relevant. However, it must be possible to pose the question to what extent it is sensible to hold all elements of new nuclear power plants to the same level of regulatory stringency.

Figure 5.2. **A schematic view of a PWR reactor with the nuclear island, the conventional island and the balance of plant**



Nuclear island	Conventional island	Balance of plant
NSSS, reactor containment building, primary mechanical and electrical systems and auxiliary system (*e.g.* used fuel pool).	Turbines, secondary mechanical and electrical support systems and feedwater system.	Transmission links, water supply and cooling towers, transportation and loading facilities, administration and workers' welfare blocks, emergency facilities, *etc.*

Source: WNA (2023), p. 41.

Supply chains

If advance planning and a constructive relationship between project operators and regulators are indispensable, they must be complemented by an efficiently performing supply chain and an adequately skilled workforce. Somewhat surprisingly, assessing whether today's supply chains for nuclear new build are adequate is as much a conceptual as an empirical challenge. The conceptual challenge hinges on the question of whether it is supply that pushes demand or whether it is demand that pulls supply.

The answer is complicated by two additional facts. First, the "supply chain" is not actually a chain but a tightly meshed network with multiple linkages and interdependencies between suppliers at different levels. Globalisation and regionalisation have added more layers to former national networks, working inside distinct but interacting incentive frameworks. In addition, these interacting networks are highly malleable and constantly reconstitute themselves according to new technical, commercial and geopolitical variables. This makes determining unequivocal causalities – from supply to demand or from demand to supply – very difficult. Second, considerable time lags exist in nuclear new build (see the paragraph above on the need for advance planning above). This means that the "supply chain" (for lack of a more precise but commonly accepted moniker) constitutes itself through the explicit contractual relationships with the project operator once the authorisation to proceed has been obtained.

Given these facts, this report argues that the provision of supplies in the form of the required technical hardware, including the provision of critical nuclear components such as the reactor pressure vessel, as well as the required "software" in the areas of informatics, logistics and project management can be sourced from the currently existing global supply chains. This point of view receives empirical support from the 2023 overview report by the World Nuclear Association on *The World Nuclear Supply Chain 2023* (WNA, 2023), which lists suppliers for all critical components of the relevant Generation III+ reactor models. The report summarises:

> Around a dozen consolidated gigawatt-scale technology vendors currently offer their designs and services across much of the plant lifecycle. Each has developed a supply chain that is global in scope, with localised capabilities to support regional deployments. While the industry remains weighted towards domestic markets, the leading vendors are, for the most part, internationally diversified in terms of their corporate make-up and their supplier base (WNA, 2023: p. iv).

Annex H of the WNA report lists 15 reactor vendors capable of providing the NSSS, including seven in OECD countries. There is also no shortage of suppliers of reactor pressure vessels and steam generators, reactor cooling systems (including large valves and actuators), steam turbines or instrumentation and control systems, even considering the constraints imposed by the current geopolitical environment. The situation is similar for providers of professional services with dedicated nuclear expertise in engineering, law, insurance, project management or logistics (ibid.: p. 143-160). Indeed, it is difficult to argue that a project operator with adequate financing could not source all the components and services required for building a state-of-the-art Generation III+ nuclear plant from competent providers located in OECD countries.

Whenever there are interruptions, delays or inefficiencies in the supply chain for a particular reactor type, the long delay between the authorisation to proceed and first cement should be sufficient for gaps to be filled. Needless to say, a complete supply chain ready to spring into action at the announcement of a project would be nice to have for the project operator. Such a supply chain is, however, a fiction. Supply chains do not exist without projects. Creating spare capacity that new projects could immediately draw on would be a costly way to manage nuclear new build, in particular considering the stop and go nature of many nuclear projects. In practice, the supply chain must gradually reconstitute itself as a new build project and its financing firms up. Transparency and advance communication between the project operator and its future potential suppliers are key here. This is an area where recent projects, e.g. Hinkey Point C, have been rather successful.

Overall, it is hard to maintain that the nuclear supply chain would constitute a binding constraint on nuclear new build and it should not be used as an argument for delaying project development. If the financing has been arranged and a competent project operator designated, then the profit motive will align an operational supply chain in a matter of months or very few years. In essence, if sound financing for building a nuclear power plant is provided, the necessary inputs will become available.

While there is a good case for being relatively sanguine about the state of the nuclear supply chain from the technical and commercial point of view, there is clearly a conversation ongoing between different stakeholders. Sometimes, it is a matter of perspective. An anecdotal example that could be cited is the statement by an executive of a small US utility at the NEA Roadmaps to New Nuclear 2023 conference who regretted that the state of his supply chain was such that he had to source some components for a major refurbishment project from eBay. While this may indicate a gap in this utility's traditional supply chain, it does not constitute a constraint on a successful project. Some countries with active nuclear new build programmes, such as Canada, Czechia or Sweden, declared at this and other conferences having few worries about their supply chain or the supply of sufficiently skilled labour. Others, such as France, worry deeply about the state of their supply chain and the availability of workers with the requisite skills.

This is more than just a case of disagreeing on whether the glass is half empty or half full. Assessments of the supply chain depend at least to some extent on what is expected of a nuclear supply chain. Is its main function to provide all the components of a new nuclear power plant conforming with required specifications on time and at least cost or is this function overlaid with neo-mercantilist concerns about domestic industrial development, including local content requirements, general international competitiveness and interference with national security issues? If it is the latter, it is obvious that establishing a nuclear supply chain will be far more difficult. Already Adam Smith remarked that restricting the size of the market means foregoing the benefits of the division of labour. In fact, each domestic constraint adds to the effort, time and cost required to build the ideal supply chain rather than just a technically and economically functional one.

Having said that, there are two areas where those who do not want to rely on economic and financial incentives alone to create well-performing nuclear supply chains have a point. The first point regards regulation. Even when quality components are reliably sourced from abroad, conformity with national safety regulations is indispensable. Admittedly, transaction costs for foreign suppliers, even if informed, trained and prepared by the project operator well in advance, may be higher than for domestic suppliers. However, choosing between the two should remain a commercial decision, albeit a commercial decision that takes all relevant transaction costs into account.

The second point regards nuclear fuel supply. As most relevant Generation III+ designs use nuclear fuels requiring enriched uranium, the exception being the Canadian CANDU design, proliferation concerns are inevitable. Dealing with those concerns is the responsibility of national governments inside the frameworks that the international community has given itself. Not that there is a particular issue with nuclear fuel supply as such. Also at the 2023 NEA Roadmaps conference, the CEO of a major nuclear fuel supplier pointed out that building a new enrichment plant would cost less, take less time to license and would be design-wise simpler than a nuclear power plant. In other words, given the timeframes for planning and building new nuclear power plants, the fuel supply industry would have sufficient time to prepare for any increase in demand. Yet, more than in any other parts of the new build process, for proliferation reasons governments need to take responsibility for building robust fuel supply chains. These considerations will only be reinforced by the advent of new SMR designs, many of which rely on high-assay low-enriched uranium (HALEU) fuels, including tri-structural isotropic (TRISO) fuels, with higher levels of enrichment and hence heightened proliferation concerns.

Apart from fuel supply, which, strictly speaking, is not part of the supply chain required for nuclear new build, the nuclear industry, even when acknowledging the inevitable interactions with a larger public sphere, must learn or re-learn to take a strictly industrial and commercial approach. Its very future as an economically viable option for the provision of low-carbon electricity depends on it.

Skills

This observation also pertains to skills. There is no doubt that projects as complex as building a new nuclear power plant require a highly skilled work force. Welders, electricians and engineers are just some of the types of professionals of which large numbers will be required in any nuclear new build project. Labour markets, just like markets for goods and services, react to incentives, even if sometimes with time lags. The large Canadian refurbishment projects undertaken by Ontario Power Generation and Bruce Power both report satisfactory numbers of qualified applicants replying to their job offers. Certainly, advance planning, training, including apprenticeship programmes offering real career opportunities, and communication are part of the picture. Project operators such as Westinghouse also emphasise the transferability of the skills that can be acquired in nuclear construction, for instance to sectors such as shipbuilding. There is nothing to be gained by overemphasising the particularities of nuclear new build as an industrial undertaking.

Ultimately, however, long-term financial incentives, which include not only the gross salary but also health and pension benefits, will be decisive. And differences can be huge. This can be shown by taking as an example the profession of welder, which is at the heart of any nuclear new build project. The lack of an adequate supply of qualified welders is often cited as a crucial bottleneck in nuclear new build. As indicated by the Groupement des industriels français de l'énergie nucléaire (Gifen), the French trade association of nuclear industries, an experienced welder in France can expect to earn a gross salary of EUR 34 000 per year with a starting salary of EUR 23 000 per year (Gifen, 2024). In the Unites States, a trade platform states that "nuclear welders earn on average about USD 66 500, while the top welders earn more than USD 150 000" and continues "if you've got the aptitude for welding… you should consider a nuclear career" (YesWelder, 2024). If such large differences in salaries persist over time, it is obvious on which side of the Atlantic bottlenecks for qualified welders are more likely to arise.

It also needs to be emphasised that salaries constitute ultimately a fairly moderate share of the costs of a new nuclear power project. Take again the example of the French welders, assuming an average salary of EUR 30 000 per year. Assume further that full employers' cost will come in at double that at EUR 60 000 and that a nuclear new build project will employ 400 welders. Doubling their salary would add EUR 24 million per year to the cost of the project. This is hardly negligible. However, if attracting sufficient numbers of welders constitutes a critical bottleneck and considering that the annual costs of a new nuclear Generation III+ project will be in the range of 1 billion, this is an amount well worth spending.

Elements of better project management II: Leadership, independent project advisory and incentives

Once the appropriate framework conditions have been set, adequate financing is in place, project planning has progressed for several years, and supply chains and labour supply have appropriately reconfigured themselves, construction proper starts with preparation of the site. At this moment, the most important elements become leadership, independent oversight and well-designed incentive structures.

Leadership

Leadership is an oft-invoked notion, which, even when it is mentioned in good faith, is rarely fully understood. There are two major aspects to leadership: the ability to co-ordinate multiple contributors to a project and the ability to deal with unforeseeable and uninsurable risk, i.e. uncertainty in the nomenclature introduced by Knight (1921). The two aspects are related in certain ways, e.g. stakeholders prefer to be co-ordinated by an authority capable of protecting them from such residual risk, but for clarity they shall be kept distinct in the following. The question of leadership poses itself in both public and private structures. Of course, styles and incentives will differ. However, the already quoted adage that "there is no such thing as a complete contract", applies equally to the public and the private sphere. In either setting, the leader is the one who is expected to bridge the gap between what can be codified in advance in contracts (laws, agreements, compacts, administrative stipulations etc.) and the refractory reality on the ground.

Thus, the more complex a project is, the more important effective, personal leadership becomes to ensuring a common vision and common rules of engagement between stakeholders. This comes back to the discussion in Chapters 3 and 4 of engineering, procurement and construction (EPC) contracts. The concept of EPC was based on the assumption, which turned out to be illusory, that all interactions in a nuclear project can be contractualised. They cannot. There is today a widespread industry consensus that the EPC concept did not live up to expectations. Figure 3.2 nicely shows how costs can run into a frontier of non-insurability in a framework aiming for comprehensive contractualisation.

In this context, the co-ordination function of the project leader can be understood as focusing the multiple contractual and hierarchical relationships that evolve around a project so that the different contributions and outputs align with the strategic objective of concluding the project successfully. In other words, the leader cuts through the transaction costs, the ubiquitous frictions, inertia, exploitation of informational asymmetries and rent seeking which characterise the interaction of different parties, each one with its specific agenda. Of course, the leader will be assisted by appropriate incentive structures (see below). A common project culture, something which can only be established over time, can be of further help. One of the most important tasks of the leader is indeed to select the kind of structure and culture that best chimes with their style. However, while appropriate incentive structures are indispensable, they alone will not be able to align all behaviour. Cutting through transaction costs in an effective manner will, ultimately, require that mysterious additional element – authority. The latter may derive from a hierarchical position in an organisational chart with the ability to mete out rewards and punishments, a record of good past performance or personal charisma and, in fact, from all three together. A project leader may get by relying on only two of these three attributes. No leader could survive on the basis of only one of them.

The second major aspect of leadership is its ability to deal with the residual of uninsurable risk. This is precisely the function of the "entrepreneur" in Knight's famous 1921 book. Of course, a new Generation III+ nuclear power project is too large even for the most buccaneering of entrepreneurs. This is why the discussion of leadership in this context must be slightly more nuanced. While the project leader in a nuclear new build project will not personally assume all risks and rewards of a project, they will need to be trusted to be able to mobilise private or public resources as well as to draw on a network of financiers, public figures and major suppliers in the case that "tail risk" materialises, i.e. when new, unforeseen and unforeseeable circumstances arise that are not covered by existing hedging arrangements.

The leader needs to be, or needs to have a direct link with, the "project owner". There are different manners of expressing such a state of affairs. "The buck stops here," is an oft-invoked phrase in such contexts. Unfortunately, it is sometimes employed in a manner that can imply uncommitted grandstanding. Its deeper meaning is precisely that at this very point monetary trading relations cease and responsibility is exerted in a more vertical manner. Being the leader or the project owner implies that all residual, non-diversifiable, i.e. non-insurable, risks reside with you.

This may include not only the responsibility for assuming the costs of those non-diversifiable risks but also a responsibility for managing them, akin to the board of a public company. For instance, it is possible to make the case that in the construction of two new AP1000 reactors at Plant Vogtle in Georgia, the Southern Company, as the ultimate project owner, should have stepped up far earlier to sort out, or rather cut through, the complicated web of non-aligned contractual commitments, informational asymmetries and incentive incompatibilities between stakeholders that had hampered construction and increased cost.

Being the leader or the project owner responsible for covering all non-insurable risks thus sounds like a thankless task. This is untrue. Indeed, a project owner is also entitled to the residual benefits or rents of a unique project. In a period of rising electricity demand but increasingly severe constraints on carbon emissions, these benefits can be substantial for a producer of reliable low-carbon baseload electricity. The size of the non-diversifiable, and hence not precisely monetisable, risks directly result from a project's unique nature and hence its ability to generate unique benefits, gains and profits. Non-diversifiable risk thus comes with the territory. "If you want to get rid of all the risk, the project is not worth doing" (Milt Kaplan, 2023, personal communication).

Managing the balance right between uncertainty on the cost side and uncertainty on the benefits side is the task of the project owner. This is the classic task of the entrepreneur. Once more it holds true that risk and financing costs are an output of projects not (only) an input. The impact of good management on financing costs is magnified by the fact that each project has spillovers that affect all future projects. It used to be said that "a nuclear accident anywhere is an accident everywhere" in order to highlight the importance of reputational externalities. This also extends to the performance of nuclear construction projects. A successful new build project in an OECD country, completed on time and on budget, would greatly reassure investors in all other countries. Of course, there are also management lessons to be learnt from successful projects. For the time being, investors are still waiting. There are successful major refurbishment projects in OECD countries, e.g. in Canada, and there is successful nuclear new build outside the OECD area, e.g. in the United Arab Emirates. There also has been in the early-2000s highly successful new build of Generation III+ ABW reactors in Japan. More recent experiences with nuclear new build in OECD countries have, however, been more mitigated. Stakeholders are hoping that soon new Generation III+ nuclear reactors will also be successfully realised in the OECD countries engaged in or committed to major nuclear new build projects, such as Czechia, France, Poland, Sweden or the United Kingdom.

Independent project advisory

The preceding paragraphs have insisted on the two crucial tasks of the leader of a nuclear new build project, which are managing the myriad bilateral and multilateral relationships of a large undertaking with a focus on the successful completion of the overall project and assuming any non-insurable risks. However, a good leader will be aware of the limits of their authority and their ability to withstand adverse impacts. In the nuclear sector, the external limits imposed on exercising project leadership are especially severe. Compliance with nuclear safety requirements is of paramount concern and a constant challenge that comes in addition to satisfying more general legal conditions such as labour laws, environmental regulations or corporate governance standards.

In this situation, it can be helpful or even necessary for project leadership to delegate some of its authority to a third party that will exercise independent project oversight. This third party might be an experienced project operator with nuclear expertise or an industrial mediator. Crucially, this trusted third party has no stake in the outcome of the project itself but will work on a fixed commission. Its role is again twofold. First, it will advise the project leadership on overall management issues; second, it will intervene in dispute resolution between the project leadership and major outside stakeholders such as tier one suppliers, the nuclear safety authority or the national government. In short, the task of the independent project advisor is to minimise transaction costs and to anticipate, prevent and manage conflicts.

Advising the project leadership will include having a second look at the project structure, the organisational chart, the allocation of responsibilities and the likely performance of incentive structures (see below). The independent project adviser will most likely also intervene in crisis management and in checking the communications strategy. Dispute resolution is the second major task of the independent project advisor. Here they will be required to assume the role of trusted third party with no stake in the project outcome in order to resolve conflict situations between major stakeholders. It has been said before: all contracts are incomplete. The higher up the chain of command and decision making, the more incomplete the contracts will be. Conflicts of interest will thus be inevitable.

At lower levels of the organisational hierarchy, where tasks are reasonably well-defined, contracts and legal procedures are more effective. It is a matter of legal cultures and relative costs to what extent a systematic internal conflict resolution mechanism can add value.

However, it is at the level of the project leadership and major stakeholders, where conflicts can amount to wasteful multi-year uncertainty affecting the whole project, where an independent project advisory is of the greatest value. The high-profile disputes surrounding the Flamanville, Olkiluoto and Vogtle projects have been damaging to all parties. Here it would have been useful to have an independent project advisor in place from the start, with direct access to project leadership, a privilege that must of course be used with discretion, and invested with the authority to convene major stakeholders at crucial junctions. Hopefully, future nuclear new build projects will take the lessons from previous projects into account.

There is one additional issue to be taken account of when considering the question of project leadership, the ability to absorb uninsurable risks and independent project advisory: the role of government. Of course, the role of government is highly dependent on institutional, cultural and political determinants. Nevertheless, to the extent that electricity consumers or the general public assume, wholly or partly, the costs of any residual risks, e.g. through mechanisms such as RAB or direct public financing, it is indeed the public or its agent, the government, possibly by way of a public company, that is the ultimate project owner. What about leadership in this case?

The general argument still applies. To the extent that society carries the construction risks, it should also have an appropriate role in project oversight. As the ultimate owner of the project, government will need to take leadership. This does not mean that technical construction issues need to be decided in ministries; however, building on time and on budget must be a matter of concern at the highest political level. The ultimate responsibility in this case must lie with the energy minister or even the head of state. This was largely the case during the successful start of the French nuclear programme in the 1970s (see Chapter 4).

Incentives

This leaves as the third building block in this section the decisive question of incentives and their compatibility. According to theory, competition, the profit motive and the rule of law will align the incentives of each individual with those of larger sets of actors, whether in a bilateral transaction, a complex construction project or the economy as a whole. Crucially, the effect of the "invisible hand" depends on the assumption of an absence of transaction costs and perfect information. For routine transactions, especially repeat transactions, in which goods and services can be fully specified, minor deviations do not matter.

Transaction costs and asymmetric information, however, play a large role in megaprojects beyond the building of a new nuclear power plant. Indeed, the following remarks are not unique to nuclear new build. They are, however, particularly relevant here due to the complexity, uncertainty and length of the projects. The gap between what can be codified in advance in a contractual document and the reality on the ground is therefore particularly large. Frictions between different parties thus go far beyond the usual elements of information gathering and the costs of negotiating and concluding contracts. This is due to the technical complexity of the projects, the fact that certain elements may have to be redesigned following requests from national regulators, quality control issues at all levels of the value chain – the list of issues for exploiting informational asymmetries, e.g. the precise composition of a module or its manner of manufacture, is very long. The fact that even long contracts drawn up by specialised lawyers could not cover all contingencies between cost-cutting suppliers and inflexible project managers has already been alluded to several times. Even if complete contracts were possible, their enforcement would impose significant transaction costs.

This gives rise to "moral hazard", a particular form of a principal-agent problem, when somebody who employs a supplier or an agent can only imperfectly control what they are doing and will know about the results of their work only after the conclusion of the contract. The agent can thus take risks or cut corners without suffering the consequences, as they are exploiting the room for manoeuvre of a contract that is incomplete, partly due to the asymmetries of information mentioned above. An oft-cited example of moral hazard is the performance of a chief executive employed by shareholders to maximise their wealth. For instance, the chief executive might be tempted to go for short-term growth and prestige rather than for long-term profit maximisation. A broad literature has studied the design of contracts in this area, all of them imperfect, but many being built around the concept of deferred share options, to align the incentives of "principals" and "agents".

Developing such complex contracts with difficult-to-elicit metrics and delays to full payment would be impractical in a large construction project, which in such a case would employ more lawyers than engineers. Careful thinking about incentive compatibility is thus all the more important and there are indeed a few basic principles whose respect can at least protect a lower bound for efficiency in project management.

Transaction cost considerations may be taken to imply that nuclear new build projects are best undertaken by vertically integrated entities, where issues of market transaction costs do not arise. This may or may not be the case. It is true that short-term market-based contractual relationships can be substituted by hierarchical relationships based on long-term contracts. The latter can leave time for the establishment of authority, trust and the delegation of responsibility, as well as an implicit understanding, sometimes referred to as institutional knowledge, of how to deal with non-codified or even non-codifiable tasks.

However, hierarchies have their own shortcomings. Establishing long-term routines may be comforting and stabilising but is not conducive to rapid innovation. Abuses of hierarchical power are as widespread as abuses of market power. Complexity and uncertainty offer ample opportunities for gaming, exploiting asymmetries of information and rent seeking also between parties nominally working for the same organisation. The optimal organisational model that will arbitrage correctly between markets and hierarchies, the title of a book by Williamson (Williamson, 1975), will result from environmental, institutional and cultural factors as much as from the concrete technical and informational challenges facing the project team.

A critical element in this mix of vertically integrated entities and market transactions is the design of appropriate contracts, both long-term and short-term, that align the legitimate, but diverging, interests of all individual parties with the overarching need to deliver the project on time and on budget. Achieving such compatibility of incentives goes beyond breaking down the projects into codifiable parts and spelling out the obligations. Parties can fully perform to their contractual duties and still not contribute to the overall effort in an optimal manner. An employee hired on a fixed-term contract may fulfil that contract but may not go the extra mile as he or she has no stake in the final project outcome. Contractors may fulfil verifiable milestones but disregard the question how their module slots in with the overall project. It can be said that in those cases contracts were incorrectly specified or incomplete. But as indicated, this will inevitably happen, as it is impossible to codify all contingencies in advance. Below are listed several items that can be integrated in contract design in a general manner to improve the overall alignment of incentives.

First, it is always good to provide and share information and proceed in a transparent manner that is easy to comprehend. On this the theorists are right: incentive misalignments are only the result of frictions or transaction costs in the market. Otherwise, each individual would have an incentive to help grow the overall pie. If negotiations are costless and all the facts on the table, a larger pie will allow everybody to get a bigger piece. Of course, negotiations are costly and information is not free. However, reducing those frictions by simple contracts, a culture of openness and transparency will also in itself reduce the issue of incentive alignment. Excessive legalisation, insistence on intellectual property rights protection as a matter of course rather than of discernment and a culture of secrecy and distrust will certainly increase incentive misalignment.

Of course, much more can be done. Bertolini (2012) provides a brief and readable introduction to co-ordination failures when private incentives do not lead to the optimal overall outcome and provides some indications for how to tackle them, mainly in the context of public projects, though the results are general. He emphasises in particular that weak or moderate misalignments require different measures than strong misalignments of preferences or incentives. The distinction between a moderate and a strong misalignment is defined by the size of the additional individual payoff that can be gained by deviating from behaviour that maximises project success, i.e. the sum of all individual payoffs.

Moderate misalignments can be remediated by information provision, social norms (communication of past behaviour) and repeat interactions (see above); there is no need for enforcement and penalties. Strong misalignments do require the formulation of binding constraints, enforcement and penalties in case of non-compliance. The partners would also need to invest in proving their credibility. Repeat interactions would only solve the problem if the number of repetitions was infinite. Interestingly, with moderate misalignments, a one-shot monetary incentive can induce sustained co-operation in a logic of nudging. This is not the case with strong misalignments. Incentive would need to be permanent, i.e. the total relative payoffs would need to be changed. He summarises that "the fundamental trade-off credibility vs. flexibility can be solved in favour of flexibility the more objectives of the involved players are aligned" (Bertolini, 2012: p. 13).

What results from this cursory overview is that activities where the gains from deviation are large and where it is difficult to monitor and enforce, say, the quality of major forgings or major construction works according to nuclear specifications, should be vertically integrated. The lower the potential gains from deviating from a line that would contribute to project success, the less stringent the oversight needs to be. This may sound like re-stating the obvious. However, many nuclear construction projects would gain by implementing these simple considerations in a systematic fashion.

The challenge is each time to align individual interests with the overall project. Sometimes the obvious is also the optimal. A good salary, a quality social package and long-term commitment by employers, the equivalent of a repeat transaction, will be sufficient to foster interest in the success of the institution. A high-powered instrument of aligning incentives further is to pay a share of either contractual payments or salaries in the form of nested bonuses, the equivalent to the monetary incentives mentioned earlier, at the level of the individual, the team and the overall project. This is an instrument frequently practised in the financial sector, which also repeats in a simplified form the structure of the executive contracts designed to overcome moral hazard. To some extent, it is easier to implement in the financial sector than elsewhere, as the metric of success – monetary profit – is unequivocal at each level. In a nuclear new build project, real resources would need to be dedicated to the establishment of an infrastructure of performance metrics. However, the experience with the successful construction at the Kashiwazaki-Kariwa and Shimane power plants in Japan, where such nested bonuses were successfully applied, shows that establishing such an informational infrastructure is money well spent.

Paying attention to incentives in a clear-headed manner, free from moral exhortations or declarations of political voluntarism, is always necessary for successful project management. This also regards the allocation of financial risks. NEA work during 2024 on financing has underlined how important this allocation is for the costs and benefits of different stakeholders. It has been argued, with good reason, that in particular the construction risk of nuclear new build projects requires some form of socialisation as the uninsurable tail risk of low-probability but high-impact events is too high for a single corporate entity to bear. This is true enough. Yet downside risk can also be a powerful incentive for efficient project management. Guaranteed protection of the project operator against all financial risks, or even against all risks beyond a certain threshold, will not make for efficient management and cost minimisation. Any rational agent would race to reach the threshold as quickly as possible. Allowing work to be carried out under a soft budget constraint is inviting inefficiency. It is necessary to keep in mind that costs and their overruns are not just regrettable inconveniences; the ability to roll over costs makes life easier on a daily level for decision makers, who can work with content employees, happy suppliers and eager consultants. It is thus crucial that all parties have a stake in the project and its outcome all throughout the project.

Keeping the balance between incentivising actors, making sure that these incentives align with overall project success and working with sustainable risk allocation is thus one of the key tasks, if not the key task, of the project leader, which may be a national government or its delegate. The project leader can be assisted in this task by building a culture that "incentivises success" through targets that are scalable, repeatable and realistic, in addition to being widely communicated. Such a culture is most easily created in a context where bonus payments are linked to fulfilling said targets. Honesty and transparency must be rewarded at every step. There can be no punishing of or indifference to the bearers of bad news.

Flaws will be found, conflicts will arise, even in corporate environments with carefully developed incentive structures. Anticipating this, remediation procedures must be in place at every corporate level and at every step of the way. “Collaborative contracting” is the concept that has been developed to better manage such competing demands (Banaszak et al., 2020). This would involve careful pre-project preparation that involves all major suppliers, can further anticipate points of tension and provides an indication of the room for manoeuvre of each party. It would also involve no fault-contracting, i.e. the common commitment to forego legal action between project parties, assuring everybody that there is a limit to legal liabilities. Needless to say, guaranteeing beforehand protection from all possible liabilities would again not provide the right incentives, even if the underlying idea has merit.

In conclusion, together with the provision of leadership and the creation of an independent project advisory, the creation of a set of coherent incentives is key to successful project management. These incentives will be crucial to delivering new Generation III+ reactors in OECD and NEA countries at a scale that makes it possible to provide the large amounts of low-carbon electricity and heat needed to reduce global carbon emissions.

Chapter 6. Special topic: How and when to involve the private sector in the financing of nuclear new build

To minimise the costs of financing nuclear new build, project operators and political decision makers need to draw on the widest possible pool of potential investors. As set out in NEA (2022), in a comprehensively de-risked political and economic environment with a credible commitment to achieving significant cuts in greenhouse gas emissions, a willingness to spread the risks of construction widely coupled with guarantees of long-term price stability, investing in nuclear new build even at relatively low rates of return will be attractive also for private sector investors. In practice, there might be limits to this argument due to doubts about the seriousness and stability of government commitments, asymmetries of information or inertia and herd behaviour on the part of private investors. The bankruptcy risk of private investors, which is higher than that of public investors that can rely on their ability to tax citizens, will also induce them to seek higher returns.[1] In other words, even when nuclear new build projects are comprehensively de-risked, the rates of return required by private investors are likely to remain higher than the borrowing costs of central government, which correspond to the risk-free rate plus the relevant country risk premium.

If this line of reasoning is accepted, the question of private sector involvement in the financing of new nuclear power plants arises in a new light. If even under the most comprehensively imaginable de-risking, public sector financing can be arranged at lower rates than private sector financing, then why bother with the latter? This is, of course, a question that goes to the heart not only of the financing of nuclear new build but of market economics in general. For market economics in general, the answer is relatively simple. The efficiency gains, cost reductions and utility improvements through innovation due to the benefits of private competition outweigh any considerations of financing costs. *Laissez-nous faire*, the legitimacy of market economics rests on its ability to harness the intellectual and motivational resources of private individuals investing their own capital and, at least in theory, fully taking on all risks, all potential benefits and losses.

This general reasoning, however convincing, does not yet apply to nuclear new build. For a brief period in the early years of the 21st century, there was hope and even expectation that the building of "merchant nuclear power plants" could be kick-started by limited government subsidies in order to evolve over time into a self-sustaining industrial activity. In the United States, this hope materialised in the 2005 Energy Policy Act, which offered loan guarantees and production tax credits for the first new Generation III+ nuclear power plants. If the US Energy Policy Act was the most comprehensive attempt, other OECD countries similarly anticipated and prepared for a market-based "nuclear resurgence".

1. A counterargument to this point is that specific investments, such as participating in the construction of a nuclear power plant whose financing has been systematically derisked could always be "sanctuarised". This would mean that in the case of a corporate bankruptcy, the nuclear investment could be sold on at its full value. In other words, bankruptcy risk should not influence the rates at which private investors are willing to allocate their capital in such projects. In practice, however, complex corporate structures, in which individual investments are judged not only on their own merits but also on their contribution to broader corporate performance, transaction costs (including costs for high-priced financial analysts, accountants and lawyers) and asymmetries of information, limit the relevance of this counterargument.

The reasons why things did not work out as planned are complex but involve the absence of sufficiently stabilised and detailed reactor designs, the realisation of the magnitude of long-term price risks in newly deregulated electricity markets, cost declines in wind and solar PV capacity, the shale gas revolution and, eventually, the Fukushima Daiichi accident. That the expectations connected with the 2005 legislative package were not entirely unrealistic is nevertheless validated by the large number of serious projects. Applications for loan guarantees were filed for projects with altogether 18 reactors, of which only four - two at Vogtle, Georgia (completed), and two at Summer, South Carolina (later abandoned) - eventually advanced towards construction (World Nuclear Association, 2024).

Twenty years later, experience suggests that even in the market economies of OECD countries the construction of large Generation III+ nuclear power plants for the generation of low-carbon electricity will not take off without substantive public involvement. Indeed, such involvement would not only need to include framework setting with regard to climate policy and electricity market design but would also require the comprehensive socialisation of construction and financing risk.[2] The justification for such wide-ranging public involvement would lie in the public benefits of nuclear power at the level of both the electricity and the energy systems. At the level of the electricity system, nuclear energy as a dispatchable source of power provides the low-carbon baseload electricity required to complement the variable output of wind and solar PV, the only cost-effective renewable sources of electricity other than hydroelectricity, which is dependent on geography. At the level of the energy system, nuclear energy is a source of electricity that is, or can be, largely based on domestic resources and thus offers a high security of supply. This is important for the realisation of ambitious strategies to electrify the provision of heat and motive power.[3] The benefits of nuclear energy for the security of supply even extend to nuclear fuel. While natural uranium can be found in large quantities in only a small number of OECD countries, it can be stored easily and at little cost and its global resource base is widely distributed.

In the low-carbon electricity and energy systems of the near future, nuclear energy is thus likely to fulfil a double function of baseload generation and, alongside other actors, flexibility provision as a supplier of last resort. The difference between nuclear energy and other currently available flexibility providers is that the latter are currently cost-effective only up to the level of a few hours and cannot be used over longer periods, in particular weekly or seasonal variations. As an electricity provider of last resort, nuclear energy thus assumes a role that is comparable to that of public infrastructure like transmission networks and distribution systems.

The extent to which nuclear energy must be considered part of a low-carbon infrastructure and to which it must be considered a technology in competition with other low-carbon generators will depend also on its relative share of the generation mix. In all cases, however, the relative costs of electricity generators and flexibility providers will need to be assessed

2. This report is concerned with the conditions for the successful construction of large Generation III+ reactors for electricity generation. There is considerable hope that the private sector will be able to finance autonomously a much larger portion of the costs and the risks of development and construction of a new generation of small modular reactors (SMRs) with a broader value proposition, in particular in heat generation and the treatment of nuclear wastes. As far as the development phase is concerned, the *NEA Small Modular Reactor Dashboard: Second Edition* (2024) lists 56 designs that are making active progress towards construction or are under construction (NEA, 2024b). Work on the vast majority of these designs is indeed privately funded. However, progressing from design to construction will require a scaling of investment of at least an order of magnitude. SMRs currently under construction in Argentina, China, Japan, Korea and Russia thus all benefit from varying forms of public support.
3. The extent to which the construction of new nuclear power plants should be undertaken primarily with the help of domestic supply chains or instead rely on a global division of labour is not a question dealt with in the present context. Suffice it to say that individual countries will develop different answers to these questions according to considerations of security of energy supply but also of industrial policy, the size of their nuclear programmes, the availability of specialised domestic suppliers and skills and so on. Undoubtedly, both at the global level and at the level of OECD countries, substantive capacity for all elements of the value chain of nuclear new build is commercially available (WNA, 2023). However, this fact will be weighed differently by different countries.

systematically at the system level and not at the plant level. This system value of nuclear energy will include the option value of its availability. While on this count nuclear energy is again in competition with other capacity providers, all of them have different strengths and weaknesses over different time horizons and under different circumstances. As already pointed out in Chapter 3, long-term system planning that assigns a determinate role to each component is an integral part of future low-carbon electricity systems.

From these two considerations, that nuclear capacity is an indispensable part of the infrastructure of low-carbon electricity systems, and that public investors will always have lower financing costs than private investors, arises a fundamental question: Why should governments be concerned at all about involving private investors? Why not go ahead and finance nuclear like other public infrastructures straightforwardly through taxes? The remainder of this chapter will outline first why it remains beneficial to involve private investors in nuclear new build projects and second how such involvement is best operated in order to maximise the complementarities of the public and private sectors.

Why private sector involvement in the financing of new nuclear power plants remains desirable

No private investor will ever be able to provide financing on terms that are more favourable than those of government or government-backed public institutions. The value of private investment is realised through cost reductions and innovation in competitive markets, where efficient firms thrive and inefficient firms close, a process that Schumpeter famously referred to as “creative destruction”. As indicated above, this otherwise highly desirable property of private investment cannot, or not yet, be realised in the nuclear energy sector. Projects are too large and too far between to allow for the indispensable process of trial and error that is required to yield the desired efficiency improvement. In addition, as mentioned repeatedly, the construction of a new nuclear power plant is subject to large uninsurable risks.

The fact that risks are uninsurable is not *per se* an argument against private sector participation. Indeed, according to Knight (1921), the very function of the entrepreneur is to assume uninsurable risks. “If you want to get rid of all the risk, the project is not worth doing,” (Milt Kaplan, 2023, private communication).” However, the otherwise irrepressible zeal of the entrepreneur will be stunted in the case of nuclear new build for two reasons. First, the uninsurable risks are so large that a single project could bankrupt the company, even if it is a well-capitalised major corporation. This might be a step too far even for the most risk-loving entrepreneur. Second, in a nuclear new build project, the entrepreneur, even if they were able to arrange the full amount of required financing with private investors, would not be the sole decision maker in advancing a complex industrial project to completion. Nuclear safety regulators, environmental NGOs and public officials, for reasons of energy security, proliferation concerns and industrial policy, will all seek to have a say in the organisation of the project.

Of course, all these stakeholders do so for good reasons and as part of a complex web of implicit or explicit trade-offs regarding risks, costs and managerial autonomy. For instance, the Paris Convention on Third Party Liability in the Field of Nuclear Energy allows national governments to provide cover for the liabilities that would arise from a nuclear accident and that would exceed the amount of EUR 700 million (see NEA, n.d.). In a sense, this socialisation of a potentially substantial portion of the risks of a nuclear accident can be seen as a quid pro quo for the strict oversight exerted in matters of nuclear safety and the added costs resulting from that oversight. Similar arguments could be constructed regarding oversight in the areas of energy security and proliferation. Listening to and engaging with environmental NGOs is part of obtaining the indispensable “social licence” required by any nuclear new build project. However, the cited examples make obvious that the archetypical figure of the swashbuckling entrepreneur who bends reality to their will and who, in other contexts, has become associated with the saying “move fast and break things”, will not be easily associated with a nuclear new build project.

So why would private investors still be interested in participating in a nuclear new build project? The answer on an abstract level is simple: because government or public entities will offer them a risk-reward trade-off that is worth taking. In practice, this will mean that private investors are fully protected against construction risks with financing rates that are, due to the particularities of the nuclear sector, somewhat higher than for investments in lower-risk projects. That leaves the question of why governments would be interested in attracting private investors in a nuclear new build project at costs higher than their own borrowing costs. There are essentially four reasons why it is worth attracting private investors:

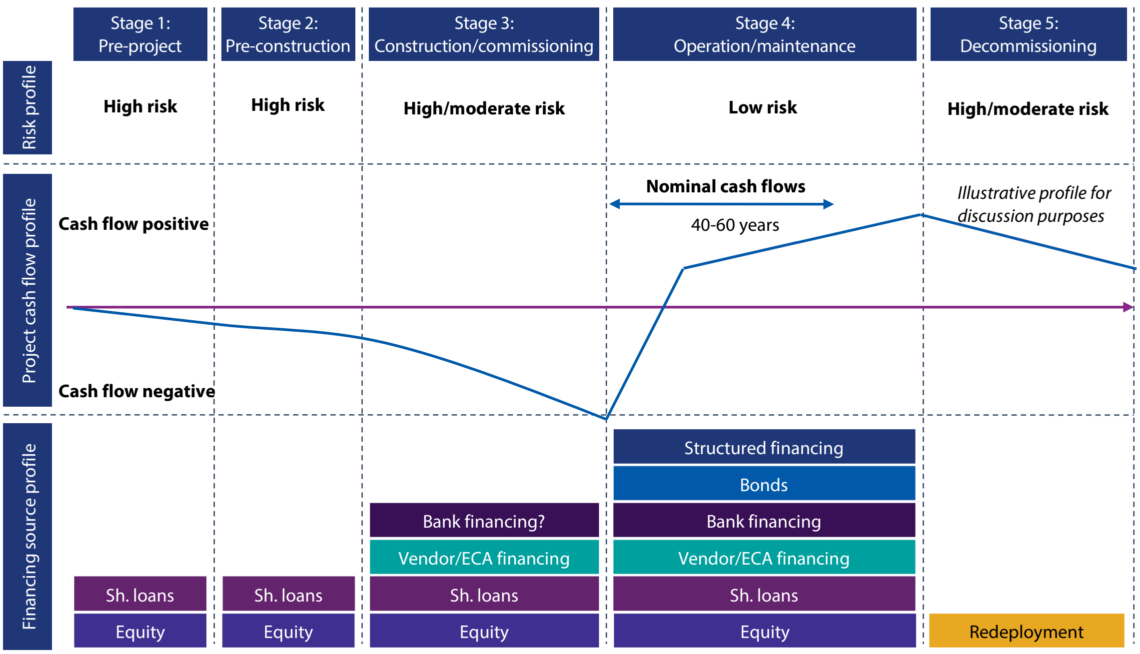
- First, the participation of private investors is an important signal that a nuclear new build project has obtained its "social licence" and that nuclear power plants constitute an investable asset class. Such participation shows that the project is validated as an industrial project, where those involved do not run any reputational risks.
- Second, if public involvement, commitment and oversight remain indispensable, the private sector has much to offer in terms of know-how in project management, contract design and in achieving cost reductions. Increasingly, financiers also understand that they need be more engaged in due diligence and project management. Private investment thus drives cost control and project delivery. Private sector engagement will be strengthened if:
  - there exists a contractual provision for a top-up to private sector returns in case projects are delivered on time and budget; and
  - private investors have direct access to project leadership during construction, in which case they provide an additional form of project oversight.
- Third, private investment in a nuclear new build project during the construction phase is an entry into the gradual transfer of ownership from the public to the private sector (see next section). A working nuclear power plant is a formidable industrial asset whose financial risks, due to volatile prices and demand, even if considerable, can and should be borne by experienced private investors. This does not yet hold true for construction risk. Anticipating the eventual transfer of the project from public to private hands should begin at the start of construction and culminate at the date of commissioning. At neither moment is exclusive public or private ownership required, but the evolution should clearly proceed from the former to the latter.
- Fourth, private sector investment allows governments to keep some of the costs of financing new nuclear power plants off its balance sheet. This holds true even if it insures private investors against project completion risk. Minimising the exposure of public accounts to debt stemming from nuclear new build has obvious benefits in terms of overall public debt metrics and the financial ratings of national debt, especially if a programme with multiple reactor projects is planned. Needless to say, transferring debt does not make it go away. In theory, transferring it to private investors would decrease the latter's ratings. It is, however, the task of specialised financial advisors to optimise the allocation of debt by choosing the entity best placed to carry it, in a manner that minimises the overall cost of debt. All other things being equal, sharing risks between public and private entities is a promising strategy, even if details must be worked out diligently in each case.

Private investors are therefore essential in the financing of nuclear new build projects and not because they would be able to offer funds at rates lower than public investors. Instead, the contribution of the private sector is essential for driving the social and political validation of a project as well as its industrial delivery. Its role would be to bring financing costs down not as an input to the project but as an output of successful project management. Clearly, government, as the ultimate underwriter of risks, must retain a sizeable share in project ownership alongside private investors during the construction phase. However, the share of public equity should decrease over the project cycle, while that of private sector investors should increase. The rhythm of this gradual evolution from a majority of public ownership to a majority of private ownership is discussed more systematically in the next section.

When and how to attract private investment into a nuclear new build project

The life cycle of a new nuclear power plant has two distinct phases, construction and operation, that have very different risk profiles from an investor's point of view. In principle, this life cycle contains a third phase, the one of decommissioning and radioactive waste management (RWM). However, this phase of less immediate concern to investors as the financial risks are limited. First, the costs of decommissioning and RWM will come due only in a future, which can be as far away as 80 years or more, which reduces their present value even at modest discount rates. Second, while the costs of decommissioning and radioactive waste disposal may be uncertain, they are covered in most OECD countries by fixed and stable contributions per MWh of electricity sold, with governments assuming the responsibility for any shortfalls (see NEA, 2021).

Figure 6.1. **Different stages of the project life cycle of a nuclear new build project present financial risks of very different magnitudes***



* Contrary to what is indicated in the text above, Gupta (2023) considers the financial risk during the decommissioning phase "high/moderate" rather than "low". This regards the variability of the absolute costs of decommissioning and hence the need for publicly financed backstops. These, however, do already exist in the majority of OECD countries. Decommissioning thus does not contribute significantly to ultimate investor risk (see NEA, 2021).

Source: Gupta, 2023, p. 8.

Financial risks during the two phases of construction and operations thus differ widely. Financing risk during construction closely interacts with project management, while financing risk during operations will be closely related to market design. Previous chapters have commented on both. The decisive difference between the two phases is that if financial risks exist during both phases, they are considerably higher during the construction phase than during the operations phase. In particular, market risk during operations, while sizeable, can to some extent be measured and anticipated and thus traded and hedged. Construction risk, at the current state of industry development and maturity of Generation III reactor construction, remains a form of uncertainty that cannot be expressed in well-behaved probability functions. Currently, construction risk cannot be hedged on private markets for risk and insurance and any attempts to do so would be prohibitively expensive.

In fact, the financial risks during construction and operations differ so strongly that during construction and up to the date of commissioning, building a new nuclear power plant is a high-risk project; during operations, from the date of commissioning onward, a working nuclear power plant is a low-risk project. Licensed and operating nuclear power plants are usually reliable generators of profit, even if not always at the desired level or even the necessary level to repay investment costs. However, operating profit stays positive in the vast majority of cases. A long list of abandoned projects instead testifies to the reality of construction risk. Until the advent of the shale gas revolution in the United States, it could even be said that nobody ever lost money on a working nuclear power plant (see Figure 6.1, which associates different stages of the project life cycle with different levels of financial risk from the point of view of an infrastructure investor).

This does not mean that the operational stage is devoid of risk. The operators of a nuclear power plant are subject both to price risk, the risk of earning lower average revenue per MWh than projected, and to quantity risk, the risk of being unable to sell their electricity due to the fact that wind and solar PV generators with zero short-run marginal cost cover the totality of demand during a significant number of hours. Recent years have seen long-term price risks materialise both in the United States electricity markets, primarily due to the arrival of low-cost shale gas and out-of-market production tax credits, and in European ones, primarily due to the introduction of large amounts of wind and solar PV capacity into markets that were essentially in equilibrium. As renewable capacity benefitted from guaranteed feed-in tariffs (FIT), their profitability was unaffected by the resulting price decline, which lasted until the one-off spike in gas and electricity prices in 2021 and 2022.

As far as quantity risk is concerned, the number of hours during which variable renewables will cover the totality of demand is likely to increase further in the future. However, the marginal increase of such zero-dispatchable generation hours as a function of each added GW of variable renewable energies (VRE) capacity will decline rapidly. This is due to the autocorrelation effect (see NEA, 2024b: p. 11 and p. 20). Since also new VRE capacity will only generate during the hours during which the existing capacity operates, new capacity will primarily increase the surplus during already existing dispatchable generation hours rather that increase the number of hours during which this happens. In any case, these are effects that can be – within some range of uncertainty, of course – estimated in anticipation. They might thus affect the amount that investors would be willing to disburse in order to acquire the rights to the output of a nuclear power plant. They do not imply *per se* an inability, notably for private investors, to assess and to assume price and quantity risk.

Thus, while there is currently a need to socialise construction risk, this does not hold for operational risk. The optimal and cost-minimising financing of nuclear new build projects needs to reflect the changing level of risk over the life cycle of a nuclear power plant. What is required is a *dynamic* approach to the financing of new Generation III plants. This means that the shares of public and private ownership over the project life cycle will change at predefined intervals. These intervals could be set according to agreed project milestones such as first concrete, completion of excavation, completion of the reactor base, installation of the reactor pressure vessel, completion of the coolant system, installation of instrumentation and control systems, fuel loading and commissioning. At each interval, private actors would assume a greater share of the financing and ownership as the project progresses and the predefined milestone has been attained.

It is important that the conditions and timing for this incremental transfer of ownership to private investors be agreed *before* first cement is poured. Only in this manner will private investors be fully committed to the project, while the government remains liable for construction risk, at least during the riskiest phases. This risk includes the financial costs of design changes, budget overruns, faulty suppliers, increases in labour cost, sub-optimal project management or legal delays, to name just a few.

Arrangements that anticipate dynamic refinancing during the construction phase during which governments or public entities would incrementally transfer their share in project ownership to the private sector would require investment in advance planning and contract formulation until the moment, typically the date of commissioning, when the handover is completed. Depending on the accounting conventions under which the project is undertaken, such arrangements could also ensure that governments do not need to carry the full costs of a new power plant on their balance sheet but only the construction risk as such. This would undoubtedly remain a sizeable risk requiring considerable provisions, but it would not include the cost of the de-risked nuclear plant as such.

Box 6.1. **Involving the private sector in Poland: The SaHo Model**

The SaHo Model is based upon co-operative models that have been employed for more than a century in the power sector, involving Polish industrial auto-producers of electricity, US co-operatives or generators operating under the Finnish Mankala model. The main idea of the SaHo Model is to allocate the risk that characterises a nuclear project to the entity that is willing and able to bear it in order to have the nuclear power plant built and low-cost low-carbon electricity delivered to consumers. Assuming the risk during different phases of the project should be linked to the interests and goals of investors.

In the basic concept of the SaHo Model, the state takes on the role of initial investor, being the sole owner of the enterprise. As owner, it is responsible for the pre-construction process, financing (the SaHo Model does not determine the capital structure), the organisation of investment and other business matters of the company. The initially high risk of the nuclear project decreases as the project progresses to a level that is acceptable to private entities. Before grid connection, the state gradually sells all shares to final investors, i.e. electricity consumers, willing and able to offtake the energy to satisfy their own needs. Part-ownership implies the right and the obligation to offtake the energy produced by a nuclear power plant under the SaHo Model, proportionally to the ownership share at the cost of production. Acquiring a share of ownership, final investors acquire the right to receive low-cost energy and the state – selling its share – raises funds needed to support, for instance, the construction of another nuclear unit or other public investments.

Final investors may be electricity consumers of many types: the manufacturing industry, especially in energy-intensive sectors, transportation (railways), entities controlled by local governments, public entities such as hospitals or military bases, households (through dedicated energy co-operatives) or others.

Since the share price of the SaHo nuclear power company is expected to rise as the project progresses and the risk decreases, there may be some private entities interested in participating in the nuclear power plant project (already during the construction phase), having the prospect of future benefits in the form of low-cost energy in mind (after the grid connection). Even without the prospect of gaining access to low-carbon electricity at stable costs, investors may decide to benefit financially by buying and selling shares of the company at different moments of the project cycle before grid connection There are only two conditions for such transfers of ownership: the risk level and the corresponding price must be acceptable for both the buy and the sell side. Thus, certain variants of the SaHo Model include private financial investors.

There is therefore a role in nuclear power plants built under the SaHo Model for both consumers, in particular large industrial consumers, and financial investors, especially as minority investors, alongside the state as majority shareholder. Financial institutions acting as intermediaries may even create something akin to a private market for ownership shares. Such securities may be very attractive for intermediate investors since the investment horizon depends on them and they may benefit from the differences in prices of shares over time of the SaHo nuclear power plant company. The SaHo Model can be adapted to intermediate investors as well as to private initial investors. Part of the shares may be also traded on the stock exchange until the moment of grid connection. Shareholders able and willing to offtake the electricity would not have to sell them before this moment either as a financial asset or as a right to receive a certain amount of electricity at costs. In reality, to attract a range of private investors, a combination of the above-mentioned ideas and specific conditions of the project should be assessed, proposed and applied as appropriate.

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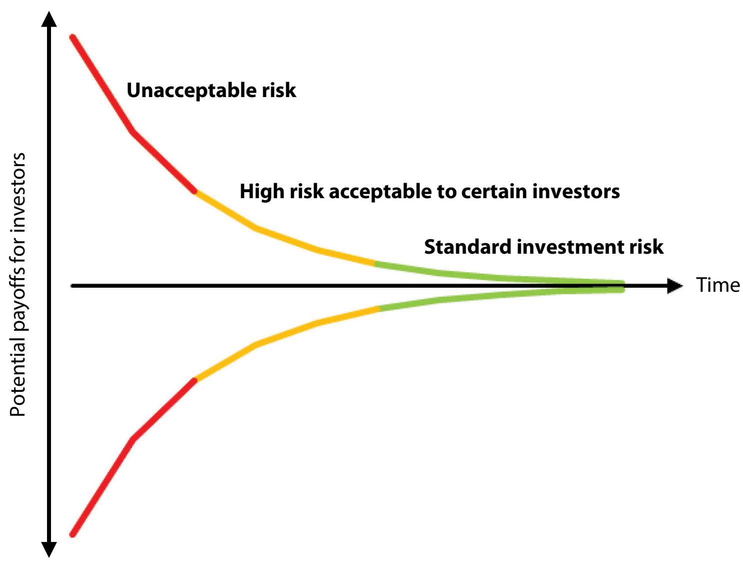
Many variants of the timing and conditions for such dynamic refinancing can be developed, reflecting the risk profiles and ability to generate financing of the different stakeholders. The concept of dynamic refinancing, in function of the decreasing level of completion risk as construction advances and the risk management abilities and risk preferences of public and private investors, is now being discussed regularly among project operators and financiers. Chances are that forthcoming nuclear new build projects will begin to integrate elements of an increasing role for private sector finance as the project progresses. A key element is, of course, the definition of the milestones and the conditions under which they can be considered to be achieved. An early model of such dynamic refinancing kind was proposed in Sawicki and Horbaczewska (2021) for the Polish context (see Box 6.1).

The SaHo Model has been developed in the context of the Polish nuclear power programme. If the idea of dynamic refinancing during the project cycle, which is contractually agreed before first concrete and sees governments gradually sell their project shares to private investors, is general, there can be national or even local specificities. Different investor groups, e.g. equity or debt investors, private equity companies or pension funds with different risk appetites, will be interested at different moments of the project cycle. The key insight here is that the risk profile of a nuclear new build project changes during construction. This means that the risk appreciation and cost calculations of different investor groups will also change during the project cycle. Completion risks that were deemed uninvestable before first concrete has been poured may look very different, for instance, once the cooling system is installed.

Figure 6.2. **The cone of uncertainty reduces through time as construction progresses**



Governments may be able and willing to take on and socialise risks during the early phases of construction but may also be interested in offloading debt at favourable conditions at the earliest possible stage. Many creative solutions can be found as long as financial engineering is undertaken with a view towards a fair and sustainable distribution of risks and rewards. France, for instance, is currently exploring the option of public loans to the project company of a nuclear new build project that will need to be paid back (*avances remboursables*) once the project advances towards completion. Again, the government would be exposed during the riskiest phase, recuperating its outlays at a later stage.

As always, risks and rewards will need to be commensurate. The interesting fact is that certain risks can be better assessed and become more investable for private investors as time goes by and the cone of uncertainty reduces (see Figure 6.2). Of course, assessing and reassessing those risk as well as reallocating them through time in function of risk preferences and portfolio effects requires specialist skills and has real costs. However, given the large size of nuclear new build projects, the benefits accruing to those who are able to organise such dynamic financial risk reallocations over the project cycle can be considerable.

Chapter 7. Conclusions and ten questions requiring answers before starting a nuclear new build project

This report continues and broadens earlier NEA work in the area of financing for nuclear new build. In particular, it highlights the close interactions of financing with the spheres of electricity market design and project management. A substantial part of this report explores the respective roles of the public and the private sector. Since the hope of the early 2000s of seeing privately financed "merchant" nuclear power plants in competitive electricity markets has decidedly receded, there is a growing recognition that governments that aim to build new nuclear capacity need to systematically take an even more active approach than in the past. This regards not only the framework conditions of nuclear new build in electricity market design, the indication of overall targets for the generation mix and financing, but also, complementarily to these functions, a more direct role in the oversight of project management. This return of industrial policy results from the intrinsic features of an energy transition that is more capital-intensive, more expensive and more disruptive than most stakeholders and governments had anticipated.

Project management during the construction of new plants is possibly the most important piece of the puzzle that is successful nuclear new build. Its impact on financing is immediate, so much so that it is possible to think about financing costs, inevitably a function of timing and risks, as an output of nuclear new build projects, especially when considering the reputational spillovers between different projects, rather than as an input determined by exogenous factors. In ensuring effective project management, two factors stand out: leadership and societal commitment. While both factors are considered "soft", i.e. difficult to define, they remain essential precisely because industrial and political leaders are the ones that will need to absorb the residual uncertainty that inevitably arises in highly complex projects closely related to the dynamic provision of public goods such as the security of energy supply and environmental integrity. The insight that "there is no such thing as a complete contract" clearly applies to the construction of a new nuclear power plant.

The emphasis on project management must not come at the expense of sound financial engineering. Earlier NEA work developed a framework that makes it possible to analyse the different financial risk dimensions of nuclear new build in a coherent manner. There is first and foremost the importance of a country's commitment to attaining net zero carbon emissions. Only in that context can low-carbon generation assets play their role of providing insurance to diversified investment portfolios, as their returns will be largely uncorrelated to the wider markets. Second, the three specific risk dimensions relating to a nuclear new build project, political risk, price risk and construction risk, which are not easily diversifiable due to project size, complexity and informational asymmetries, each require specific measures of "de-risking", that is socialising risks, in order to allow projects to go ahead.

While political risk can be hard to outline, its contractual insurance through a commitment by governments to indemnify investors in case of a politically motivated termination of nuclear power is straightforward. Things are more complex with price risk, as electricity market design is a highly complex issue, riven by conceptual as well as political disagreements. Insuring against price risk is usually understood as providing long-term contracts for the output of a nuclear power plant at essentially fixed prices though mechanisms such as regulated tariffs, power purchasing agreements or contracts for differences. This, however, interferes with the operations of the deregulated electricity markets that have become the norm in most OECD and NEA countries.

As it happens, electricity market design also interacts closely with the allocation and insurance of construction risk. This is the primary reason why the United Kingdom currently plans to use a financing mechanism called regulated asset base (RAB), which shifts the cost of construction from project operators and investors to ratepayers. The implicit understanding is that ratepayers, that is consumers, will reap benefits later through the reliable low-cost provision of low-carbon electricity. In principle, the interference with market operations is less than with long-term contracts even though the current UK model also includes a regulatory module for pricing electricity output. In the field of designing electricity markets for the low-carbon economy, intrinsically difficult due to the latter's high capital intensity, the notion of hybrid markets begins hence to emerge. Maintaining the competitive dispatch practised in deregulated markets, which improves operational efficiency, hybrid markets include targeted support measures for different low-carbon technologies, be they capacity mechanisms for low-carbon flexibility providers, fixed-price contracts for variable renewables such as onshore wind and solar PV and, as mentioned, a pre-financing of construction costs through ratepayers for large, capital-intensive baseload providers such as hydroelectricity and nuclear.

A justification of the socialisation of construction risk can be found in the work of economic theorists such as Arrow and Lind. Such arguments, however, find their limits in a number of conditions. The most important is again the decorrelation of the newly financed project from broader economic developments. The next most important is the need to maintain incentives for efficient project execution. Indemnifying against all financial risks, even with the best of justifications, stunts incentives for speedy project conclusion and cost control.

Given the sobering experiences with recent nuclear new build projects in OECD countries, the need for renewed reflection on improving the management of nuclear new build projects is gathering pace. No clever market design, no optimised risk allocation, no organisational model can substitute for competent project management in order to realise successful nuclear new build. The engineering-procurement-construction (EPC) model structured around the idea that an independent logistics provider could source all required material inputs and services from competitive markets has, so far, not worked in an industry as complex and as sensitive as nuclear energy. Information asymmetries and market transaction costs are just too high to allow for high degrees of external subcontracting with competitive procurement and layered supply chains.

Certain elements of better project management, such as better advance planning, systematically monitoring supply chains and ensuring the development of an adequately skilled and well-paid workforce, are now widely recognised. While necessary, these elements are not sufficient. This report has argued that leadership, the ability to align complex webs of relationships and to assume residual, unforeseeable and non-codifiable risks, independent project advisory and, most importantly, coherent incentive structures at every level of the value chain are indispensable elements of any successful nuclear new build project. The notion of nested incentives as practised in the financial sector, where bonuses for successful performance accrue at the level of the individual, the team and the project, can provide some general guidance in this area.

The report concludes with the special topic of private investment in nuclear new build. Even if government involvement remains indispensable, it does remain desirable to continue to associate private investors in nuclear new build projects. Public-private co-operation yields the greatest benefits if it is mindful of the respective strengths in risk management and risk preferences of both public and private investors. Associating private investors from the beginning of the project, even if they will never be able to offer capital at rates lower than those at which sovereign governments can borrow, remains attractive for four reasons: (1) as a signal that the project has obtained its "social licence"; (2) for the competence of private investors in project management, cost control and structuring incentives; (3) to allow a dynamic transfer of ownership as the project progresses; and (4), if required, to keep part of the project costs off public balance sheets.

Organising the participation of private investors in an optimal and cost-minimising manner needs to reflect the changing level of risk over the life cycle of a nuclear power plant. A nuclear new build project remains a relatively high-risk project until commissioning, although construction risks and financial risks decline with each technical milestone that is passed. It is a relatively low-risk project from that day onwards. This requires a *dynamic* approach to the financing of new nuclear power plants, which means that the shares of public and private ownership over the project life cycle will change at predefined intervals as ownership is incrementally transferred from public to private investors. It is important that the conditions and timing for these transfers be agreed *before* first cement is poured. Country specificities remain important in this context. One of the earliest conceptual approaches for dynamic refinancing was developed in Poland with the SaHo Model.

Many variants of the timing and conditions for such dynamic refinancing can be developed, reflecting the risk profiles and ability to generate financing of both public and private stakeholders. Of course, assessing and reassessing those risk as well as reallocating them through time according to risk preferences and portfolio effects requires specialist skills and has real costs. However, given the very large size of nuclear new build projects, the benefits accruing to those who are able to organise such dynamic financial risk reallocations over the project cycle can be considerable.

In all, large-scale nuclear new build will only be successful if it is embedded in broad societal strategies that inform the three inter-locking dimensions of financing, electricity market design and project management. Policymakers should define those strategies on the basis of transparent and comprehensive societal discussion processes. The concluding section below offers a checklist of ten decisive questions that will arise in any nuclear new build project. Each of them will require a coherent and politically sustainable answer that is developed by stakeholders and governments together. Those answers will then create the frameworks in which investors, entrepreneurs and industrial project managers, each group motivated by appropriate incentives, can apply their skills at the industrial level in order to turn into reality the vision of a substantial contribution of nuclear power to the net zero economies of the future.

Ten questions requiring answers before starting a nuclear new build project

On the basis of the preceding chapters, the following checklist of ten key points that require discussion is designed to structure the conversations to be had in the lead-up to the construction of a new nuclear power plant. This is not a checklist for project managers during the actual planning and building of a new nuclear reactor. Its purpose is to assist stakeholders far earlier, when societal and political discussion processes prepare the strategic orientations that define the conditions under which nuclear new build will take place.

In keeping with the structure of this report, these conditions are primarily in the four areas of financing, electricity market design, project management and involving private investors. These conditions will need to consider in every case issues of economic efficiency, answer questions of distribution and fairness, and reflect on the adequacy of institutional structures, responsibilities and incentives. A fundamental transversal question, the answer to which will colour many of the preceding issues, is to what extent nuclear generating capacity is an industrial asset like any other and to what extent its role as a dispatchable low-carbon provider of last resort and a contributor to energy security makes it more akin to public infrastructure.

On the basis of their culture, experience, generation mix, societal structure and industrial fabric, OECD and NEA countries will undoubtedly reach different answers to the questions that are implicitly and explicitly contained in the following ten points. However, it is indispensable for all to not avoid the challenging conversations surrounding them. Skirting or displacing those strategic questions will come back to haunt any major new project. While it is possible to have different degrees of public involvement during the construction process, it is unambiguously the responsibility of governments to ensure that the following points are addressed before construction gets under way. Once these relevant strategic orientations have been clarified, project managers can concentrate on addressing the technical, industrial and organisational challenges head-on and thus maximise the chances for successful nuclear new build.

1. **Net zero carbon targets:** How important are climate change emission reduction objectives as a long-term determinant of energy and climate policies? The answer to this question is not only of political and environmental interest but also economic and financial. Under a strict carbon constraint, the returns on investments in low-carbon generators such as nuclear power will act as a financial hedge against investments in other sectors that will be negatively affected by the effort to reduce carbon emissions. This would reduce financing costs and hence the total costs of nuclear new build projects.

2. **Energy transition costs:** Even at the level of a mid-sized country, the costs of the energy transition over the next three decades are measured in hundreds of billions or even trillions of USD or EUR. Costs of this magnitude will accrue independently of specific technology choices. While many find the benefits of nuclear energy as a scalable and dispatchable low-carbon baseload provider obvious, and it will reduce the costs of attaining net zero targets in most NEA countries, societies must be aware of the magnitude of the tasks ahead and will need to decide on the pace at which they want to advance and how they want to share the resulting financial burden.

3. **Systems approach adoption:** The net zero electricity systems of the future will be built around a mix of nuclear energy, hydroelectricity, wind and solar PV. Low-carbon hydrogen will be used in niche applications, while electrification can reduce emissions in transport and industry. Each technology has distinct strengths and weaknesses and will fulfil a function that is complementary to the others. Achieving an efficient least-cost generation mix requires systematic advance modelling of different technology options. Centralised planning of the mix must be coupled with elements of competition in each segment of the system as well as with appropriate technology-specific support measures to achieve the desired levels of capital-intensive, low-carbon generation capacity. Sound analytical work needs to be complemented by a broadly shared long-term vision of the future electricity system at the societal level.

4. **Systematic risk management:** The large-scale build-out of nuclear power that is part of a clear path to achieving net zero targets at reasonable costs will require the comprehensive de-risking of different risk dimensions of nuclear new build. Beyond the financial insurance function of low-carbon generation in economies operating under stringent carbon constraints, this requires measures to insure against political risk, price risk and construction risk. Each of these dimensions requires comprehensive provisions in terms of legal frameworks, market designs and risk allocation. Each time, this will vary the risk exposure for different stakeholder groups. There thus needs to be transparency, discussion and ultimate consensus that the costs of nuclear power during construction and its benefits during operation are fairly shared.

5. **Low-carbon infrastructure:** Even with careful system analysis and advance planning, the low-carbon electricity systems of the future will not consist of off-the-shelf solutions. Innovation, experimentation and market competition will thus need to be complemented by a sturdy and reliable base in the electricity mix providing an insurance function for the system as a whole, even beyond day-to-day generation. There needs to be discussion about the extent to which nuclear energy fulfils this function of a low-carbon infrastructure that reliably ensures the minimum required levels of security of supply and carbon emission reductions. The fact that the benefits of such dispatchable low-carbon backup relate to the public good of security of supply further strengthens the argument that some socialisation of the costs and risks of nuclear new build is appropriate.

6. **Electricity market design:** To what extent are current designs appropriate for the low-carbon energy transition and conducive to nuclear new build? There is no need to construct intransigent oppositions between deregulated and regulated markets, competition and vertical integration. Pragmatic exemptions from purely market-based financing have regularly been granted for new nuclear projects in North America, Europe and Asia Pacific. However, a substantive expansion of nuclear new build will require a

more systematic review of whether the current framework conditions are adequate. This regards, in particular, the question of whether current electricity market designs allow for a degree of revenue certainty and the ability to prefinance projects with the help of ratepayers or taxpayers.

7. **Project management framework conditions:** The management of projects as complex as a new nuclear power plant is an enormous industrial undertaking. The task of policymakers in this context is to insist on publicly discussing and setting the appropriate frameworks that define management structures. This regards, in particular, the relative strengths of relying on a competitive international supply chain and global labour markets on the one hand and on vertically integrated national structures on the other. The right balance needs to be found according to country-specific cultures, histories and industrial strengths. At the same time, nuclear new build projects must not be burdened with additional objectives, such as strengthening the industrial fabric or redressing the trade balance, which are extraneous to efficient project execution. In any case, policymakers, as the ultimate project owners holding the residual risk, will need to commit more systematically than in the past to active management oversight.

8. **Project management and execution:** Organising projects of this magnitude and allocating responsibilities must be matters of transparent, public discussion. As ratepayers and taxpayers are assumed to take on sizeable portions of the financing of construction, they have the right to public oversight in appropriate form. This may or may not be combined with independent technical oversight. Leadership and its link to political power, the ultimate arbiter, must be clearly and publicly defined. Of key importance are the incentive structures at all stages of the value chain. Only if agents have something to lose will they exert themselves to contribute timely and efficiently to overall project success. The nature of those incentive structures should form an explicitly formulated and transparently communicated module of the overall project.

9. **Private investor involvement:** The degree of involvement of private investors, even if they will never be able to offer capital at rates lower than those at which sovereign governments can borrow, should be discussed as an economic policy issue. In principle, their involvement remains attractive for four reasons: (1) as a signal that the project has obtained its "social licence"; (2) to benefit from the competence of private investors in project management, cost control and structuring incentives; (3) to enter into a dynamic transfer of ownership as the project progresses; and (4) if required, to keep part of the project costs off public balance sheets and thus limit public borrowing costs. However, these contributions come at somewhat higher overall returns on capital. The costs and benefits must thus be carefully analysed, weighed and communicated.

10. **Private investor involvement modalities:** Organising the participation of private investors in an optimal and cost-minimising manner needs to reflect the changing levels of risk over the life cycle of a nuclear power plant. A nuclear new build project remains a relatively high-risk investment until the day of commissioning, even if construction risks and financial risks decline with each technical milestone. The same nuclear project is a relatively low-risk investment from the day of commissioning onwards. This requires a *dynamic* approach to the financing of new nuclear power plants, which means that the shares of public and private ownership over the project life cycle will change at predefined intervals as ownership is transferred *incrementally* from public to private investors. It is important that the conditions and timing for these transfers are agreed *before* first cement is poured. While primarily a technical issue of financial engineering, dynamic refinancing as project milestones are reached is an important way to reduce the overall costs of the project for all stakeholders.

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Financing, Market Design and Project Management in Nuclear New Build

Realising the full contribution of nuclear energy to achieving net zero targets requires mastering the challenge of financing and constructing significant numbers of new reactors. This new NEA report shows that this entails treating the financing and the management of new nuclear construction projects as interrelated issues in the framework of electricity systems designs appropriate for the low-carbon energy transition. "Hybrid markets" will thus combine competitive short-term dispatch with centrally co-ordinated incentives for long-term investment. The benefits of nuclear energy at the level of the energy system on the one hand and the current size of nuclear construction risk on the other both argue for sharing construction risk with either taxpayers or electricity consumers. Fairness requires that benefits and responsibilities be shared equally. New forms of co-operation between the public and private sectors will thus need to ensure that effective leadership, independent project advisory and coherent incentive structures lead to the efficient construction of new nuclear capacity, which in the majority of OECD countries will be part of the low-carbon energy infrastructure of the future.

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