A Global Playbook for Nuclear Energy Development in Embarking Countries

Six Dimensions for Success

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About

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Clean Air Task Force (CATF) is a global nonprofit organization working to safeguard against the worst impacts of climate change by catalyzing the rapid development and deployment of low-carbon energy and other climate-protecting technologies. With 25 years of internationally recognized expertise on climate policy and a fierce commitment to exploring all potential solutions, CATF is a pragmatic, non-ideological advocacy group with the bold ideas needed to address climate change. CATF has offices in Boston, Washington D.C., and Brussels, with staff working virtually around the world. Learn more at catf.us.

About the EFI Foundation

The EFI Foundation is a Washington, D.C.-based 501(c)(3) nonprofit organization dedicated to educating the public on issues relating to harnessing the power of technology and policy innovation to accelerate the clean energy transition. The EFI Foundation adheres to the principle of analytical independence from its public and private sponsors. Under the leadership of Ernest J. Moniz, the 13th U.S. Secretary of Energy, the EFI Foundation builds on the legacy work of the Energy Futures Initiative, a nonprofit organization co-founded by former Secretary Moniz in 2017. Lean more at efifoundation.org.

About the Nuclear Threat Initiative

The Nuclear Threat Initiative is a nonprofit, nonpartisan global security organization focused on reducing nuclear and biological threats imperiling humanity. Learn more at nti.org.

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Acronym List

AP	Additional Protocols
BOO	build-own-operate
BOOT	build-own-operate-transfer
BOT	build-own-transfer
BWRs	boiling water reactors
CSA	Comprehensive Safeguards Agreement
DAC	design acceptance certificate
DBFMO	design-build-finance-maintain-operate
DBT	design basis threat
ECA	export credit agency
ENR	enrichment and reprocessing
EPC	engineering, procurement, and construction
EPRI	Electric Power Research Institute
ExIm	export-import
Gen III+	Generation III+ reactors
Gen IV	Generation IV reactors
GJ	gigajoules
GW	gigawatts
HALEU	high-assay, low enriched uranium
HEU	highly enriched uranium
IAEA	International Atomic Energy Agency
IBNI	International Bank for Nuclear Infrastructure
ICAO	International Civil Aviation Organization
IDO	integrated development organization
IEA	International Energy Agency
INDO	international nuclear development organization
INIR	integrated nuclear infrastructure reviews
INPO	Institute of Nuclear Power Operators
IPCC	Intergovernmental Panel on Climate Change
IPD	integrated project delivery
ITSO	international technical support organization
LCOE	levelized cost of energy
LEU	low enriched uranium
LWR	light water reactor
MDBs	multilateral development banks
MIBs	multilateral infrastructure banks
MWh	megawatt hours
NEA	Nuclear Energy Agency
NEPIOs	nuclear energy program implementing organizations
NHSI	Nuclear Harmonization and Standardization Initiative
NLB	new local build
NPT	Treaty on the Non-Proliferation of Nuclear Weapons
OECD	Organisation for Economic Co-operation and Development
O/Os	owner/operators
PCSR	pre-construction safety report
PWRs	pressurized water reactors
R&D	research and development
RFP	request for proposal
SMRs	small modular reactors
TRISO	tristructural isotropic particle fuel
TSOs	technical support organizations
TWh	terawatt-hours
WANO	World Association of Nuclear Operators

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Foreword

The global energy transition to a low-carbon energy system has been taking place for the last decades, but it has encountered many challenges—even with the trillions of dollars spent on solutions for decarbonization. As the world aims for a net-zero economy by midcentury, we need to ramp up efforts and options to address these challenges. Recently, increased interest has arisen in expanding nuclear energy deployment as an important tool to meet clean energy demands.

In many ways, today is the best of times and the worst of times for nuclear energy. On the one hand, numerous studies and a growing chorus of government leaders, energy and climate thinkers, and environmental organizations are concluding that nuclear energy could be critical for managing climate change while contributing to doubling global electricity consumption and to decarbonizing fuel, bolstering energy security and reliability, and moderating energy transition costs. More than 70 advanced nuclear companies exist in the world, offering advanced nuclear reactor designs after a multi-decade innovation drought. Several ongoing nuclear technology programs are being funded and deployed to demonstrate the next generation of reactor technologies. On the other hand, notwithstanding the more than 50 new reactors in construction today, nuclear energy expansion is modest globally, and its growth is far from scaling up to its full potential.

To change course and have nuclear energy make a meaningful contribution, we need to rethink how we conceive, build, regulate, and finance this technology. We need an overhauled industrial and regulatory ecosystem that produces and delivers standardized, commoditized cost-competitive ***products*** rather than costly and risky multi-decade ***projects***. And we need to do so in a way that maintains and promotes strong nonproliferation and nuclear security standards. Many current efforts to revitalize the nuclear sector are on point but they individually address one or two key challenges.

Hence, we offer this playbook, particularly to embarking countries, for assistance in managing an integrated approach of deploying new nuclear energy to meet clean energy goals. We call it a “playbook” as an analogy to a sports team’s strategy for addressing various dimensions of the game and developing and implementing a sequence of winning strategies or plays. It certainly is not a “one-size-fits-all” playbook—but rather a comprehensive set of actions, some simple and others more complex, to help the team move forward toward the goal. We target “embarking” countries as that is the term used by the International Atomic Energy Agency (IAEA) for the countries that do not currently have a nuclear infrastructure but have plans to implement and deploy nuclear energy in their countries.

Nuclear energy can have an important role to play in global decarbonization and as part of the energy transition. This playbook summarizes a comprehensive strategy that we urge embarking countries to consider as we create a global nuclear ecosystem that can deliver historically large annual nuclear deployments for an extended period. This is our call to action!

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Executive Summary

Mitigating climate change, improving energy security, and creating the conditions for social progress through sustainable economic growth are interrelated challenges. Nuclear energy can play a pivotal role in addressing all of them. Growing recognition of this potential presents a unique opportunity to craft a global strategy for deploying new nuclear technologies. But to make impact at required scale, nuclear energy would need to be deployed alongside other clean energy solutions at a pace and scale of many tens of gigawatts (GW) per year from now until 2050. Much of this deployment will occur in countries that currently do not have any commercial reactors, referred to as "embarking countries" by the International Atomic Energy Agency (IAEA). Any approach to scaling nuclear energy will need a comprehensive strategy to help these countries chart their individual nuclear journeys.

This playbook is a collaboration of the EFI Foundation, the Nuclear Threat Initiative, and the Clean Air Task Force. It outlines pathways for the responsible, sustainable, and effective development of new nuclear projects and industries in embarking countries. Throughout, the playbook emphasizes the need for a holistic approach to scaling nuclear energy, considering the unique challenges and opportunities specific to each country, and highlights the role that new international institutions could play in supporting a global nuclear expansion.

One of the main drivers behind this effort is the recognition that, to meet the world's growing energy demand while combating climate change, massive electrification of all sectors of the world economy is essential. Nuclear energy could be a major source of abundant, continually available, zero-carbon electricity and thermal energy to meet this demand. It could be a significant contributor to industrial decarbonization, replacing fossil fuels in the production of high-quality heat—a new application of nuclear energy in both embarking countries and others with established nuclear programs. Moreover, its compact spatial requirements and relatively lower life cycle material usage make it a favorable option for increased energy supply in a crowded world. Despite these advantages, only a limited number of countries are currently engaged in nuclear power projects, while numerous developing nations aspire to harness nuclear energy. However, nuclear energy has been marked with a history of high costs, frequent cost and schedule overruns, regulatory uncertainties that discourage investment, a diminishing skilled workforce due to prolonged underinvestment as well as the continual concerns surrounding nonproliferation and nuclear security and spent fuel management. If new nuclear is to be a feasible option in the future energy portfolios of any country – and especially embarking countries – all of these challenges must be meaningfully addressed and at scale.

Although the playbook draws heavily from best practices observed over multiple decades of experience with civilian nuclear energy development around the world, it is not intended to be prescriptive. The playbook is organized around six key dimensions of capability and capacity building that are imperative to any successful new nuclear development:

- project execution and capability building
- regulatory system development
- project bankability and finance
- nuclear nonproliferation and security
- spent nuclear fuel management
- workforce development

We also offer cross-cutting themes, challenges, and perspectives. Our aim, recognizing that embarking countries will have different priorities, capabilities, and needs, is to identify core principles and options that, in aggregate, offer pathways to responsibly developing nuclear programs that align with broader national goals.

Reflecting our view of the potential importance of new international institutions, the playbook devotes considerable attention to the question of what form these institutions might take and what benefits they might provide—not only to embarking countries but also in nations that already have operating nuclear plants. Embarking countries can make an especially strong case in calling for the formation of these institutions. Recognizing that this may take some time, however, the playbook also offers recommendations for what can be done in the near term, even without new institutions. Indeed, much progress can be made now, while additional supportive institutional infrastructure is developed collaboratively in parallel.

The playbook's recommendations apply to any nuclear technology that can meet prudent finance, regulatory, and nonproliferation models. They emphasize the importance of tailoring strategies to individual countries' unique contexts, to ensure responsible nuclear energy expansion. The report highlights the potential for shared benefits and synergies between embarking countries and existing nuclear power nations as they work toward scaling nuclear energy and fostering a robust global commercial ecosystem. There will be substantial synergies and shared benefits between embarking countries and existing nuclear power nations as both invest in building scale, developing innovative, harmonized regulatory approaches, and increasing financial confidence. Taking these initiatives together, successful execution of this playbook can build confidence in the responsible scale-up of this technology as a necessary and beneficial global energy solution.

Specific recommendations that this playbook offers for the six key dimensions include:

Project Execution

Nuclear project execution is complex, involving numerous activities, tasks, and processes that need to be carried out to construct, commission, and operate a nuclear facility. Capacity building for project execution is critically important in embarking countries to efficiently use scarce resources, avoid or at least mitigate the development and construction challenges of the past and build momentum and support for nuclear projects. Insights can be drawn from successes of well-executed projects and advancements in nuclear project cost reduction, but there is currently no defined model for doing so.

What can be done now:

- Use best practice project management.
- Develop integrated development commercial entities that can unite different delivery elements and associated risk.
- Assemble multi-off-taker buyer consortia that can generate large orderbook demand that facilitates large upstream investment in manufactured, standardized nuclear projects.

Further options:

- Establish formal public-private global partnerships to provide integrated project delivery.

Regulatory System

Establishing a robust nuclear regulatory regime is of paramount importance for sustaining a nuclear industry, particularly for an embarking nuclear country. Such a regime serves as a cornerstone for safe and responsible nuclear development, ensuring the well-being of both the public and the environment. Embarking countries face regulatory development challenges because key considerations surface when implementing a regulatory system and several options emerge for doing so. Furthermore, although existing institutions and pathways for building regulatory regimes in embarking countries exist today, new institutions and pathways could expedite the process and optimize nuclear deployment.

What can be done now:

- Create multilateral agreements for international transfer of design certifications.
- Develop in-country regulatory capability, borrowing from global best practice through bilateral and multilateral partnerships.

Further options:

- Establish an international technical support organization (ITSO) to support nuclear development in embarking countries by assisting with license applications, inspections, and regulatory training, and addressing resource constraints and accelerating nuclear deployment.
- Pursue more extensive global licensing harmonization.

Project Bankability and Finance

Market-only mechanisms to finance nuclear projects are insufficient; national governments must play an active role at the outset of a nuclear program. A first challenge is creating the economic conditions to attract sufficient capital for successfully planning, building, operating, and decommissioning nuclear energy facilities. Enabling business models that effectively leverage public and private resources is a key task for public administrators. Three principles to increase the bankability—or investment quality—of new nuclear projects in embarking countries should guide these efforts: (1) minimize and contain project costs, (2) minimize the cost of capital, and (3) support adequate revenue models. Specific business models and financing pathways could be selected to adequately address all three.

What can be done now:

- Establish clear signals welcoming nuclear investment.
- Generate orderbook for multiple builds of the same design.
- Require implementation of integrated project delivery (IPD) best practices.
- Share risk of cost overruns on early deployments.
- Choose an appropriate project delivery approach.
- Work with certified designs and proven delivery entities.
- Promulgate an adequate revenue model ahead of time.

Further options:

- Create a multilateral International Bank for Nuclear Infrastructure to offer capital and financing options, augmenting country-specific and developer resources

Nuclear Nonproliferation and Security

Security and nonproliferation are necessary foundations for a global expansion of nuclear energy. As countries consider nuclear energy options, they face decisions in several areas that bear on nonproliferation and nuclear security, including (1) choice of reactor design, fuel type, and fuel cycle; (2) acquisition of nuclear fuel; (3) security; and (4) application of international safeguards and transparency measures. On each of these issues, adherence to international best practices and standards will help clear the path to successful nuclear energy development.

What can be done now:

- At least initially, adopt a once-through fuel cycle based on light water reactor (LWR) technology and low enriched uranium (LEU) fuel, which offers decades of proven experience.
- Opt for procuring fuel on the international market, as it has proven to be the more reliable, cost-effective, and proliferation-resistant choice for sourcing fuel.
- Incorporate security planning from the early days of project design.

Further options:

- Exceed bare minimum requirements to enhance transparency and avoid proliferation sensitive technologies.

Spent Nuclear Fuel

The siting of permanent disposal sites for spent nuclear fuel is an important goal that nuclear power stakeholders must work toward; in addition, a responsibility exists to safely manage these wastes in interim storage while progress toward a permanent disposal solution continues. These imperatives have proved challenging for many of the countries with advanced nuclear energy programs. Although this process can seem complex, spent nuclear fuel can be managed safely, securely, and economically with appropriate effort. Countries that are embarking on nuclear energy programs can forge a path to success by considering three key aspects: permanent spent fuel disposal, timeline for considering disposal options, and interim spent fuel storage.

What can be done now:

- Adopt once-through LEU fuel cycle that allows for the direct disposal of spent fuel (by contrast, reprocessing and recycling generate multiple waste streams and incur significant additional costs).

- Build efficiencies by considering waste disposal from the early phases of project development and learning from the positive and negative waste management experiences of countries with established nuclear programs.
- Consider options for interim spent fuel storage, ensuring that policies and practices prioritize safety and security.

Further options:

- Develop regional solutions for the interim storage and permanent disposal of spent fuel.

Workforce Development

Workforce development is foundational to nuclear embarking countries. However, nuclear technology's specialized workforce requirements can turn staffing into a choke point for new projects. Embarking countries face common, global workforce problems, as well as acute constraints particular to new entrants. As its nuclear program matures, an embarking country must decide whether roles will be outsourced or insourced. Embarking countries are highly likely to rely on both foreign and domestic talent, but there exists a range of possible combinations. Countries should choose a workforce model that fits their own resources and goals, and back up their decisions with financial investment.

What can be done now:

- Develop a workforce assessment and national strategy that ensures all stakeholders are aligned and helps the embarking country prepare for either recruiting foreign talent or forging a domestic pipeline of talent.
- Leverage existing regional partnerships to support joint workforce development.
- Embed junior managers from embarking countries in new and ongoing international nuclear build and operation projects.

Further options:

- An embarking country can supplement its existing educational system with a national or regional nuclear training center, while also leveraging resources available in other countries.
- Given that workforce training is best conducted through applied practice, constructing and operating a research reactor not intended for commercial purposes could be a valuable educational resource.
- Multiple embarking countries could also share scarce human resources, such as through an ITSO to support regulator development, or a regional nuclear training center.

CHAPTER 1

Introduction

Mitigating climate change, improving energy security, and creating the conditions for social progress through sustainable economic growth are interrelated challenges. Nuclear energy can play a pivotal role in addressing all of them. Growing recognition of this potential presents a unique opportunity to craft a global strategy for deploying new nuclear technologies. But to make impact at required scale, nuclear energy would need to be deployed alongside other clean energy solutions at a pace and scale approximating many tens of GW per year from now until 2050. Much of this deployment will occur in countries that currently do not have any commercial reactors, referred to as “embarking countries” by the IAEA. Any approach to scaling nuclear energy will need a comprehensive strategy to help these countries chart their individual nuclear journeys.

This playbook is a collaboration of the Clean Air Task Force, the EFI Foundation, and the Nuclear Threat Initiative. It outlines pathways for the responsible, sustainable, and effective development of new nuclear projects and industries in embarking countries. Embarking countries here denote those that have no current civilian nuclear fleet. Throughout, the playbook emphasizes the need for a holistic approach to scaling nuclear energy, considering the unique challenges and opportunities specific to each country, and highlights the role that new international institutions could play in supporting a global nuclear expansion.

Although the playbook draws heavily from best practices observed over multiple decades of experience with civilian nuclear energy development around the world, it is not intended to be prescriptive. Our aim, recognizing that embarking countries will have different priorities, capabilities, and needs, is to identify core principles and options that, in aggregate, offer pathways to responsibly developing nuclear programs that align with broader national goals.

Reflecting our view of the potential importance of new international institutions, the playbook devotes considerable attention to the question of what form these institutions might take and what benefits they might provide – not only to embarking countries but also in nations that already have operating nuclear plants. Embarking countries can make an especially strong case in calling for the formation of these institutions. Recognizing that this may take some time, however, the playbook also offers recommendations for what can be done in the near term, even without new institutions.

Each of the six chapters of this playbook addresses a distinct element of nuclear energy capability and capacity building.

Project Execution and Capacity Building: To increase the quality, speed, and scale of nuclear deployment, best practices for planning, engineering, procuring, and building new nuclear facilities (and related supply chains), must be consistently applied and customized for local conditions. Concurrently, the approach to new nuclear builds must change to avoid the recent history of schedule delays and cost overruns. Early attention to fundamental design considerations such as modularity and manufacturability, together with more efficient and IPD mechanisms can reduce costs and construction times and maximize the odds of project success.

Regulatory System Development: Embarking countries will need to develop and/or access adequate regulatory capabilities in a timely manner. International regulatory frameworks can be harmonized to increase licensing efficiencies. Furthermore, regulatory support can be centralized and effectively directed to fill gaps in nuclear licensing capabilities that embarking countries may experience.

Project Bankability and Finance: New business models need to be considered as new off-takers for nuclear power emerge, as well as innovative models for risk sharing between project stakeholders, including private and public entities. Financing mechanisms and institutions that support large orderbooks for a given reactor design, while also supporting appropriate knowledge sharing mechanisms, can help spur deployment. Models that recognize the clean, firm energy output of nuclear energy could be used to bolster its value proposition. Countries can help create the conditions for larger capital flows to new nuclear energy through cost minimization, cost of capital minimization, and revenue support approaches.

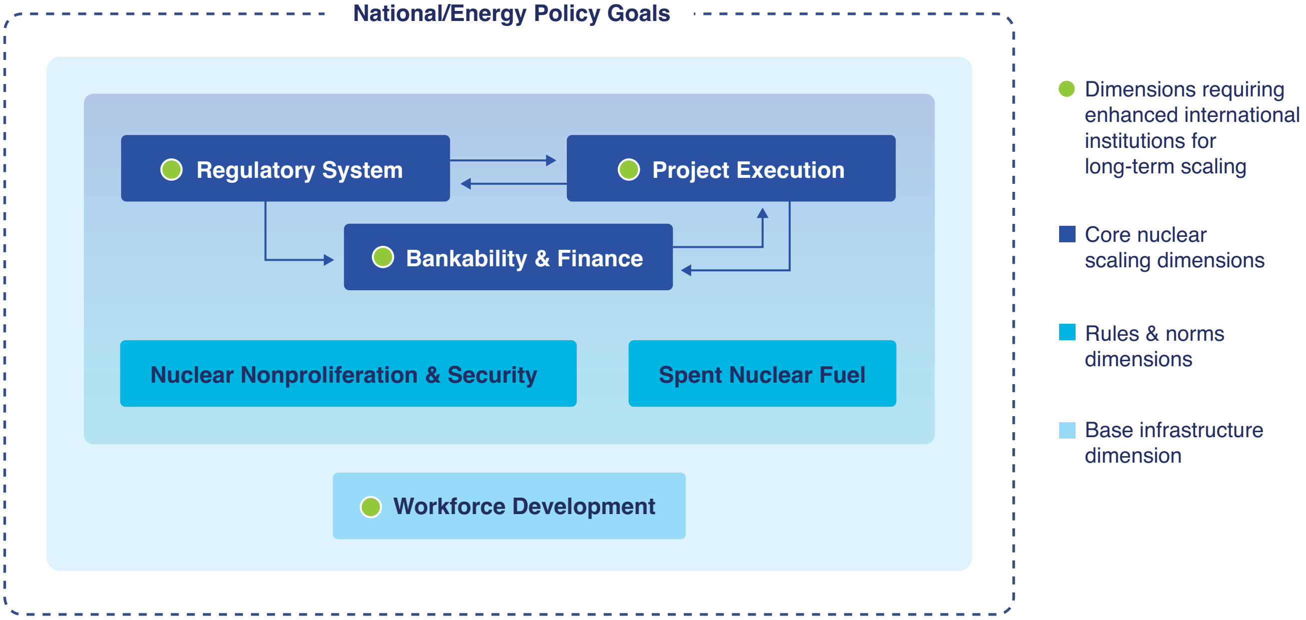
Nonproliferation and Nuclear Security: Security and nonproliferation are the necessary foundations for a global expansion of nuclear energy. This requires countries to thoughtfully consider the fuel and fuel cycle characteristics of nuclear projects; the methods and facilities needed to source, manage, store, and dispose of these fuels and their waste products; appropriate safeguards and transparency measures; and security for the reactor itself. Countries can adopt a set of well-defined principles and practices that bolster security, assure other countries that the program will be used for peaceful purposes, reduce risk, and gain internal and external support for nuclear energy development.

Spent Nuclear Fuel Management: With current international arrangements, all nuclear power programs will require permanent waste repositories, but some fuel cycle options simplify the task of managing the back end of the fuel cycle. Strategies for storing and disposing of spent fuel can be streamlined and related costs can be reduced if these issues are tackled early in project planning. Although managing spent fuel is often viewed as a significant barrier to nuclear energy expansion, prudent policies from day one can help ensure implementable and widely supported solutions.

Workforce Development: Nuclear energy programs require workers with a range of regulatory, management, manufacturing, craftwork, and operations skills. Supplying this talent will likely require a combination of investment in in-country training and the recruitment of experts from experienced countries. The evolution of a country’s nuclear workforce must align with its overall energy strategy and other national priorities. Countries have various options to build, obtain, and access the right skills as their nuclear program matures, requiring a strategy defined early in their nuclear journeys.

This sequence of chapters in this playbook is not accidental. Efficient project execution, best practice safety regulation, and affordable financing are all threshold requirements for enabling the large-scale expansion of nuclear energy in embarking countries. If they cannot be met efficiently, nuclear programs will stall. Success on these factors, in turn, puts more pressure on the capabilities discussed in later chapters: nonproliferation and security, spent fuel management, and workforce development. Figure 1 illustrates how all these dimensions fit together within an embarking country context, keeping in mind the advantages of new international institutions to enable adequate scaling of new nuclear globally. Nuclear energy can fit into a country’s overarching strategy for various national goals and energy policy. Crucially, the six dimensions of the playbook are to be interpreted within each country’s specific boundary conditions, including national economic, energy, and environmental goals.

Figure 1: Interrelationships of the six dimensions and where new international institutions are needed to scale new nuclear energy globally

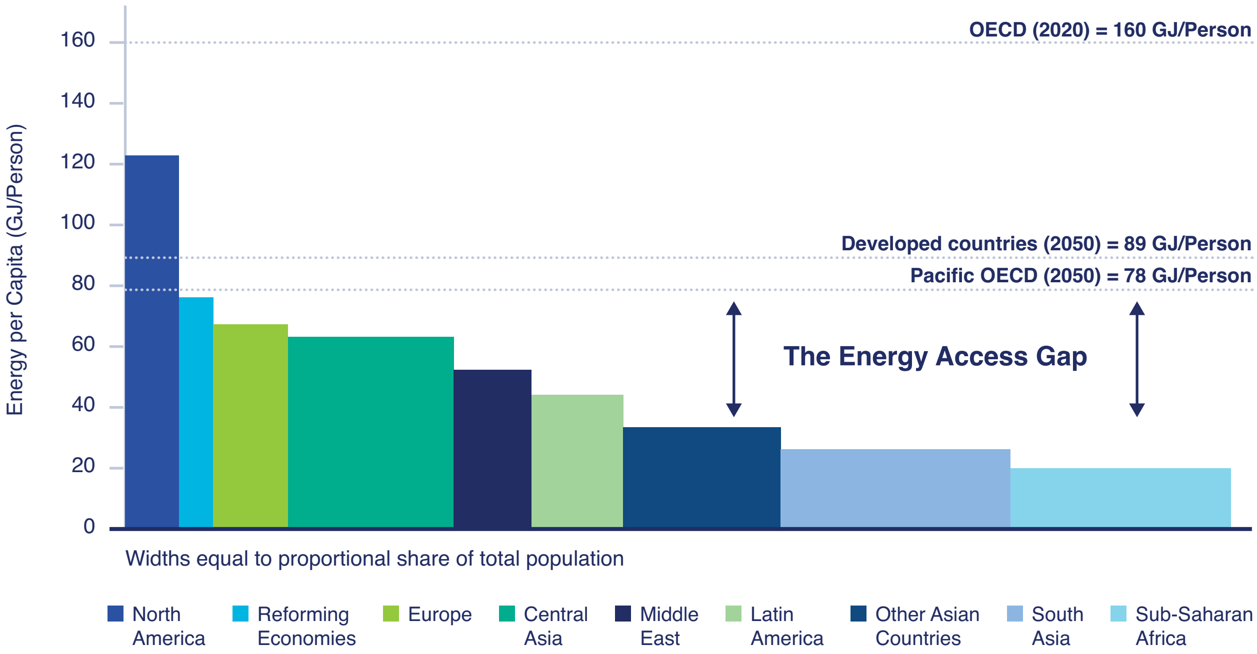


1.1 Why Nuclear Energy for Embarking Countries (and Everyone Else)?

Most analyses of global energy needs in a prosperous and climate-managed future conclude that, even with increased end-use energy efficiency, the world will need to double or even triple its electric power output by midcentury. This increase will be required to support the electrification of major sectors such as transport, industry, and buildings while also meeting increased demand from rising living standards and expanding energy access in the developing world. In a sustainable development, net-zero scenario developed by the International Energy Agency (IEA), for example, world electricity demand nearly triples, from 28,000 terawatt-hours (TWh) in 2021 to 73,000 TWh, by 2050.[1] And these projections don't necessarily capture the potential for continued energy demand growth in the global south beyond 2050: 13% of the world's population currently lives without electricity and 40% (three billion people) do not have access to clean fuels for cooking. With up to ten-fold differences in energy use per capita between different regions of the world, as shown in Figure 2, projections of future electricity demand from the IEA, the Intergovernmental Panel on Climate Change (IPCC), and other sources may still be understating the challenge of achieving deep decarbonization while also addressing stark inequities in global energy access.[2]

Figure 2: Projected energy demand in 2050 by region in IPCC scenarios

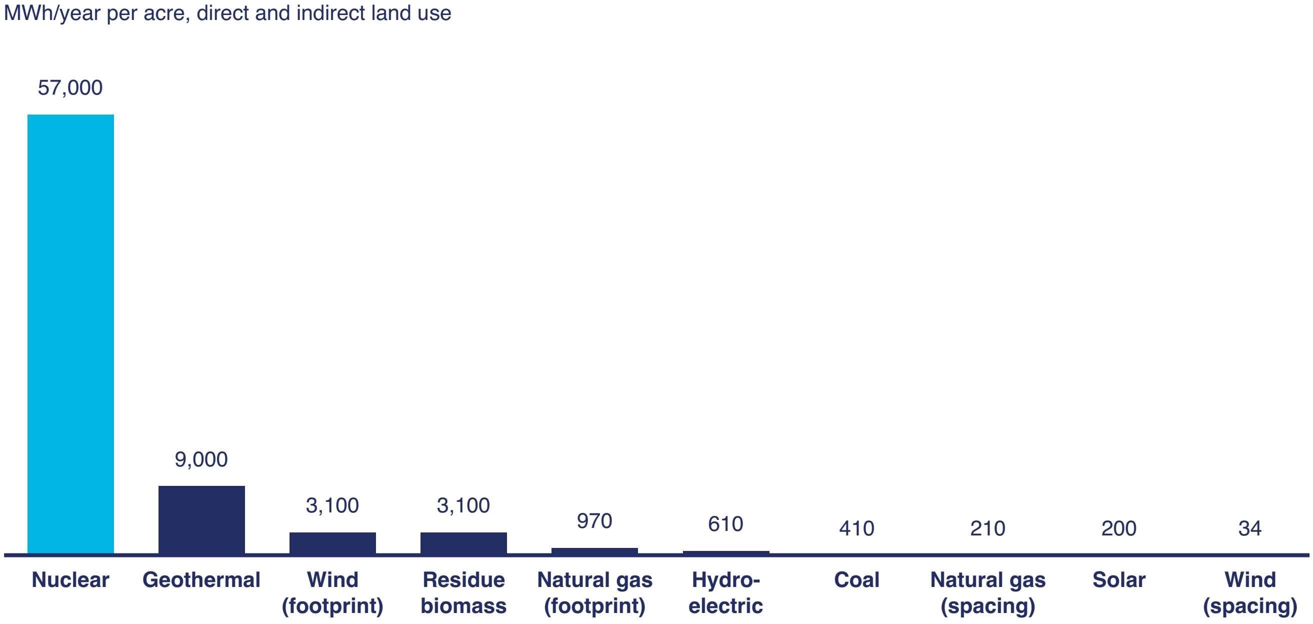
Source: Clean Air Task Force, with data from IPCC Sixth Assessment Report, average across scenario categories C1-C4. Development includes North America, Europe + Pacific OECD. Pacific OECD includes Japan, Australia, NZ. 2020 OECD: IEA WEO 2021



Three consistent themes emerge from nearly every major study of how to decarbonize energy systems while ensuring economic development, energy security, and reliability. First, as much of the global economy as possible needs to be electrified, which by itself means doubling or tripling the amount of electricity we produce in the next few decades. Second, while renewable resources like wind and solar can carry much of the burden, output from these types of generators varies substantially over multiple timeframes, especially seasonally. This means that firm, dispatchable, always-available zero-carbon sources will likely be needed to complete the power generation portfolio.[3] Firmness of electricity production is a critical dimension of a generating source that is not captured by the traditional levelized cost of energy (LCOE) metric, which could lead to false equivalence across energy technologies.

Third, many sectors of the economy may be challenging to electrify, and some forms of zero-carbon fuel will be needed for heat, combustion, and industrial feedstock. Nuclear energy is one important option to generate abundant zero-carbon electricity while also providing clean thermal energy and the energy to make zero-carbon liquid or gaseous fuels such as hydrogen and ammonia. Nuclear energy has two other major advantages in a land- and materials-constrained world: its spatial requirements are relatively compact due to its high-energy density (see Figure 3) and it requires considerably less concrete, steel, and other critical materials per unit of energy output compared to other zero-carbon energy sources.[4] Both factors are key considerations for the global development of large, critical energy infrastructure.

Figure 3: Land use efficiency of electricity generating technologies[5]



For these and other reasons, numerous studies, by the IEA[6] and others,[7] conclude that nuclear energy production might need to double, quadruple, or even increase ten-fold by midcentury to minimize costs and manage the reliability of a fully decarbonized electric system. Reaching even the most modest of these targets would require speeding up current annual nuclear energy deployment considerably.

1.2 Filling the Gap

Although the need for nuclear energy has come into clearer focus, effective approaches to scaling nuclear energy—even with new technologies such as small modular reactors (SMRs) and microreactors—remain elusive.

Of 195 countries in the world, only 35 plus Taiwan operate, or are in the process of constructing, nuclear power plants; of these, relatively few have developed the institutions and experience to further scale this technology. Meanwhile, much of the emerging demand for this technology comes from nations that have not been part of the nuclear club to date—especially nations whose ability to develop industry and raise living standards depends on energy access.

These include countries in Sub-Saharan Africa, like Ghana, Kenya, Niger, Nigeria, Sudan, and Uganda, as well as countries in Southeast Asia, like Indonesia, the Philippines and Vietnam, and in the Middle East, like Jordan and Saudi Arabia.

As part of their national policies, these countries have announced their intent to pursue nuclear energy and have been working with the IAEA to implement its “Milestones Approach” for supporting a sound development process for new nuclear power plants. Attempting to meaningfully deploy nuclear energy with limited to no nuclear infrastructure and no history of commercial nuclear development and operation, or government or other institutional knowledge, however, is uniquely challenging. The technology is complex; developing, licensing, building, and operating reactors requires specialized skill; and the institutions needed to govern the nuclear industry in each country require carefully considered structures, procedures, and know-how, not to mention funding.

1.3 Cross Cutting Themes and Caveats

Although subsequent chapters delve into these issues in detail, a few key themes are worth highlighting at the outset.

Nuclear delivery models, regulation, and finance are closely linked. Although this playbook addresses bankability, project execution, and regulation in separate chapters, many of these factors are in fact highly interdependent (see Figure 1). Specifically:

- As discussed in Chapter 4, the primary challenges to financing nuclear energy at scale especially for new local builds of a given design are managing costs, managing the cost of capital, and providing an adequate revenue model.
- These factors in turn are heavily influenced by the nuclear business and delivery model challenges described in Chapter 2 and the regulatory challenges addressed in Chapter 3. Licensing uncertainties plague nuclear new-builds even in mature markets; licensing new reactor designs (especially innovative ones) will be even more challenging in embarking countries that lack nuclear regulatory resources. Furthermore, the current construction-heavy, bespoke delivery model for nuclear projects contributes to increased costs and uncertainty around delivery times. All these factors are seen as red flags by investors and lenders; furthermore, they can drive up capital costs, make off-takers and governments reluctant to adopt revenue models that shoulder regulatory and project delivery risk, and increase the cost of capital.
- Addressing these challenges in an integrated way can turn a vicious circle into a virtuous one. A potential pathway forward may lie in adopting standardized, “productized,” highly manufactured plants and delivery models and IPD (using practices that have been demonstrated in other industries, such as gas-fired power and marine shipping), supported by large orderbooks. Regulatory harmonization and technical support for host country regulation can further reduce project cost, regulatory and delivery time, and risk. Coupled with a new multilateral institution that can catalyze access to global financial markets, these initiatives can enable the scale-up of nuclear in embarking countries.
- Targeted policy decisions are key to facilitating this industrial transformation and establishing new regulatory paradigms, and also to supporting the creation of new, nuclear-focused multilateral institutions.

1.4 Accelerating Sustained Development through New International Institutions

Just as equitable access to energy and managing climate change are global imperatives, so too is international cooperation to enable responsible nuclear energy deployment in embarking countries. Most of the initiatives described in this playbook will require multilateral cooperation. This will include coalitions of countries, likely a mix of embarking and established, in order to make progress. Indeed, we envisage a potential role for several new international and multilateral institutions: an ITSO to build regulatory capacity; arrangements that harmonize regulation across borders; and an International Bank for Nuclear Infrastructure (see Figure 1). Although these options would accelerate nuclear deployment in embarking countries, progress can still be made even without new international institutions through bilateral commercial, technical, and regulatory collaboration; shared know-how; and other resource sharing.

1.5 Approaches Benefitting Both Established and Embarking Countries

Although this playbook was designed for embarking countries, many of the options it outlines relating to bankability and finance, regulation, project execution, spent fuel management, and workforce development could also benefit nations that have already adopted nuclear energy, especially given expressed national policies concerning energy security, decarbonization and economic development. Nuclear energy is a globalized technology, operating in global capital markets with a globalized workforce and subject to norms that cross boundaries. And it is no secret that nuclear energy deployment in existing nuclear energy adopters has largely slowed to a crawl, partly due to many of the obstacles that also face embarking countries. Yet many existing nuclear energy nations have recently announced plans to increase nuclear energy deployment as part of larger national policies. Substantial synergies and shared benefits emerge between embarking countries and existing nuclear power nations as both invest in building scale, developing innovative regulatory approaches, and increasing financial confidence.

1.6 Applicable to Multiple Kinds of Reactor Technologies

Although SMRs, microreactors, and Gen IV designs with alternative fuels and coolants potentially offer certain benefits compared to large LWRs in operation today, the timing of their commercial availability is uncertain. Indeed, embarking nations will most likely wish to adopt commercially proven technologies with some track record of successful operation. The options described in this report are generally agnostic as to nuclear technology; however, countries will need to carefully evaluate how some new technologies impact economic, regulatory, and proliferation risks. It also true that a robust financial support system coupled with a harmonized regulatory system, as envisaged in this report, could be especially useful in accelerating the adoption of innovative technologies when they become commercially available.

1.7 One Size Will Not Fit All

This playbook provides multiple options for the responsible diffusion of civilian nuclear energy in embarking countries. But as with any playbook, the choice of particular options will depend on the financial, institutional, industrial, cultural, and political characteristics of each embarking nation and region. Options will also be shaped by the overall national energy policy ambitions set by each country. The options cover a wide range of possibilities; we hope this report will stimulate discussion about which elements might work best where.

1.8 The Role of Public Opinion and Public Acceptance

This playbook does not directly address public opinion regarding nuclear energy in embarking countries or elsewhere. Public attitudes toward nuclear technology, which may differ among different segments of the population, will doubtless play a role in how fast and where nuclear energy scale-up occurs in the coming decades. Much has been written on this topic that we do not have the space to cover here. However, two observations may be relevant. First, public opinion around the world is rapidly shifting toward greater support for nuclear energy, in part due to increasing awareness of the urgency and imperative to address climate change.[8] Second, some of the chief objections to nuclear energy on the part of decisionmakers and opinion leaders, as well as the public, stem from the view that it is too expensive, takes longer to deploy compared with other options, and comes with challenging waste and security issues. Successful execution of this playbook can provide convincing answers to those objections and build confidence in the responsible scale-up of this technology.

CHAPTER 2

Project Execution and Capacity Building

Chapter Summary

Nuclear project execution is complex, involving numerous activities, tasks, and processes that need to be carried out to construct, commission, and operate a nuclear facility. Capacity building for project execution is critically important in embarking countries to efficiently use scarce resources, avoid or at least mitigate the development and construction challenges of the past, and build momentum and support for nuclear projects. Insights can be drawn from successes of well-executed projects and advancements in nuclear project cost reduction, but there is currently no defined model for doing so.

What can be done now:

- Use best practice project management, integrating lessons learned globally from six decades of experience.
- Develop integrated development commercial entities that can unite different delivery elements and associated risk.
- Assemble multi-off-taker buyer consortia that can generate large orderbook demand that facilitates large upstream investment in manufactured, standardized nuclear projects.

Further options:

- Establish formal public-private global partnerships to provide IPD.

Nuclear project execution is complex, involving the numerous activities, tasks, and processes required to successfully construct, commission, and operate a nuclear facility. Various aspects of a project must be coordinated, including site assessments, procurement and technology selection, engineering, procurement, and construction (EPC); testing; regulatory compliance; operation and decommissioning and safety protocols, to ensure the facility is built and operated according to design specifications, within budget, and within the stipulated timeline. Project execution can be especially challenging for embarking countries, which may lack the resources (e.g., financial, human, etc.) and infrastructure needed to support projects of this type. These countries will need to simultaneously develop and execute nuclear projects while also building the institutional, organizational, and technical capacities needed to support safe nuclear operations in the near and longer term.

Most currently available nuclear facilities are large GW-scale LWR power plants that may have limited near-term potential to attract investments in some circumstances, given their design and construction complexity. Taking such large projects forward typically requires a significant commitment from the government of the host country or an external vendor country. Even in many established nuclear countries, some recent deployments have been beset by delays in investment, design, construction, and licensing and projects have often incurred cost and program overruns even after commitments are made. Although SMRs, whether LWR or non-LWR (i.e., Gen IV), may be more suitable for some embarking countries, those plants will present their own challenges given the technology's commercial nascency.

Capacity building for project execution is critically important in embarking countries to efficiently use scarce resources, avoid (or at least mitigate) the development and construction challenges of the past, and build momentum and support for nuclear projects. Insights can be drawn from well-executed projects and from progress in nuclear project cost reduction, but currently no defined model exists for success. This chapter identifies key challenges and current approaches to nuclear project execution, offers a framework for embarking countries to consider as they pursue new nuclear projects, and offers innovative options for project execution and capacity building.

2.1. Key Challenges in Nuclear Project Execution

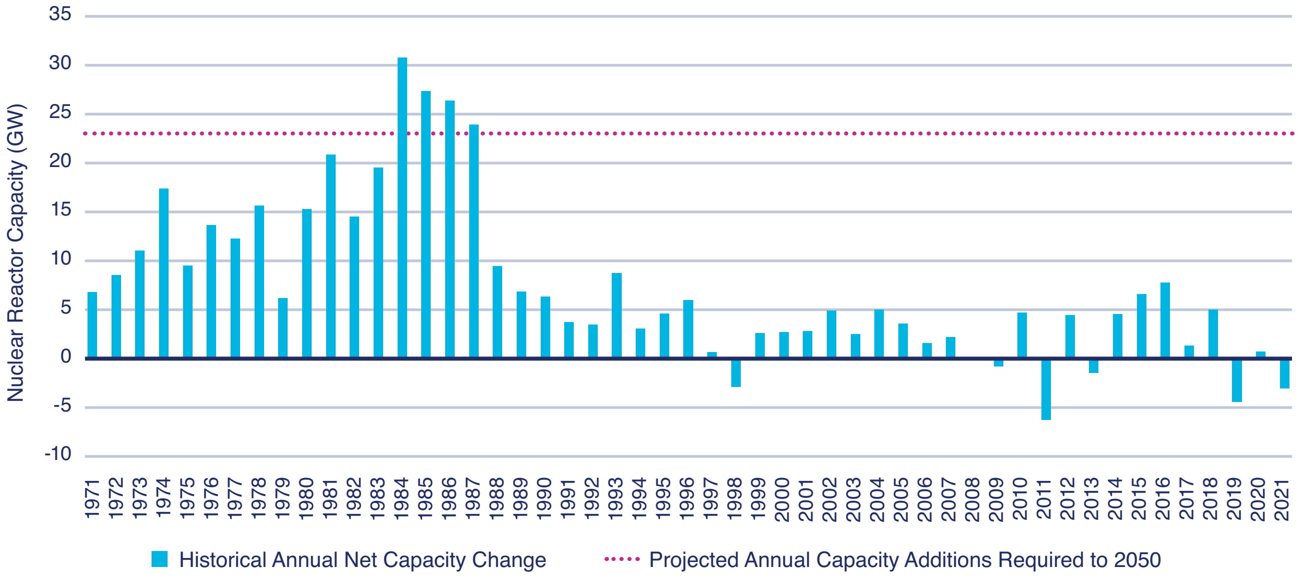
Even in countries that already have a nuclear fleet, deploying new reactors can be challenging, because these are usually extremely large, bespoke infrastructure projects that are based on first-of-a-kind reactor designs. As recent nuclear projects in the West have demonstrated, deployment barriers will be even more daunting in embarking countries if these challenges are not addressed adequately. The most salient challenges are briefly summarized below.

Complexity and Timeframe: The multiple complex activities involved in building a nuclear facility can take up to 15 years to complete, from design to concept through construction and on to operation. Moreover, the process from initial site identification and technology selection to commercial operation and eventual decommissioning has many interrelationships that will not be managed by a single organization. No integrated full-service development organization currently exists that could create an orderbook to catalyze standardization in the manufacturing and supply chain for nuclear projects.

Financial Challenges: Nuclear projects are capital-intensive and come with relatively high financial risk and long investment periods. New builds usually require state financial support and may face political hurdles. As a result of these hurdles, the pool of private investment capital available to bring new facilities into operation is limited. This is especially true for new local builds (NLBs), even in cases where the design is well tested (the proven South Korean APR-1400 design being built at Barakah in the United Arab Emirates (UAE) provides an example). This is also the case for SMRs, where the appropriate unit of analysis is an orderbook of multiple reactors of a given design in order to harness learning effects for cost reductions.

Supply Chain and Infrastructure: Globally, nuclear supply chains and industrial capability are limited because nuclear plant deployment during the past decades has been both relatively limited and quite sporadic (Figure 4). Moreover, the current project delivery model, with its emphasis on bespoke, customized construction projects, does not enable or promote investment in nuclear-related supply chains and resources. This results in supply chain bottlenecks and long lead times, including a constrained supply chain for nuclear fuel. New suppliers also face barriers to entry because they must make large investments to qualify performance and enhance their capabilities without a large orderbook to underwrite these efforts.

Figure 4: Change in global annual civilian nuclear reactor capacity, 1971 – 2021[9]



Licensing and Design: Licensing processes for nuclear plants are complex and challenging. This is especially true for new Gen III+ and Gen IV designs because of their novelty and because regulators lack experience with them.

Development and Construction: Several challenges flow from the lack of standardized "products" for build-out and series deployment, where construction considerations have not been explicitly embedded in the engineering design process. This can lead to incomplete pre-construction designs; complex and inefficient on-site construction; a dearth of capable and experienced workers; suboptimal management practices; and a lack of accumulated knowledge—in part because each nuclear project has a different program management process and lessons are not learned. The result is inefficient execution and project delivery, where fragmented processes do not facilitate cost reductions from the first-of-a-kind unit to the nth-of-a-kind unit. Utilities that purchase nuclear plants typically lack the in-house capability to manage and oversee the construction of these plants; instead, they rely on EPC firms and vendors, whose incentives are often not aligned with those of the utility.

Commercial Complexities: Because currently few global nuclear project enterprises exist, the market for project developers is constrained by the availability of a few large architecture and engineering firms, program management companies, and large consultancies competing for each project. Nuclear technology vendors typically do not assume a project development role as they view themselves as being in the business of selling nuclear plants, not delivering end-to-end projects. In addition, the very large capital investment required to construct new plants means that the financial appetite to take on an orderbook of multiple builds is beyond the balance sheet capability of most private actors. Even fewer firms are prepared to tackle the commercial complexities of developing new business models that involve non-electric uses of nuclear energy such as for industrial heat, hydrogen production, and desalination.

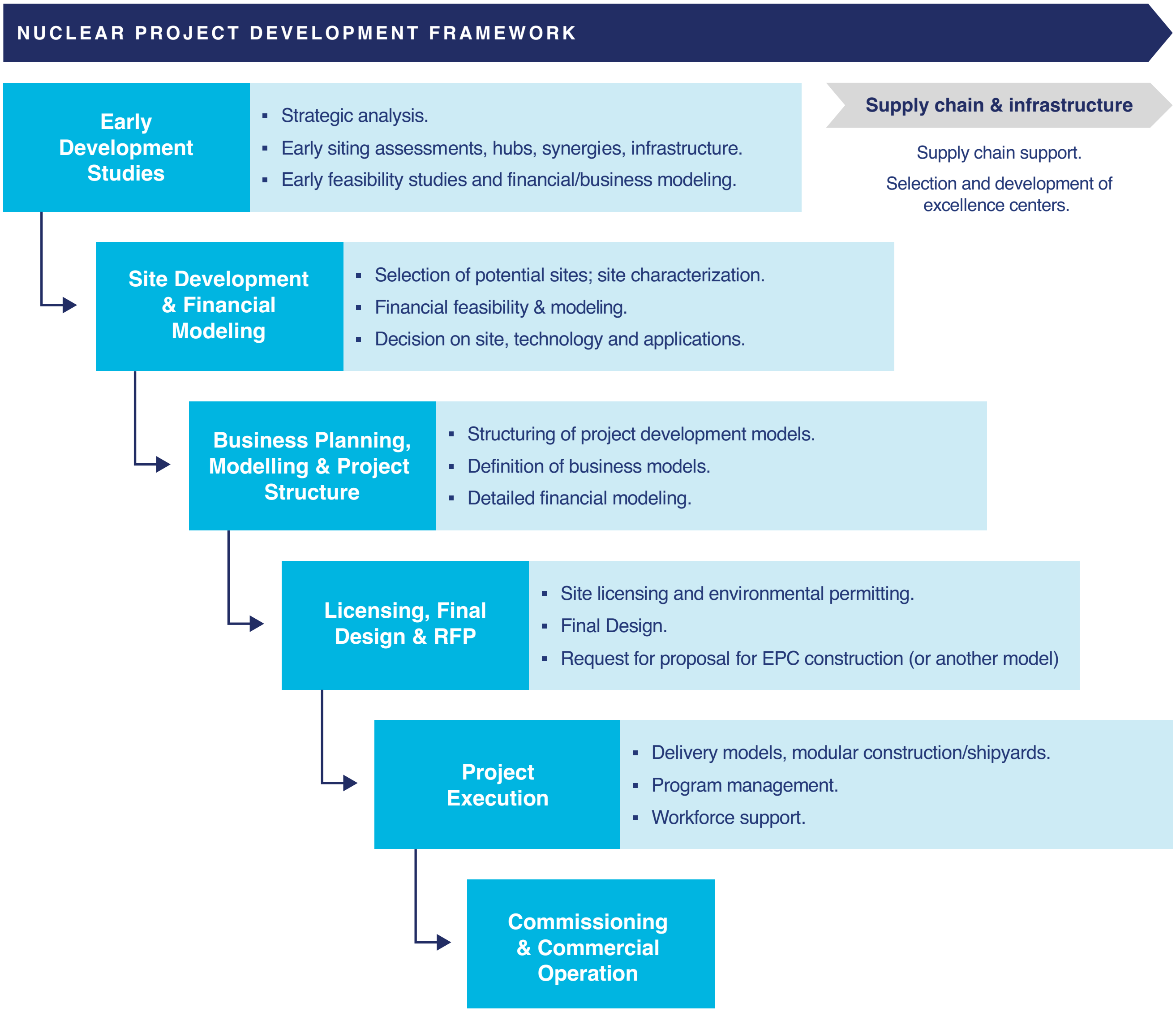
In summary, industry fragmentation, project complexity, and a small and sporadic orderbook means that insufficient predictable demand exists to catalyze an efficient supply chain and achieve continual learning. Moreover, no organization currently has the capability and skillset to integrate all nuclear project development steps from end-to-end and provide embarking countries with the project execution capability to support NLBs.

2.2 A Phase-Based Framework for Executing Nuclear Projects

Figure 5 presents a phase-based nuclear project development framework that could better address the project execution challenges described in this chapter. Considering that each country has different capacity and infrastructure to execute the phases of a nuclear project, a strategy for success that adequately accounts for local conditions and country preferences is needed at each step in the nuclear development framework.

Potential actions that should be considered in each phase of a project to enable more efficient overall deployment are presented in Table 1. Embarking countries need not incorporate all actions in their development plans; however, the table provides a broad overview of the range of aspects to consider.

Figure 5: Nuclear project development framework showing requirements at each stage in the process



NUCLEAR PROJECT DEVELOPMENT FRAMEWORK

Early Development Studies

- Strategic analysis.
- Early siting assessments, hubs, synergies, infrastructure.
- Early feasibility studies and financial/business modeling.

Supply chain & infrastructure

Supply chain support.

Selection and development of excellence centers.

Site Development & Financial Modeling

- Selection of potential sites; site characterization.
- Financial feasibility & modeling.
- Decision on site, technology and applications.

Business Planning, Modelling & Project Structure

- Structuring of project development models.
- Definition of business models.
- Detailed financial modeling.

Licensing, Final Design & RFP

- Site licensing and environmental permitting.
- Final Design.
- Request for proposal for EPC construction (or another model)

Project Execution

- Delivery models, modular construction/shipyards.
- Program management.
- Workforce support.

Commissioning & Commercial Operation

Table 1: Summary of end-to-end nuclear power development and potential actions for faster nuclear deployment

Nuclear Project Phase	Potential Actions to be Considered for Faster Nuclear Deployment
Early Development Study	● Lean on support from experienced and proven entities. ● Create a national or regional commission/body of knowledge/specific organization to integrate and oversee project development in its entirety (end-to-end). ● Study and explore applications of nuclear technology as part of national/regional energy plans. ● Enable technology transfer and facilitate nuclear imports policy. ● Integrate and centralize nuclear project development decision-making.
Site Development and Financial Modeling	● Select strategic sites considering technical requirements, hubs, potential applications, grid infrastructure, etc. ● Propose new business model applications for non-electric uses such as industrial heat, hydrogen production, and desalination. ● Propose new financial models to share and reduce risk.
Business Planning, Modeling, and Project Structure	● Select business model (BOO, BOOT, BOT/turnkey, IPP, EPC, PPP, etc.). ● Select energy contract model (regulated asset base [RAB], contract for difference [CfD], power purchase agreements [PPAs], physical/financial delivery, Mankala, heat purchase agreements [HPAs], etc.) and propose long-term agreements. ● Define funding structure: private equity, federal financing, export credit agencies (ECAs), bonds, and other debts alternatives for funding. ● Propose financial support policies (tax incentives, construction, and production tax credits or similar). ● Create orderbook for scalability, standardization of products, and robust regional/local supply chains, strengthening the nuclear sector for growth. ● Minimize and contain cost of capital by bulk purchasing (orderbook), providing financial backstop, supporting nuclear energy, selecting approved designs, choosing proven construction, and operating entities, support adequate revenue model, offer sovereign guarantee, long-term contracts, etc., as is further explained in Chapter 4.
Licensing, Final Design, and Request for Proposal (RFP)	● Create and structure local regulatory body. ● Engage with international institutions (IAEA, WANO, INPO, EPRI, ITSO/GLA, etc.). ● Promote qualification and training for required skills, knowledge, and capabilities of individuals, organizations, and institutions involved in nuclear power projects for capacity building. ● Select licensed and proven designs. ● Prepare RFP models that share completion risk with contractors. ● Establish long-term business relationships, preferably an equity partnership: joint venture (JV) or qualified consortium with EPC and vendor. Incentivize creating consortia or joint ventures including vendors, experienced EPCs, owners. ● Study scenarios where state-led turnkey model for a few select designs could lead to standardization and commoditization of the nuclear industry.
Project Execution (Construction) Commissioning and Decommissioning	● Establish a single management party or owner’s engineering company with proven expertise in integrating and managing several contractors (and subcontractors) at the same site on a single- or multi-project development. ● Apply Milestones Approach for sharing risk with contractors. ● Only start project execution when design is more than 90% complete. ● Promote product-based approach and promote standardization, modularization, shipyard models, etc. ● Promote training and qualification of workforce and use local workforce from similar industries. ● Create knowledge and skills transfer programs.
Supply Chain and Infrastructure	● Provide government support for building the orderbook to reduce risk and back up supply chain investments and create excellence centers. ● Promote standardization across designs. ● Integrate and build the necessary infrastructure for the nuclear power construction and operation. ● Adopt IAEA Milestones Approach (19 nuclear infrastructure issues).

2.3 Important Considerations for Embarking Countries on Delivering Nuclear Projects

A key to enabling nuclear energy development that is more financeable, faster to license, and easier to deliver to embarking countries is changing the global nuclear energy enterprise from a bespoke "project" model to a standardized "product" model. This approach is used routinely in other industries, such as those that deliver large airplanes, combined cycle gas turbines, marine ships, and offshore oil production rigs. One key lesson from past nuclear development projects is that the general lack of standardized designs leads to bespoke construction, which in turn does not fully allow for knowledge creation and transfer that could be applied in a repeated fashion. Therefore, it will be critical to leverage alternative, commoditized, and modularized approaches, while also exploring other delivery models that can drive down costs. Analysis of past successful nuclear scale ups in Canada, France, and South Korea shows that repeating near-identical designs that are fully complete before any concrete is poured is key to achieving cost reductions and on-time delivery.

Further reductions in cost and construction time can be achieved by increasing the nuclear plant content that is manufactured offsite, in large factories or shipyards, and by using design optimization for manufacturing and deployment (e.g., by standardizing parts, simplification, and enhanced constructability). The "productization" of nuclear energy facilities would not only reduce costs and speed delivery but could also simplify the licensing process because it would reduce complexity and variation across delivered products.

2.4 Standardization

Standardization can simplify regulatory processes, enhance knowledge transfer, and boost operational predictability—especially when paired with multiple deployments. By streamlining design approval and implementation, standardization can reduce uncertainties and costs by allowing for learning from previous projects. These benefits can be pivotal in driving nuclear development, because they involve creating a market for commodity components, fostering cost savings through economies of scale, enhancing manufacturing efficiency and quality control, and creating a more robust supply chain. Furthermore, standardization can drive synergies if the same reactor design is used across multiple sites, or at a multi-unit site, which creates opportunities to standardize common systems and components while enabling the sharing of platforms, equipment, and infrastructure.

2.5 Modularization

Modularity may be relevant for nuclear development in two ways. First, it can allow for the aggregation of reactor units (built in series or parallel, mitigating investment risk) to establish a larger nuclear plant, which would remove redundancies in regulatory approvals, design, and construction site mobilization, and take advantage of more durable demand signals. Second, modularity can support the use of prefabricated modules with final assembly at the actual site. This can significantly reduce costs and allow for faster project delivery.

2.6 Factory-Based Manufacturing vs. On-Site Construction

Another possibility for improving the delivery of nuclear energy is to shift to manufacturing of maximum content of nuclear plants. This could allow project developers to leverage lessons learned from other heavy industry manufacturing sectors mentioned above which have proven productivity, manufacturing flexibility, cost competitiveness, and high-quality standards.

One example of such a manufacturing-based approach would be using state-of-the-art shipyard sites to manufacture and assemble portions of a nuclear plant which would avoid some of the infrastructure needs associated with traditional on-site construction, reducing overall costs and delivery time. Another advantage of using shipyards for nuclear construction is the automation these shipyards already have in place and their experience with advanced manufacturing techniques to deliver large complex products repeatedly, within budget and on schedule.

2.7 Potential Initiatives for Project Execution and Capacity

Recognizing that most countries still lack the capability and experience to integrate all the steps in nuclear project development shown in Figure 5, we propose two broader initiatives that could address these shortcomings, support specific solutions identified in our phase-based development framework, and thereby enable a commercially viable "product" that embarking countries and economies could buy and deliver locally on a more integrated, end-to-end basis. The two initiatives we propose are an integrated nuclear development organization and buyer consortia. Together, they have the potential to drive the nuclear industry to adopt a product (vs. project) approach and significantly increase manufacturing and supply chain capabilities by creating a large orderbook.

2.7.1 Integrated Development Organization

Creating a nuclear integrated development organization, or many such organizations, would be a strategic solution to accelerate project development and deployment. Such an organization would not be aligned with any specific technology vendor or single geopolitical interest, permitting it to focus on getting standardized products built as fast and inexpensively as possible.

Such an organization could provide integrated assistance to embarking countries from the early project planning and siting stage to the deployment and commissioning stages, supporting them with the right technical and management expertise throughout. It could also be responsible for specific, selected phases of project development, depending on the host country's capabilities and needs.

A nuclear development organization could take different forms (e.g., private, public consortium, public-private partnership, international public/state consortium, or other), and could even be created by a consortium of states. A further function it could serve would be to support the creation of centers of excellence across regions that could supply skills and material for a large nuclear build-out. Case-by-case, an organization of this type could support embarking countries by:

- Assisting with the procurement process to ensure the best technology option for the country is procured.
- Providing support for siting assessments, feasibility studies, and early project development.
- Working with technology providers to develop nuclear energy project applications to the benefit of the country.
- Interfacing with potential funders to secure financial investment.
- Using the design acceptance certificate (DAC) (discussed in Chapter 3) to reduce project delivery risk and speed up licensing.
- Working with the ITSO (Chapter 3) and in-country regulators to ensure proper and efficient licensing and permitting of nuclear projects.
- Implementing a shipyard-built and multi-country product procurement model with dedicated factories, supply chain infrastructure, and transportation networks.
- Identifying and propagating lessons learned and best program management practices.
- Providing technical, legal, and financial modeling, coordination, and development skills.

Such organizations could operate in different formats on a case-by-case basis—for example, as an international organization that delivers projects to the embarking country with support from countries with more developed programs, or as a new local entity tasked with implementing and integrating each step in the nuclear development framework with assistance from other experienced countries and stakeholders. Possible permutations include:

- A single, external entity serving each host country's specific needs.
- An external regional and/or global nuclear development organization (for example, an "Eastern European Buyers Consortium").
- A new local entity or power utility that would subsequently transfer to the state, as in a build-own-transfer (BOT) model.
- An in-country cooperative (co-op power) model (such as the Finnish "Mankala" model) in which energy users are included as shareholders in a project.
- A state-led entity that offers a few turnkey designs with the aim of supporting greater standardization and commoditization in the nuclear industry.

An international nuclear development organization (INDO) of this type could catalyze investment by providing integrated, end-to-end support in collaboration with embarking countries and according to their specific needs. In some cases, it could lead the entire process of project development; in others, it could assist in specific areas where the host country lacks requisite skills and expertise. In all cases, the host country would still play a large role in the process and would be the final decision-maker.

2.7.2 Buyer Consortia to Enable Orderbook Formation

Scale and repeatability are critical to the success of a cost-managed nuclear industry, as many studies have shown.[10] They can be achieved only if the orderbook for nuclear designs is large and certain. By creating the necessary scale of demand, buyer consortia would facilitate a commoditized product supply chain, standardization and learning through doing. Such consortia could be organized around specific regions and coalitions of countries, industry clusters, or public-private partnerships. Whatever their form, they would leverage their combined buying power to commission dozens of units of the same design under umbrella contracts, sharing the benefits of scale and learning from doing. Consortia could participate as off-takers through PPAs, as turnkey owners via BOT models, or as joint equity participants (e.g., the Finnish "Mankala" model referred to above). Organized buyer consortia could also integrate and share expertise for the development of nuclear power locally and regionally.

CHAPTER 3

Regulatory System Development

Chapter Summary

Establishing a robust nuclear regulatory regime is of paramount importance for sustaining a nuclear industry, particularly for an embarking nuclear country. Such a regime serves as a cornerstone for safe and responsible nuclear development, ensuring the well-being of both the public and the environment.

Embarking countries face regulatory development challenges because key considerations surface when implementing a regulatory system and several options emerge for doing so. Furthermore, although existing institutions and pathways for building regulatory regimes in embarking countries exist today, new institutions and pathways could expedite the process and optimize nuclear deployment.

What can be done now:

- Create multilateral agreements for international transfer of design certifications.
- Develop in-country regulatory capability, borrowing from global best practice through bilateral and multilateral partnerships.

Further options:

- Establish an ITSO to support nuclear development in embarking countries by assisting with license applications, inspections, and regulatory training, and addressing resource constraints and accelerating nuclear deployment.
- Pursue more extensive global licensing harmonization.

Establishing a robust nuclear regulatory regime is of paramount importance for sustaining a healthy nuclear industry, particularly for an embarking nuclear country. Such a regime serves as a cornerstone for safe and responsible nuclear development, ensuring the protection of both the population and the environment. It does so by providing a structured framework to oversee the entire nuclear life cycle, enforcing strict adherence to international safety standards, and minimizing the risk of harm from accidents or radiation exposure. A strong regulatory regime also fosters international credibility and cooperation by signaling a commitment to responsible nuclear practices, facilitating collaboration, and attracting foreign investment. Finally, effective regulation enhances public confidence and acceptance, addressing concerns and promoting informed decision-making while aligning nuclear endeavors with the societal interests of the embarking country.

This chapter briefly explores the regulatory development challenges faced by embarking countries, the role of the IAEA, key considerations for implementing a regulatory system, and several options for structuring such a system.

3.1 Challenges for Developing a Regulatory System

Licensing remains a challenge for large-scale deployment of nuclear energy even in markets with decades of experience licensing and deploying reactors. For one, the lack of a harmonized international nuclear licensing regime means that vendors undergo duplicative licensing processes in different jurisdictions. Furthermore, established regulators have also struggled to adapt regimes designed for large LWRs to newer, advanced reactor technologies. Licensing a nuclear project in an embarking country is especially challenging, however, because along with building the power plant itself the embarking country needs to simultaneously create the government infrastructure necessary to license and regulate ongoing plant operations. These activities require each embarking country to establish a robust, technically skilled licensing agency with the resources needed to review license applications. Key challenges for regulatory system development are summarized below.

Lack of Human Resources in Embarking Countries: Because most embarking countries lack comprehensive nuclear licensing programs, they must either cultivate substantial domestic technical expertise or allocate significant financial resources to obtain outside technical support.[11]

Lack of Financial Resources in Embarking Countries: Embarking countries with developing economies face additional financial challenges for nuclear program development. Although they can seek external financing to build facilities, external financial support for establishing nuclear regulatory capabilities is typically limited. Creating related programs at domestic universities or sending students abroad is costly, and retaining human resources becomes expensive as trained experts are often lured away to positions in other countries that offer higher salaries. Mature market regulators often use technical support organizations (TSOs) to supplement internal capabilities, but this option is viable for only a few well-funded countries.

Lack of Adequate Human Resources Globally: Developing a domestic nuclear licensing program requires resources that are already in limited supply even in countries with an established nuclear industry (workforce development issues are discussed further in Chapter 7). In fact, technical nuclear expertise is limited globally, and many nuclear engineers and scientists are nearing the end of their careers. Developing a replacement workforce will take time, initiative, and resources.

Inefficiency of the Current Regulatory Model: The current regulatory model assumes that any country building a nuclear power plant is pursuing a full-scale nuclear program, including GW-scale reactors and comprehensive regulatory capabilities. However, many countries today are exploring SMRs and microreactors for various applications, as these technologies have inherent safety features and lower operational demands. For these countries, the current model creates barriers because it requires a heavy investment in nuclear regulatory capabilities—at the same level as countries that are pursuing larger reactors—which could lead to an inefficient use of scarce resources.

Lack of a Harmonized, Streamlined Approach: As already noted, the lack of a harmonized international nuclear licensing regime is an obstacle to licensing new nuclear reactors, even in mature markets. Without an effective process for streamlining the licensing process, embarking countries could take different regulatory approaches. In that case, nuclear suppliers would have to sink resources into multiple repetitive, concurrent design reviews, which would increase costs and exacerbate the difficulties of deploying a given design in more than one country. The fact that suppliers have finite resources to go through multiple country licensing reviews creates inefficiencies and could have a chilling effect in the ability of embarking countries to pursue nuclear projects.

3.2 The Role of the IAEA

The IAEA plays a vital role in assisting embarking countries as they pursue nuclear energy programs. Its Milestones Approach, which consists of three sequential phases and 19 milestones, provides a structured framework to guide countries in developing nuclear regulatory infrastructure. The IAEA also conducts integrated nuclear infrastructure reviews (INIR) to help embarking countries assess their status in terms of having the national infrastructure to introduce nuclear power using the phases and metrics in the Milestones Approach. In addition, the IAEA has a technical cooperation program that provides support in areas such as nuclear knowledge development and management, radiation safety, and nuclear security.

With respect to harmonization,[12] IAEA's Nuclear Harmonization and Standardization Initiative (NHSI) aims, among other objectives, "to increase regulatory collaboration among member states, avoid duplication of efforts, increase efficiency, and facilitate the development of common regulatory positions without compromising nuclear safety and national sovereignty." This support for harmonization is very important given the IAEA's ability to engage broadly with member states and bring attention to the regulatory obstacles that confront nuclear energy globally.

The IAEA's programs, however, are limited. As a multilateral organization, the IAEA is hampered by the inherently slow nature of international consensus-building and decision-making, and the need to respect each country's sovereignty, which includes acting only when a member state requests it. The IAEA is not a technical support organization or consultancy, and although it can offer some technical support, this assistance is limited and cannot be commercial in nature. The IAEA is also not a regulator—because it can only issue guidelines, the licensing function must still be performed by a national authority. As a result, embarking countries, although they can look to the IAEA for some support, must still shoulder the primary burden of developing the regulatory infrastructure and human resources to implement nuclear power programs.

3.3 Some Options

New options could be considered to address these challenges. Ideally these approaches would consider several key criteria, such as those described below.

3.3.1 Design Licensing vs. Site Licensing

The distinction between design and site licensing is a critical consideration in deploying nuclear reactors because each of these types of licensing has a vital role to play in ensuring the safety, efficiency, and regulatory compliance of nuclear power projects.

Design licensing focuses on approving the reactor's design itself, which includes evaluating its technical specifications, safety features, and overall suitability for operation. This stage is paramount as it sets the foundation for a reactor's safety performance throughout its operational lifespan. Rigorous design scrutiny helps identify potential vulnerabilities, ensures adherence to international safety standards, and allows for improvements based on lessons learned from existing reactors. By scrutinizing the reactor design, regulatory authorities can significantly reduce the risks of a nuclear accident and enhance public confidence in the technology.

On the other hand, site licensing pertains to approving the specific location where the reactor will be constructed and operated. This phase involves a comprehensive assessment of the chosen site's geological, environmental, and infrastructure characteristics to ensure that it can safely accommodate the nuclear facility. Proper site selection minimizes natural and man-made hazards, addresses potential impacts on local communities and ecosystems, and enhances emergency preparedness. The site licensing process aligns with the broader goal of mitigating potential risks and ensuring that the reactor operates in a secure and stable environment. Both design and site licensing, although they constitute distinct requirements, are interdependent components that collectively contribute to the safe and effective implementation of nuclear energy projects.

However, significant efficiencies could be achieved if embarking countries were to rely on multilateral design licensing processes as described below, focusing the bulk of local regulatory effort on-site licensing.

3.3.2 LWR vs. Non-LWR Licensing Needs

When establishing a regulatory regime, embarking countries should consider the types of technologies they will be deploying.

Regulating LWRs versus advanced reactors entails distinct considerations due to differences in technology and design. LWRs, which include pressurized water reactors (PWRs) and boiling water reactors (BWRs), have been extensively operated and regulated for decades.

They benefit from a wealth of operational experience, well-established safety protocols, and a comprehensive understanding of their behavior under various conditions. Regulatory frameworks for LWRs have evolved over time, supported by lessons learned from operational incidents and accidents such as Three Mile Island and Fukushima. This accumulated knowledge has led to refined safety standards, robust emergency response plans, and enhanced engineering practices, all of which contribute to the overall safety and reliability of LWRs.

In contrast, regulating advanced reactors introduces novel challenges. Because these reactors often use innovative designs, alternative fuels, and diverse cooling methods, they require tailored regulatory approaches. Although advanced reactors offer potential advantages such as increased efficiency and reduced waste generation, their unique characteristics mean that a comprehensive evaluation is needed to ensure safety. Regulatory agencies must work closely with developers to assess new technologies, address potential risks, and establish appropriate licensing criteria. The experience gained from regulating LWRs provides a valuable foundation, enabling regulators to draw insights from established practices while adapting these practices to the evolving landscape of advanced reactor technology. This accumulated expertise can be very helpful in maintaining a proactive, adaptable regulatory environment that fosters the safe and responsible development of new nuclear facilities. Nevertheless, even industrialized countries with substantial nuclear programs, as a rule, struggle to provide adequate regulatory regimes for new technologies.

3.3.3 Governance Structure

Distinct approaches to governing nuclear power, including approaches that separate oversight and promotional roles, offer value in striking a balance between harnessing nuclear energy's benefits and upholding rigorous safety, security, and environmental standards. Although many countries and organizations opt for an independent regulator to ensure unbiased decision-making, various governance models could be effective. Independent regulator models establish clear boundaries between regulatory oversight activities and activities to promote nuclear expansion with the aim of reducing conflicts of interest and bolstering transparency and public trust. Regulatory authorities, focused on safety and security, objectively assess projects, enforce international standards, and ensure operational integrity. Alternative approaches might involve collaborative regulator–industry partnerships that simultaneously drive research and societal benefits while also assuring safety and fostering confidence in responsible nuclear development.

The IAEA itself highlights “effective independence” as a core principle with the objective of protecting regulatory autonomy from undue influence, as reflected in standards like its Fundamental Safety Principles and Code of Conduct on the Safety and Security of Radioactive Sources. Regulatory autonomy is critical to guarantee objective decision-making and transparent execution of responsibilities, which in turn serve to bolster public confidence, potentially enhance nuclear safety, and prevent potential conflicts of interest that could compromise regulatory effectiveness.

Regulators in Organisation for Economic Co-operation and Development (OECD) countries tend to share characteristics that include technical expertise, transparent communication, collaboration with stakeholders, and continuous improvement. These regulators often maintain a two-way relationship with relevant governmental bodies, research institutions, and international organizations to exchange best practices, harmonize regulations, and stay abreast of emerging technologies and safety advances. Regular interactions with industry stakeholders and the public allow regulators to address concerns, encourage feedback, and integrate diverse perspectives into their decision-making processes. Additionally, prioritizing continuous improvement encourages regulatory adaptations in response to evolving scientific understanding, lessons from operational experience, and advances in safety practices.

3.4 Potential Regulatory Approaches for Embarking Countries to Consider

In light of the challenges and necessary considerations detailed above, strategies for reducing licensing barriers in embarking countries can take different forms but would ideally involve two key elements: (1) minimizing human resource and financial demands, and (2) creating a framework that would streamline nuclear licensing across countries.

The experience of the UAE, described in the box, is an example from a country that has recently experienced the regulatory development process while striving to incorporate these elements. A related option, explored here, is to create an ITSO that could provide licensing and oversight assistance to regulators in embarking countries.[13] A further option, which could be complementary, is to establish a mechanism whereby an international body grants certifications of new reactor designs; these certifications could then be used by the embarking country to begin its in-country licensing process.

UAE Experience

The United Arab Emirates embarked on the process of establishing a nuclear regulatory authority and licensing approach for its nuclear energy program starting in the mid-2000s. This involved engaging in extensive international cooperation and seeking guidance from established nuclear countries and their regulators, the IAEA, and other relevant organizations. Key steps included creating an autonomous regulatory body, called the Federal Authority for Nuclear Regulation (FANR), and developing a comprehensive legal and regulatory framework that aligns with international standards and best practices, including the IAEA's milestones.

Importantly, while the UAE benefited from international experience, it did not copy any established regulatory regime and opted to not develop design licensing capabilities or authorities. Instead, the government accepted the reactor design review from its chosen reactor vendor's country of origin. In all, the UAE's approach offers a successful representation of the business-as-usual model. It must be noted, however, that the UAE has an abundance of resources that many potential embarking countries do not have. This is why other options will be needed.

3.4.1 International Technical Support Organization

Establishing an ITSO would help ameliorate the problem of constrained resources and accelerate nuclear deployment by providing various services to host countries, including:

- Conducting and reviewing license applications for constructing and operating new nuclear power plants;
- Assisting with inspections while constructing and operating new nuclear power plants; and
- Providing training services to national regulatory bodies to help with oversight functions, which would supplement training and support provided by the IAEA. The purpose of training is to support and accelerate the ability of national regulatory bodies to eventually perform their regulatory functions without significant support from the ITSO.

These services would be provided by a pool of subject matter experts drawn primarily from existing TSOs, which are traditionally composed of private consulting firms and national organizations and are used extensively by established national regulatory bodies. The UAE, for example, used three different TSOs to support the reviews of the construction and operating license applications, as well as to support inspection services. However, the UAE had the financial resources to pay for the services of these TSOs. The ITSO and the services that it provides, on the other hand, would ideally be funded by vendor country governments, and potentially other sources, initially like philanthropies.

Voluntary commitments by emerging nuclear countries to use the services offered by the ITSO and to accept design reviews conducted by another competent nuclear regulatory body, such as was done in the UAE, would be an important element of this approach. Such commitments would facilitate streamlined licensing by preventing the development of disparate design licensing regimes in each embarking country and avoiding repetitive design certification processes.

The ITSO would have several key design objectives:

- **Safety**: Every aspect of the ITSO would be designed and implemented with nuclear safety as the primary objective.
- **Independence**: The ITSO would be an independent organization with "firewalls" in place to prevent domination or control by any government or private entity.
- **Minimal Permanent Structure**: To make the ITSO function more effectively and efficiently, its permanent staff would be limited to a small group of core management and administrative support personnel.
- **Funding**: The ITSO would be predominantly funded by the governments of nuclear vendor nations, although some philanthropic funding is also possible.

With these features, the ITSO would help embarking countries accelerate not only progress toward realizing their nuclear programs but also progress toward developing the human capital necessary to support long-term nuclear operations.

3.4.2 International Cooperation on Design Certification

To further streamline the licensing process, embarking countries could also make a voluntary commitment to accept design reviews conducted by an international cooperative body. The embarking country's regulatory body would have the option to confirm the design review, or a subset of the review, but would not be obligated to conduct a full review itself. There is precedent for this approach—as already mentioned, the UAE accepted the design review conducted by South Korea for purposes of licensing and constructing the Barakah Nuclear Power Plant. This approach helps lower costs for suppliers and project developers by avoiding repetitive design certification processes, maximizing modularity and standardization across the global fleet, and expediting the deployment of reactors by several years. This process would have some similarity to the "type certification" approach used by member countries of the International Civil Aviation Organization (ICAO) to harmonize licensing for aircraft.[14]

Using the ICAO precedent, an international body would provide civil nuclear reactor technology developers with a process to achieve a globally acceptable DAC. The process for obtaining a DAC would be based on the best and most appropriate regulatory procedures for designing and assessing the safety of advanced nuclear reactor technologies. However, in contrast to the ICAO model, the international nuclear body would also issue the DAC, rather than just promulgating its certification process to participating states.

In this model, when a nuclear reactor technology has obtained a DAC, that certification would be acceptable to any country that has integrated the DAC certificate and process into its regulatory regime. Thus, the DAC could offer existing regulators or, in this case, regulators in an embarking country, a generic assessment of the candidate technology's safety and design, before committing to a project. The DAC would form a basis for the pre-construction safety report (PCSR) with appropriate site-specific technical information and environmental impact assessments. It could range in comprehensiveness, from a full design review that requires no further in-country review (as in the UAE example) to an early-design review (as with the Canadian regulator's pre-licensing vendor design review). It would be the embarking country's prerogative to decide which level of review to accept.

Ultimately, the host country must take ownership of the licensing process for a nuclear technology, and that process must be designed and specified by a country's nuclear regulator in accordance with the regulator's licensing model. However, the DAC option could potentially reduce licensing time by several years, depending on what level of review an embarking country chooses.

CHAPTER 4

Project Bankability and Finance

Chapter Summary

Market-only mechanisms to finance nuclear projects are insufficient; national governments must play an active role at the outset of a nuclear program. A first challenge is creating the economic conditions to attract sufficient capital for successfully planning, building, operating, and decommissioning nuclear energy facilities. Enabling business models that effectively leverage public and private resources is a key task for public administrators. Three principles to increase the bankability—or investment quality—of new nuclear projects in embarking countries should guide these efforts: (1) minimize and contain project costs, (2) minimize the cost of capital, and (3) support adequate revenue models. Specific business models and financing pathways should be selected to adequately address all three.

What can be done now:

- Establish clear signals welcoming nuclear investment.
- Generate orderbook for multiple builds of the same design.
- Require implementation of IPD best practices.
- Share risk of cost overruns on early deployments.
- Choose an appropriate project delivery approach.
- Work with certified designs and proven delivery entities.
- Promulgate an adequate revenue model ahead of time.

Further options:

- Create a multilateral “International Bank for Nuclear Infrastructure” to de-risk early deployments.

Nuclear energy facilities are characterized by high technical complexity, a demanding regulatory environment, relatively long construction duration, high capital intensity, low and stable operating costs, and very long operational lifetimes. Because of these characteristics, market-only mechanisms to finance nuclear projects are insufficient—national governments must play an active role at the outset. For many of them, creating the right economic conditions and attracting sufficient capital to successfully plan, build, operate, and decommission nuclear energy facilities will be a key challenge.

Although countries like Canada, France, the UAE, and the United States relied heavily on domestic public sector capital sources when they developed their commercial nuclear programs, this approach is likely not possible or desirable for countries now, especially embarking countries. Instead, embarking countries can benefit from nuclear expertise—and capital—provided by foreign counterparts such as international public and private infrastructure investors, experienced developers, and foreign export-import (ExIm) banks. This is not to say that embarking governments will have a minimal role in capitalizing new nuclear projects. Rather, their efforts may be better directed to enabling business models that effectively leverage public and private resources and create an environment that fosters sufficient capital flows. Put another way, embarking country governments may be better served by using targeted interventions to increase the quality of new nuclear investments.

The first step is to select project delivery and operating models that adequately account for local governance structures and capital availability and facilitate access to supportive foreign public and private financial instruments. Multiple pathways exist. Even so, some countries will face financing challenges due to various sovereign constraints that could otherwise be ameliorated by multilateral and/or regional development and/or infrastructure banks. At present, however, almost all such institutions are choosing not to fund new nuclear construction. Given the capacity limits of foreign ExIm banks and percentage and content funding limitations to which they're subject, a new purpose-built nuclear infrastructure bank (such as the proposed International Bank for Nuclear Infrastructure—IBNI)[15] may be needed to support simultaneous nuclear development efforts by multiple embarking countries.

4.1 Principles to Increase the Bankability of New Nuclear in Embarking Countries

Three principles should guide efforts to increase the bankability—or investment quality—of new nuclear projects in embarking countries: (1) minimize and contain capital costs, (2) minimize the cost of capital, and (3) support adequate revenue models. Specific business models and financing pathways should be selected to adequately address all three.

The first principle is crucial given the prominence of capital costs in the overall cost structure of nuclear facilities. These costs will be especially large for NLBs, even in cases where the project is well characterized. Costs should come down with successive builds, as inefficiencies are addressed and as local capacities (regulatory, construction, and operation) improve. Nevertheless, efforts to minimize capital costs will reduce the total financing required, make facilities more economically competitive, and ensure more efficient use of scarce resources. An emphasis on cost containment also promotes a risk mitigation mindset and attention to proven tools for reducing risk (e.g., IPD models, design-build-finance-maintain turnkey solutions, etc.), as discussed in Chapter 2.

A related priority is minimizing the cost of capital, which is directionally related to the aggregate risk of the underlying project. Given the size of the capital outlays needed to execute a nuclear project, the cost of capital usually represents a material portion of the overall project budget. Moreover, cost of capital is relatively higher for NLBs given the new institutional, economic, political, and development demands they entail, even for entities that are experienced with financing foreign projects. The cost of capital also represents the aggregate preference of investors to place capital into a given kind of project as measured by the total supply of funds available. Currently, the fact that many multilateral development banks, multilateral infrastructure banks, and regional infrastructure banks will not finance new nuclear builds significantly constrains available capital supplies. Minimizing the cost of capital through various sovereign and foreign de-risking approaches will have first-order effects in terms of reducing economic barriers to new nuclear deployment.

Finally, a project must generate adequate revenues to provide a reasonable return on capital investment, in addition to covering all fixed and variable costs. Once built, nuclear plants can be expected to provide baseload power and heat for 60-plus years with relatively low and steady operating costs. This means that the initial capital expenditure (capex) needs to be financed over a long period of time before investors realize positive returns—in other words, it can take from 15 to 20-plus years to recoup the initial investment. Facilities, once built, must achieve high utilization and adequate unit revenue to generate the overall cashflow needed to meet investor (debt and equity, public and private) demands. Revenue risks are defined by the challenge of securing stable and sufficient cashflows to cover debt service and return capital and margin to equity investors. Even an industry that has achieved successful commercial deployment may still fail to generate enough revenue to attract private investment—for various reasons that might include, among others, a lack of long-term sales contracts, unfavorable electricity market rules, and challenging federal incentive structures.

The three principles of capital cost containment, cost of capital minimization, and revenue sufficiency are clearly interconnected. Addressing all of them simultaneously will increase the bankability of new nuclear projects in embarking countries. Crucially, this means considering and designing the principles into policies and tools early in the development of a nuclear regulatory regime. Mechanisms to increase bankability must be present well before any funding is tendered for specific facilities, so that project sponsors and investors can accurately assess investment prospects and select a delivery model that maximizes the odds of success.

4.2 Increasing the Bankability of New Nuclear Projects in Embarking Countries

This section reviews specific strategies for increasing the bankability of new nuclear projects in embarking countries.

4.2.1 Strategies for Minimizing and Containing Capital Costs

We identify four strategies for minimizing and containing capital costs, all of which could be applied to building new nuclear facilities in embarking countries.
As countries gain experience, the specific mix of approaches may change based on each country's outlook for supporting a domestic nuclear industry and the status of its capabilities and resources.

4.2.1.1 Require Implementation of Integrated Project Delivery Best Practices

Multiple studies indicate that significant cost reductions can be obtained for nuclear facilities through rigorous and extensive use of construction planning best practices.[16,17,18,19] Best practices include (1) completing design before starting construction; (2) conducting a detailed review of the design's constructability, as well as design-to-construct and design-to-operate analyses; (3) making a project go/no-go decision only once there is a resource-loaded, achievable, and detailed integrated project schedule; (4) maintaining strict adherence to quality assurance/quality control and documentation standards; and (5) implementing a rigorous risk assessment across the life cycle of the project. The goal of IPD is to integrate people, systems, business structures, and practices to "optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction.[20] To that end, it aligns design, engineering, major component, construction, and financing so that all the entities involved share information, pool resources, and share risks appropriately. Irrespective of experience, IPD should be a standing requirement for all nuclear project developers; it is also a key element across the project delivery framework outlined in Figure 5.

4.2.1.2 Choose an Appropriate Project Delivery Approach

Although IPD should always be implemented, countries can choose from various development models.
For example, a country that has strong experience implementing complex infrastructure projects, wishes to own nuclear facilities, and has access to adequate financing, may opt for an EPC model. By contrast, a country that simply wants to enable nuclear development, isn't interested in taking any ownership stake, and wants at most a minimal role in direct financing may find that a build-own-operate (BOO) model is more appropriate. Countries' preferences and circumstances can change.

Table 2: Examples of development models that are amenable to new nuclear construction and subsequent operation

Criteria	BOO (Build-Own-Operate)	BOOT (Build-Own-Operate-Transfer)	DBFMO (Design-Build-Finance-Maintain-Operate)	EPC (Engineering, Procurement, Construction)
Ownership	Project developer retains ownership	Ownership transferred to the government after concession period	Government retains ownership	Government retains ownership
Financing	Project developer responsible for lead financing	Project developer finances, then transfers to government	Private entity finances and maintains	Government typically finances
Operations & Maintenance	Developer responsible for O&M	Developer responsible for O&M until transfer	Private entity responsible for O&M	Government or separate operator handles O&M
Risk Allocation	Developer bears construction risks	Risk allocation depends on project phase; developer holds construction risk	Private entity bears maintenance risks	Government bears construction risk
Control	Government has limited operational control	Control transferred to government	Government has limited operational control	Government maintains operational control
Revenue & Profit	Developer generates revenue and profit for itself	Revenue and profit to developer before transfer; revenue to government after	Private entity generates revenue and profit for itself; government receives service (e.g., power)	Government gains revenue, controls pricing
Expertise & Resources	Uses private sector expertise to build and operate	Uses private sector expertise to build and operate; government builds capacity to operate in parallel	Leverages private sector expertise to provide a set of services to the government	Leverages private sector expertise to build; government assumes control/operation after construction
Regulatory Control	Government retains regulatory control	Government retains regulatory control	Government retains regulatory control	Government retains regulatory control
Transfer of Ownership	No ownership transfer from developer	Ownership transferred at end of period from developer to government	No ownership transfer from government	Ownership may transfer from government to private entity

4.2.1.3 Encourage an Orderbook or Pursue Bulk Purchases

An orderbook in this context is defined as multiple identical orders for a given design. As discussed extensively in Chapter 2, the orderbook concept promotes cumulative learning, enables investment by providing certainty about future demand, and thus reduces costs and risks. It is used in the aviation industry, where it is common for multiple airlines to order aircraft of a specific design for future delivery. For example, from November 2022 to March 2023, Boeing received orders from two Saudi airlines, Air India, and United Airlines for approximately 200 of its 787 Dreamliners to be delivered in the coming decade. In the case of nuclear facilities, countries can create an orderbook by themselves or partner with other countries. A regional approach could involve a mix of established and embarking nuclear countries and could provide an opportunity to spread the burden of implementing a financial backstop mechanism, as discussed below. For example, a coalition of countries could agree on an orderbook of a particular design, with the first reactor deployed in an established country. Subject to favorable results, the subsequent reactors, given the knowledge gained from the first, could be deployed in embarking countries.

4.2.1.4 Provide a Financial Backstop for the First Few Local Builds of a Given Design

A financial backstop is another way to reduce exposure to risk for project developers and investors. Such backstops often take the form of a government commitment to inject public capital (in the form of a loan or grant, or a mix thereof), if project costs exceed a predetermined threshold for specified reasons, and the project is still incomplete. Provided that IPD best practices have been used, a financial backstop creates a tiered sharing of risk where the public sector provides capital assurance in the event that private (or mixed) capital is prematurely exhausted. Backstops can be structured to ensure the developer remains motivated to successfully complete the project—for example, by using backstop access fees or exit penalties for incomplete work. They can also be funded in different ways, for example by creating a pool of reserve funds that is released by formula, when certain criteria are met. A financial backstop can be made available only to the first few facilities or kinds of facilities, and only until certain design, build, and/or operating targets been achieved. An alternative, though somewhat weaker approach is to offer financial incentives such as cost-share grants or low-cost debt to project sponsors if they complete construction drawings and other front-end engineering and design work, and thereby reduce the probability of cost overruns.

4.2.2 Strategies for Minimizing the Cost of Capital

We describe four strategies for minimizing the cost of capital for new nuclear projects. All four should be used in any new nuclear build, but the specific mix of approaches may change based on country preferences and circumstances.

4.2.2.1 Build Public Support for Nuclear Energy

If the embarking country explicitly states that it desires nuclear energy as part of a national strategy (see Figure 1) and if this posture is generally reflected in the population at large, that sends an important signal to outside developers and investors. Contentious projects that do not have a social license to operate can lead to community resentment both tacit and explicit.
For NLBs especially, nuclear energy must be positioned as a solution that resonates with the needs of the country, and explained in terms that the population understands. Moreover, there must be a clear articulation of benefits to specific groups (e.g., energy security and reduced pollution for the public; high-quality, reliable power for industry; carbon-free generation for companies with decarbonization mandates and environmental advocates, etc.). Embarking countries can use information from the IAEA and other sources to help accomplish these goals; furthermore, they can present nuclear energy as part of a portfolio of solutions in the context of national commitments and strategic plans related to climate change mitigation, economic development, and other broadly supported objectives. Efforts to ensure that the benefits generated by nuclear development are shared with key stakeholders will help enhance the credibility of these statements over time.

4.2.2.2 Work with Certified Designs

Reactor designs that have been certified by existing nuclear countries should be the only ones pursued by embarking countries, especially for NLBs. Ideally, at least one plant of the same design should be in operation or under construction somewhere in the world to help demonstrate technological maturity, constructability, and operational performance. Personnel involved in constructing and operating existing facilities should be retained as consultants and experts to help inform decision-making at key junctures of a new facility's life cycle. This guideline can be applied broadly across the delivery models described in Table 2.

4.2.2.3 Use Proven Entities for Construction and Operation

Given the complexity and expense of nuclear projects, embarking countries should contract with entities that are familiar with IPD and have both a proven track record and a verifiable delivery model. Referring again to Table 2, depending upon whether an embarking country wishes to spur a private market and its ability to manage complex civil projects of any kind, the development approach could be either a build-own-operate-transfer to government (BOOT or full turnkey approach) or BOO model. In the former, the private entity is responsible to build, own, and operate the facility, and transfer it to the government after a given concession period. The latter does not transfer ownership. The BOOT model would be appropriate after a domestic skillset has been established; the BOO is appropriate if that is not the case, or if it is undesirable and the government is interested only in the output. The BOOT model allows for ownership but a government could then tender the operation to another entity or sell the facility outright to a domestic private actor.

4.2.2.4 Elucidate the Revenue Support Model Ahead of Time

Developers and investors will be keen to understand the conditions for recouping their investment—namely the revenue model. The embarking country should make its revenue model known well in advance of tendering support for any project. In fact, all support mechanisms should be developed in parallel with the regulatory system—before specific projects go forward. Enshrining such mechanisms in statute, as the United Kingdom did with its Nuclear Energy (Financing) Act of 2022[21] with the regulated asset base model, will have clear benefits given that inconsistent government support has exposed the nuclear industry to boom–bust cycles in the past.[22]

4.2.3 Strategies for Supporting an Adequate Revenue Model

This section discusses four strategies for supporting an adequate revenue model for new nuclear. The appropriate mix of strategies may change depending on the market structure for energy and heat in a given country, and the presence of other mechanisms or policies, such as a carbon tax.

4.2.3.1 Offer a Sovereign Guarantee on Debt Post-Commencement of Commercial Operation

A sovereign guarantee on debt posted against a project is separate from a financial backstop in the case of project cost overruns. Crucially, this guarantee would take effect only after a plant begins operating, thereby ensuring that the embarking country in not exposed to two types of risk (i.e., near-term project cost risk and longer-term revenue risk) during construction. A guarantee of this type would be especially important if the nuclear facility operates in an energy-only competitive market where dispatch order is governed by marginal cost.[23] In such a market construct, generation dispatch is ordered from lowest to highest marginal cost. Renewables typically have close to zero marginal cost and are dispatched first. If no value is placed on capacity—the ability to dispatch generation at any time, which is not a robust feature of renewables—then higher marginal cost generation such as nuclear power may be unable to earn adequate revenue. The guarantee could be reduced or removed if certain market reforms (hybrid market) or other revenue support mechanisms are introduced. In any case, the presence of a debt guarantee may offer additional piece of mind to NLB investors.

4.2.3.2 Pursue Long-Term Contracts with Creditworthy Counterparties

Irrespective of electricity market design, long-term contracts with creditworthy counterparties for a significant portion of the nuclear facility's output will help secure cashflows. Counterparties could include government entities or public facilities (e.g., military facilities, government buildings, desalination facilities, hydrogen production plants, etc.), or large industrial or energy demand centers (e.g., manufacturing plants, data centers, chemical plants, etc.). National governments can help broker these contracts. Long-term contracts with government off-takers can be offered beyond the first nuclear build, as they would be under a design-build-finance-maintain-operate approach. If geography and transmission connections allow, embarking countries can sign take-if-available contracts with neighboring countries. As costs decline, such contracts could be reduced or eliminated. Another example would be to allow private or public entities to sign cooperative agreements with utilities to call upon a certain percentage of output under certain conditions (sometimes called building "captive" power). The regulatory regime for electricity markets would need to be made fit for this purpose.

4.2.3.3 Establish Price Collars in Competitive Electricity Markets

Price collars, which combine a price floor with a price ceiling, can be a useful complement to other mechanisms (such as long-term contracts) for reducing long-term revenue risk. Under this approach, the utility is compensated if the market price for a nuclear plant's electricity output falls below the price floor, but it cannot charge above the ceiling if market prices rise too high. In effect, the price collar provides revenue certainty around a defined price band, which can be especially useful in energy-only competitive electricity markets that often exhibit high volatility, The price floor could be relatively progressive (meaning it could be set fairly high) for first-of-a-kind or next-of-a-kind facilities, and decline for next-of-a-kind facilities that have had a chance to benefit from operational experience and become competitive with other generators in the changing grid mix.

4.2.3.4 Price Carbon Emissions and Use of Credible Carbon Offset Credits

If decarbonization is a priority for the embarking country, then it could consider implementing a carbon tax or cap-and-trade program to create market incentives for reducing carbon emissions. Although this would not reduce the cost of nuclear-generated electricity, it would make nuclear energy more competitive with conventional fossil-fuel generation, which would incur higher costs under a carbon pricing mechanism. Pricing carbon is widely considered to be one of the most efficient and effective ways to reduce carbon emissions, but it would also be part of a much larger regulatory project that would affect many energy sources in addition to nuclear. Furthermore, nuclear energy could be imagined as part of a larger industrial system, enabling lower-carbon production of goods fit for export to regions that impose carbon tariffs such as carbon border adjustment mechanisms. Such consideration should be included as part of a country's energy, economic, and industrial policy.

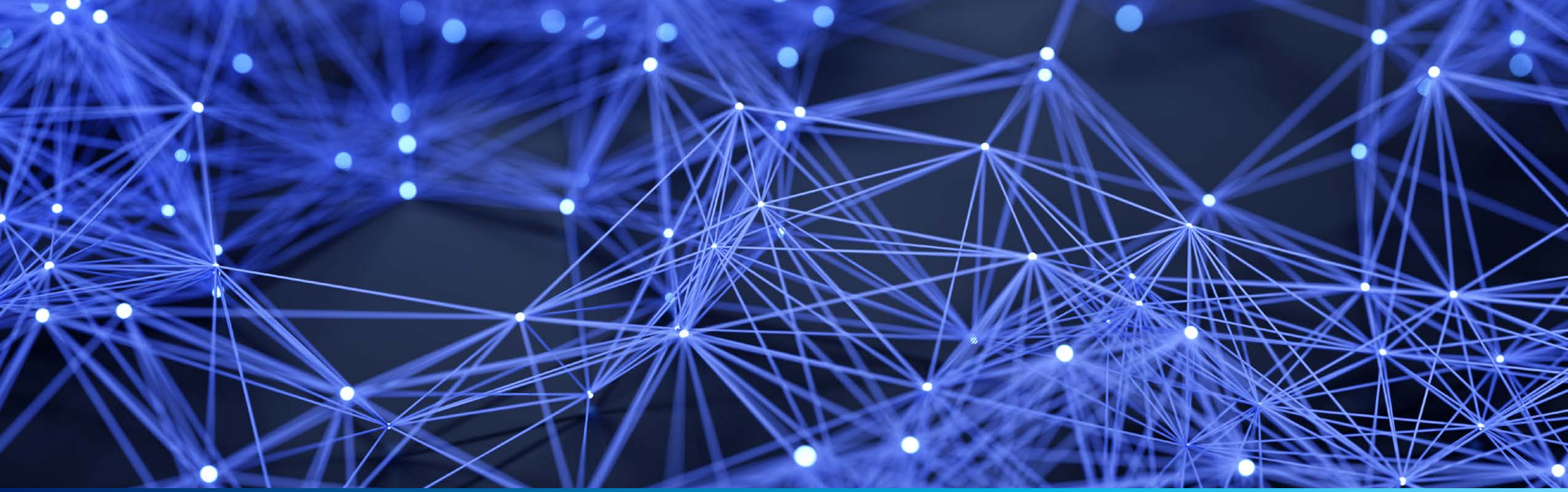
4.3 A Need for New Financing Entities

Strategies for increasing the bankability of new nuclear projects may be necessary to support deployment in embarking countries, but they may not be sufficient—given the overall scarcity of capital available for investment in nuclear—if multiple countries choose to launch programs at the same time.

Multilateral development banks (MDBs) and multilateral infrastructure banks (MIBs) are widely considered to be broadly capable at mobilizing public and private investments into the energy sector.[24,25] They typically offer multiple financial instruments and mechanisms, including loans, equity investment, private-public partnerships, and blended finance.[26] By helping to finance technologies and projects that would be deemed too risky by the private sector alone, MDBs and MIBs will likely continue to play a major role in facilitating the energy transition.[27]

Although a 2022 IAEA report on nuclear power and climate change identified MDBs and MIBs as important potential source of financial support for nuclear energy projects and development,[28] most MDBs have policies that prohibited financing nuclear projects, and those that do allow for financing nuclear (European Investment Bank and the European Bank for Reconstruction and Development) generally provide only limited support, such as lending for safety-related projects and decommissioning.[29] As long as this is the case, an important path to scaling new nuclear technologies is effectively blocked. There have been calls from governments that support nuclear energy to change the policies of MDBs and MIBs; however, because these institutions operate on consensus-basis, policy change has proved elusive to date. Nevertheless, such policy change is clearly desirable for reasons of both economic development and climate change risk mitigation.

Going one step further, a specialty infrastructure bank—purposely built to provide financing and other support for nuclear programs within member countries, such as the proposed IBNI—could enable MIB financing for nuclear energy, IBNI would provide financing not only for nuclear reactor programs, but also to support supply chain development, nuclear fuel production, spent fuel repositories, etc. Lending by this bank would be subject to a set of standards designed to promote bankable nuclear programs, while the bank's specific focus on nuclear would allow it to deploy its technical capabilities to assess programs, manage risk, and implement effective financing strategies. The standards would allow IBNI to instill market confidence in nuclear projects, creating a multiplier effect that would catalyze public and private capital. Establishment of an IBNI would occur in parallel with a continued push for policy changes at existing MDBs and MIBs. If that policy change happens, IBNI would finance nuclear alongside MDBs and MIBs.



CHAPTER 5

Nonproliferation and Nuclear Security

Chapter Summary

Nonproliferation and security are necessary foundations for a global expansion of nuclear energy. As countries consider nuclear energy options, they face decisions in several areas that bear on nonproliferation and nuclear security, including (1) choice of reactor design, fuel type, and fuel cycle; (2) acquisition of nuclear fuel; (3) security; and (4) application of international safeguards and transparency measures. On each of these issues, adherence to international best practices and standards will help clear the path to successful nuclear energy development.

What can be done now:

- At least initially, adopt a once-through fuel cycle based on LWR technology and LEU fuel, which offers decades of proven experience.
- Opt for procuring fuel on the international market, as it has proven to be the more reliable, cost-effective, and proliferation-resistant choice for sourcing fuel.
- Incorporate security planning from the early days of project design.

Further options:

- Exceed bare minimum requirements to enhance transparency and avoid proliferation sensitive technologies.

It has long been recognized that some nuclear technologies and materials—namely, enrichment, reprocessing, highly enriched uranium (HEU), and plutonium—can be used for peaceful purposes such as nuclear energy but also to build nuclear weapons. Over time, the international community has developed a series of principles and practices that newly embarking nuclear countries can apply to bolster safety and security and to provide confidence that their nuclear program is exclusively for peaceful uses. Fortunately, these practices are not only readily achievable, they offer the clearest pathway to accelerating nuclear energy development.

As countries consider their nuclear energy options, they face decisions in several areas that bear on nonproliferation and nuclear security, including (1) choice of reactor design, fuel type, and fuel cycle; (2) acquisition of nuclear fuel; (3) security; and (4) application of international safeguards and transparency measures. On each of these issues, adherence to international best practices and standards will help clear the path to successful nuclear energy development.

5.1 Reactor Design, Fuel Type, and Fuel Cycle

A fundamental decision for starting a nuclear power program concerns reactor type and fuel cycle. Various options are available, but choosing among them need not be overly difficult. A good first step is for governments to take stock of their core goals for developing a nuclear program in the first place, whether those goals focus on emission reductions, bolstering energy security, supplying affordable baseload electricity—or some combination of all three. Further consideration must then be given to safety, security, and waste management. Throughout the history of nuclear power, these issues have been thoroughly examined and solutions have emerged for most efficiently and effectively meeting fundamental goals.

Reactor Design Options

- LWRs
- Alternative reactor technologies (e.g., gas-cooled reactors, metal-cooled fast reactors, and molten salt reactors)
- Reactor size (e.g., large reactors and SMRs); these can be LWRs or various alternative technologies

Fuel Type Options

- Standard-assay LEU, enriched to 3%–5%
- High-assay low enriched uranium (HALEU), LEU fuel enriched above 5% and below 20%[30]
- HEU, enriched to 20% or more
- Plutonium, including uranium/plutonium mixed oxide (MOX) fuels, and other fuels that use separated plutonium[31]

Fuel Cycle Options

- Once-through
- Reprocess and recycle

Most commercial nuclear power plants operating today are LWRs using standard-assay LEU fuel and a once-through fuel cycle (meaning that the fuel is used once and then disposed of). Decades of experience have been amassed with this combination of reactor design, fuel type, and fuel cycle, with impressive results in terms of safety, reliability, and efficient, low-cost operation for the global reactor fleet overall. From a nonproliferation perspective LWRs in once-through mode perform strongly, as weapons-usable nuclear material is never introduced into the fuel cycle.

Given these characteristics, countries have generally not been motivated to look at other reactor and fuel cycle options, at least in recent decades. Concerns about the adequacy of global uranium supplies did prompt interest in a plutonium-based fuel cycle, with reprocessing to extract reusable plutonium from spent fuel, in the 1970s. But recognition that uranium was more abundant than originally thought,[32] combined with concerns over nuclear proliferation, caused most countries to abandon this approach. Plutonium separated from spent fuel is weapons usable, whereas the once-through LEU fuel cycle does not deal in separated plutonium, nor is LEU weapons usable. Given the proliferation risks, high cost, complexity, and substantial safety and security requirements of the plutonium fuel cycle, this picture has remained largely unchanged for several decades: Today, of the 32 countries and areas around the world that operate nuclear power plants, only five use, or have imminent plans to use, plutonium fuels. With current and foreseeable conditions, use of plutonium fuels is considerably more expensive than continued reliance on LEU fuel.

The popularity of the once-through LEU cycle has not stopped some stakeholders from making a new push for alternative fuel cycles. Some new reactor designs propose to use HALEU fuel, which promises certain potential advantages. For example, high-temperature gas-cooled reactors using HALEU TRISO[33] fuel can provide not just electricity, but also process heat that can power industrial activities such as desalinization, chemical processing, and hydrogen production. HALEU is considered a type of LEU and is not suitable for weaponization. However, HALEU fuels are currently not widely deployed and it will likely take time before they reach the level of supply security and regulatory maturity of standard-assay LEU. Besides HALEU, other advanced reactor designs propose to revisit the plutonium fuel cycle as a potential solution to nuclear waste concerns. These concerns are discussed in Chapter 6.

5.2 Sourcing Nuclear Fuel

Once countries have settled on a reactor design and fuel type, fuel procurement becomes an important next step. Countries can turn to international markets for nuclear fuel or attempt to develop indigenous uranium enrichment and fuel processing capabilities.

Today, nearly all countries with operational nuclear power plants rely on the international market for nuclear fuel. This approach is working well, with several reliable suppliers in China, Europe, Russia, and the United States that are well situated to continue meeting fuel demands for the foreseeable future. Relying on the international market is also the far more cost-effective and efficient option for countries that are planning relatively limited nuclear energy programs. The UAE, which started its first nuclear power plant in 2021, put it succinctly:

> *… A number of factors underlie [the UAE's decision to forgo enrichment and reprocessing], including the economic infeasibility of operating enrichment and reprocessing facilities for comparatively small nuclear fleets, concerns from the international community regarding spent fuel reprocessing and enrichment plants in developing countries, and the dual use nature of components employed in fuel fabrication and processing. In consideration of these factors, the UAE will not seek to develop domestic capabilities in those areas, either as part of its evaluation of nuclear energy or as a component of future UAE nuclear program.*[34]

Relying on the international market also brings nonproliferation benefits, limiting the spread of sensitive technologies that also have weapons applications and sending a strong signal to the global community about the peaceful intent of a country's nuclear power program. To reinforce that signal, governments can make additional commitments: The UAE and Taiwan, for example, have made legal commitments not to pursue enrichment and reprocessing (ENR) as part of their nuclear cooperation agreements with the United States. Vietnam has stated that it will rely on the international market for its fuel supply. Passing national legislation is another option.

Further assurance about the stability of international fuel supplies is provided by the IAEA's LEU Bank, which offers protection against temporary supply disruptions for IAEA member states in good standing with their nonproliferation obligations. The Bank consists of a physical stock of 90 metric tons of LEU suitable to make fuel for a typical LWR in the event of a fuel supply disruption. This diminishes any rationale for creating domestic enrichment capacity.

Although the international nuclear fuel market is working well, some countries may want to explore further commercial arrangements to bolster supply assurances, such as expanding or establishing multinational facilities for fuel enrichment or manufacture. The Urenco consortium, which is jointly owned by Germany, the Netherlands, and the United Kingdom and which operates facilities in all three countries, as well as in the United States, represents an example. Multinational facilities would still need to be subject to strict international monitoring and limits on access to sensitive technology.[35]

The option of developing indigenous enrichment and fuel fabrication capabilities has not proved attractive to many countries (countries that have pursued this option are generally countries that developed nuclear weapons) given its high cost, technical complexity, and inherent connection to proliferation concerns, and because the international fuel market offers a viable alternative. The fact is that domestic enrichment makes no economic sense absent a large nuclear power program. A further barrier is that, while there are no international legal prohibitions against developing or providing enrichment technology, in practice, major supplier countries have not sold enrichment technology to countries that do not already have it since the 1970s.

5.3 Physical Security

Embarking countries also face important decisions regarding the physical security of nuclear power plant infrastructure. Security requirements are simpler for countries that choose LEU fuels, because such fuels cannot be directly used in nuclear weapons, but they are still important—for example, to protect against the risk of sabotage of a reactor vessel or spent fuel pool that could lead to a radiological release. Robust security measures should be fully integrated into nuclear facility design, construction, and operation from the very first phases of a project. This approach requires a strong commitment to security from all stakeholders, including governments and operators, but it enhances effectiveness, reduces costs, and allows for the seamless prioritization of security in all aspects of facility operations.

The IAEA publishes a guide on facility security that countries can use in facility design: Information Circular 225, *Nuclear Security Recommendations on Physical Protection of Nuclear Material and Nuclear Facilities.*[36] With regard to security considerations during the reactor design phase, the IAEA circular states:

> *"For a new nuclear facility, the site selection and design should take physical protection into account as early as possible and also address the interface between physical protection, safety and nuclear material accountancy and control to avoid any conflicts and to ensure that all three elements support each other."*

5.4 Safeguards and Transparency

All countries using civil nuclear technologies that are a signatory to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) as non-nuclear weapons states must have in place a Comprehensive Safeguards Agreement (CSA) with the IAEA, the international organization charged with verifying that country programs are used for exclusively peaceful purposes. Safeguards—including on-site visits, sampling, and monitoring—are the means by which the IAEA assesses if countries are living up to their commitment not to use peaceful nuclear programs for nuclear weapons purposes. A CSA is bilateral agreement between a country and the IAEA that sets out the obligations and responsibilities of the country and the agency. In addition to a CSA, countries can also adopt the IAEA's Additional Protocol (AP), which provides the IAEA with additional information and verification tools. Though voluntary, the AP has been adopted by 140 countries and EURATOM and is now widely considered the international standard for safeguards.[37]

Similar to the approach to physical security, countries embarking on nuclear energy programs should begin considering safeguards implications—in cooperation with the IAEA—from the early phases of the project. This is particularly true if the country is considering deploying novel reactor technologies, as those may require new safeguards approaches.

For embarking states, adopting the AP and committing to not develop indigenous enrichment or reprocessing capabilities sends a powerful signal, both about upholding international nonproliferation standards and about the seriousness of a country's nuclear energy development plans. In the rare case where a country wishes to develop indigenous enrichment or reprocessing capabilities or explore multilateral or regional enrichment consortia, by contrast, it can expect to face greater scrutiny of its nuclear program and intentions and the bar for reassuring the international community and potential partners would be considerably higher. The UAE has stated that its decision to put in place the highest nonproliferation standards enabled it to receive considerable international support for its civilian nuclear power program.

In such cases, countries can commit to additional transparency, monitoring, and verification measures beyond the AP. For example, countries could commit to IAEA monitoring of the entire uranium supply chain and continuous monitoring of enrichment-related activities (e.g., through cameras and other remote monitoring technologies), including centrifuge component production and assembly. This would provide added confidence that nuclear material or technology is not being diverted for nuclear weapons purposes. Countries should also consider adopting additional restrictions and transparency measures with respect to nuclear weapons-related activities. This could include, for example, a commitment to forgo developing multi-point detonation systems useful for nuclear devices and allowing the IAEA to confirm their absence. Finally, countries might also voluntarily limit stockpiles of enriched material to keep only what is needed for nuclear fuel or confine any research and development (R&D) on uranium and plutonium metallurgy to topics that are directly relevant to fuel fabrication for the country's specific reactors.

CHAPTER 6

Spent Nuclear Fuel Management

Chapter Summary

The siting of permanent disposal sites for spent nuclear fuel is an important goal that nuclear power stakeholders must work toward; in addition, a responsibility exists to safely manage these wastes in interim storage while progress toward a permanent disposal solution continues. Although this process can seem complex, spent nuclear fuel can be managed safely, securely, and economically with appropriate effort. Countries that are embarking on nuclear energy programs can forge a path to success by considering three key aspects: permanent spent fuel disposal, timeline for considering disposal options, and interim spent fuel storage.

What can be done now:

- Adopt once-through LEU fuel cycle that allows for the direct disposal of spent fuel (by contrast, reprocessing and recycling generate multiple waste streams and incur significant additional costs).
- Build efficiencies by considering waste disposal from the early phases of project development and learning from the positive and negative waste management experiences of countries with established nuclear programs.
- Consider options for interim spent fuel storage, ensuring that policies and practices prioritize safety and security

Further options:

- Develop regional solutions for the interim storage and permanent disposal of spent fuel.

All nuclear reactors produce some form of spent, or used, nuclear fuel. When fissile material inside a reactor undergoes fission reactions, energy is released in the form of heat and new elements are formed inside the core. Over time, the fuel becomes less efficient at sustaining fission reactions until at some point it is considered "spent" and must be removed from the reactor core. Typically, spent fuel is placed in water-filled pools for a period of years to ensure that it cools sufficiently for longer-term storage or final disposition. All nuclear fuel cycles, including cycles that use the reprocessing of spent fuel, create waste byproducts that require permanent disposal. Siting permanent disposal facilities has emerged as a key challenge for nuclear energy development around the world and one that requires all stakeholders to work together to address. Meanwhile, a responsibility exists to safely manage nuclear wastes in interim storage while progress toward implementing permanent disposal solutions continues. Although this can seem a daunting task, experience in many established nuclear countries suggests that spent nuclear fuel can be managed safely, securely, and economically with appropriate effort.

6.1 Fuel-Cycle Considerations for Permanent Waste Disposal

Every expert scientific panel in every country that has examined the backend of the nuclear fuel cycle has concluded that a permanent disposal solution for nuclear waste is needed. Spent nuclear fuel contains long-lived radioactive elements that take hundreds to hundreds of thousands of years to decay. As already noted, this is true for countries that use an LEU once-through fuel cycle, as well as countries that use reprocessing and plutonium fuels.[38] That said, different options for managing the back end of the fuel cycle will produce different waste streams and present varying levels of complexity in terms of safe disposal.

The once-through LEU fuel cycle discussed in Chapter 5 leaves a final waste product of intact, solid spent fuel elements that can be stored and disposed of relatively simply: Once taken out of the reactor and cooled, spent fuel can be put directly into a storage or disposal facility.

Another option is to reprocess and recycle spent fuel ahead of permanent waste disposal. Reprocessing, a technology that was originally contemplated for use in the nuclear fuel cycle to alleviate uranium supply concerns, has been rebranded by some stakeholders in recent years as a possible solution to the nuclear waste dilemma. Reprocessing not only fails to eliminate nuclear waste or obviate the need for a permanent waste disposal facility, but it also introduces several complexities to waste management that do not exist with the LEU once-through cycle

Waste streams from reprocessing generally include high-level wastes in the form of vitrified solids, various intermediate-level and low-level wastes that can be in solid or liquid form, and gaseous wastes. Reprocessing does reduce the physical volume of high-level waste, but it greatly increases the number of waste streams that must be managed and the volume of intermediate and low-level waste. Moreover, volume is not the main challenge for disposing of nuclear waste. All spent fuel from every nuclear power reactor ever operated on the planet can roughly fit inside the confines of a football stadium if volume were the only criterion. In reality, the space needed to dispose of this material is not so much a function of its physical volume, rather it is a function of the waste's heat-load and level of radioactivity. To manage waste forms over very long timespans, scientific consensus has converged on burial in a deep geological repository as the most cost-effective and technically viable option. Thus, all countries that have developed civilian nuclear energy, including those that have pursued reprocessing, face the need to site a permanent geological repository for nuclear waste.

Reprocessing also separates plutonium from the most toxic and radioactive elements in spent fuel, rendering a relatively pure, weapons-usable material that presents serious security and proliferation concerns. This is a consideration not just for countries that are contemplating an indigenous reprocessing capability, but also for countries that are considering using reprocessing services from countries with existing capabilities. Any introduction of separated plutonium fuel presents substantial risks that are not present in the LEU once-through cycle.

One additional option that may merit consideration is the idea of a spent fuel takeback or leasing program that would allow a country to return spent fuel to its country of origin for processing or disposition. Although such arrangements could help simplify spent fuel management for embarking nations, true takeback programs have often run into political challenges in the countries to which the fuel is returned. Those countries that have offered some version of this service have generally reprocessed the spent fuel and sent the resulting high-level waste back to the country where the fuel was used. Thus, the country that used the fuel is still responsible for developing permanent disposal capability for nuclear waste.

6.2 Timeline for Considering Disposal Options

Recognizing that waste storage and permanent disposition will be required for all nuclear fuel cycles, advanced planning can save large amounts of time, money, and effort, particularly for embarking countries. Like the security-by-design concept discussed in Chapter 5, many efficiencies can be gained by considering waste disposal from the early phases of project development. Key considerations for any waste disposal program include (1) public health and safety, (2) community acceptance and consent, (2) environmental protection, (3) costs, and (4) security and nonproliferation.

Nuclear waste disposal can be handled by countries individually, through bilateral arrangements with partners, or through multilateral agreements. Although the history of siting geological repositories has often been discouraging and fraught with controversy, particularly around the issue of obtaining local consent, positive examples also exist that embarking countries can learn from. Numerous studies, drawing from experience in a range of countries that are working toward permanent geological repositories, have identified the following considerations as critical to success:[39]

- Clear and understandable legal and technical frameworks for site selection and operation.
- Financing for local governments and communities to conduct their own analyses of site suitability and other siting issues.
- Compensation for all local communities that participate in site investigations.
- Earnest efforts to promote awareness of nuclear waste issues through mechanisms such as seminars, studies, and evaluations of the social and economic impacts on local communities.
- Openness and transparency among all stakeholders, including national government, local government, and civil society actors.
- Other geological disposal options, such as deep borehole disposal, are not well developed scientifically.

6.3 Considerations for Interim Spent Fuel Storage

In addition to permanent disposal, all nuclear fuel cycles require interim waste storage capabilities. Once spent nuclear fuel is removed from a reactor, it must first be cooled properly before it can be safely handled, transported, and placed in a final repository. Depending on specific fuel characteristics, this can usually be accomplished through various forms of wet or dry storage over a period of several years to a decade. Options include on-site wet storage in pools, on-site dry storage in casks, offsite wet storage in pools, and offsite dry storage in casks. Because managing the back end of the nuclear fuel cycle, and particularly long-term disposal, has historically been underprioritized when countries developed their nuclear power programs, interim storage facilities have often become de-facto long-term storage providers over a period of decades. Although this scenario presents myriad challenges, prioritizing the safety and security of these storage arrangements is an effective way to reduce unnecessary risk.

Spent nuclear fuel can be managed safely and securely, as it is all over the world on a routine basis. The primary safety risks from spent fuel come from extreme events, such as a catastrophic natural disaster. While extremely rare, history shows that such events have a potential to lead to a loss of coolant that cannot be remedied by operator intervention, which could result in a release of radiological material. The primary security risk is an intentional act to disperse radiological material from spent fuel, either through kinetic attack or a sabotage that leads to meltdown. Risk also exists that spent fuel in the middle of an active war zone could take accidental damage, leading to radiological release. Although reactors are resilient and can safely adopt to various security environments, risk has become more acute in recent years because of two phenomena. First, some countries and facilities use pools at reactor sites as a primary means for storing large volumes of spent fuel, where vulnerabilities are usually greater than in dry casks or other designated interim storage infrastructure. Second, the attack on Ukraine's Zaporizhzhia nuclear power plant has highlighted the risks that arise when nuclear energy infrastructure is in the crosshairs of international combat. This underscores the importance of all countries addressing spent fuel storage as a means of minimizing risk.

Safety and security challenges with interim spent fuel storage can be significantly mitigated in several ways. First, where spent fuel is stored in pools, robust and redundant cooling infrastructure and electricity sources can be put in place to minimize the chance of system failure and ensure that any single point of failure cannot lead to a radiological release. The IAEA publishes a detailed set of safety standards for spent fuel storage that outline the specific actions that governments and operators can take.[40] Second, spent fuel should be adequately protected from attack based on a design basis threat (DBT) assessment. Such assessments typically involve a collaboration between industry and government to analyze potential threats from internal and external adversaries who could attempt to attack, sabotage, or steal material from a reactor. Formulating a DBT involves collecting and analyzing threat information from intelligence and open sources and considering past security events in a country or location. This includes identifying potential adversaries, their capabilities, and the likelihood of an incident. Whereas a DBT assessment broadly covers all aspects of a nuclear power plant, spent fuel storage and management systems should be designed with the DBT in mind. This can include spent fuel storage in dry casks, which make for much harder targets than spent fuel pools.

CHAPTER 7

Workforce Development

Chapter Summary

Workforce development is foundational to nuclear embarking countries. However, nuclear technology's specialized workforce requirements can turn staffing into a choke point for new projects. Embarking countries face common, global workforce problems, as well as acute constraints particular to new entrants. As its nuclear program matures, an embarking country must decide whether roles will be outsourced or insourced. Embarking countries are highly likely to rely on both foreign and domestic talent, but there exists a range of possible combinations. Countries should choose a workforce model that fits their own resources and goals, and back up their decisions with financial investment.

What can be done now:

- Develop a workforce assessment and national strategy that ensures all stakeholders are aligned and helps the embarking country prepare for either recruiting foreign talent or forging a domestic pipeline of talent.
- Leverage existing regional partnerships to support joint workforce development.
- Embed junior managers from embarking countries in nuclear build and operation projects internationally now.

Further options:

- An embarking country can supplement its existing educational system with a national or regional nuclear training center, while also leveraging resources available in other countries.
- Given that workforce training is best conducted through applied practice, constructing and operating a research reactor not intended for commercial purposes could be a valuable educational resource.
- Multiple embarking countries could also share scarce human resources, such as through an ITSO to support regulator development or a regional nuclear training center.

Workforce development is foundational to nuclear embarking countries, especially since nuclear technology's specialized workforce requirements can easily turn staffing into a choke point for new projects. Embarking countries face common, global workforce challenges (e.g., an evaporating pipeline of nuclear experts), as well as acute constraints particular to new entrants (e.g., willingness and ability to make upfront investments and potentially sustain support for local public and/or private apprenticeships). At multiple stages in the development of a nuclear energy program, an embarking country must decide whether roles will be outsourced or insourced. Embarking countries are highly likely to do both, but there exists a range of possible combinations. Countries should choose a model that fits their own resources and goals, and back up their decisions with financial investment.

The IAEA deems human resource development one of 19 key infrastructure issues for embarking countries.[41] In fact, it intersects with many other infrastructure challenges, which depend on having a qualified workforce. Embarking countries can follow a range of models to manage workforce needs, all of which carry speed, cost, and geostrategic implications; decisions must consider policy objectives and existing capabilities. As with other elements of a successful nuclear program, workforce development will require both substantial financial investment and early decision-making.

7.1 Global and Specific Workforce Development Considerations

A first and foremost challenge for all countries with existing or planned nuclear energy facilities is the limited pool of available workers. In addition to the specialized expertise necessary for many nuclear industry roles (including education, training, and safety and security competence), workers must meet additional requirements such as medical fitness, security checks, ability to manage contractors, and ability to work with an international workforce.[42] Retaining qualified workers and expert knowledge for the full duration of a nuclear plant project poses challenges as well.

Globally, the pipeline of nuclear expertise is drying up, a consequence of the industry's stasis in recent decades.[43,44] Moreover, the severe workforce limitations that already exist around the world will only be exacerbated as additional countries seek to build new nuclear capacity.

Other workforce considerations are particular to embarking countries:

- **Lack of Resources.** Embarking countries may be more likely than incumben:s to lack the resources (financial, educational, etc.) that have enabled the latter to build nuclear workforces.
- **Upfront Investment:** Building up a homegrown workforce requires substantial financial investment *before* commissioning a country's first reactor. This funding could be public or private, and could entail investment in education, training exchange programs, and R&D. Some embarking countries may be unwilling or unable to make this investment without a guarantee of return in the form of a successful nuclear energy program.
- **Competition:** Workers who are trained abroad, especially outside a coordinated workforce development program, may not return to the embarking country. With a skillset that is in high demand and an interconnected global nuclear industry, foreign-trained experts may choose to take advantage of opportunities abroad rather than at home.
- **Speed of development:** Training a homegrown workforce takes time. Incumbent countries that rely primarily or exclusively on homegrown talent have had decades to build up their human resources infrastructure. Many embarking countries, on the other hand, are hoping to produce nuclear power as soon as possible in the face of climate and energy security concerns.
- **Reliance on International Partners.** Leaning more on foreign expertise comes with tradeoffs too. Turnkey or BOO projects can in some cases be relatively more expensive, and countries may lose out on some of the positive economic ripple effects of employing domestic labor. Countries must also weigh geopolitical considerations if they are thinking of tying their nuclear power program to an international partner.

7.2 Role-Specific Workforce Decisions

Nuclear workforce functions may be divided into six categories, modeled on the taxonomy laid out by the OECD:[45]

- Nuclear power plant new build (e.g., design, supply, construction)
- Nuclear plant operation (e.g., operation, maintenance, waste management, plant safety)
- Nuclear plant decommissioning (e.g., decommissioning operations, waste management and disposal)
- Regulation (e.g., assessment and review, inspection, and enforcement)
- Support ecosystem (e.g., R&D, education, policy, enabling infrastructure)
- Finance/project finance[46]

Each of these categories encompasses a multiplicity of roles, spread across the many organizations that have a role to play in nuclear infrastructure development, including nuclear energy program implementing organizations (NEPIOs), owner/operators (O/Os), and regulators, as well as government agencies, research and education institutions, and the private sector. The IAEA lists more than 40 roles, requiring more than 1,000 employees, that an O/O must fill to run a two-reactor-unit nuclear power plant.[47]

Decisions about outsourcing vs. insourcing to fill a given role should consider both the requirements and characteristics of the role, as well as domestic resources or preferences:

- **Ease of Outsourcing/Insourcing:** Some roles may be more easily filled with foreign nationals. For instance, international vendors will already employ experts with experience designing and building plants around their reactor designs. On the other hand, any country is likely to have workers who, with little additional training, could fill both low-skill (e.g., clerical) and higher-skill roles (e.g., nuclear-grade welding, chemistry).[48]
- **Local Knowledge:** It may be important for other roles to be filled with homegrown talent, *despite* additional initial inefficiencies, such as jobs requiring local knowledge (e.g., siting, public engagement) or long-term continuity (e.g., project management).
- **Existing Resources:** An embarking country with enabling resources may be inclined to develop more of its workforce domestically. For instance, countries that can leverage sovereign wealth to stand up education programs, or that have existing science and engineering expertise in related fields, may be able to create a pipeline of domestic talent more quickly.
- **Policy Preferences:** Domestic policy preferences may incline an embarking country toward one option or another; for instance, a desire for energy independence or local job growth may incline a country toward developing homegrown labor.

The choices for any given role may also vary between the first reactor(s) and subsequent reactors as a pipeline of domestic talent grows.

7.3 Enabling Successful Workforce Development

There is no one-size-fits-all approach to workforce development, but the experiences of recent embarking countries provide some guidance for a successful approach. First, it is crucial that workforce planning ensure both the competence of a country's nuclear workforce and the sustainability of the overall workforce program.[49,50] Competence encompasses a country's ability to be "an 'intelligent customer' and a qualified overseer" of their nuclear project(s). It requires both high-quality domestic workers (trained in a strong safety and security culture) and the ability to interface successfully with foreign workforces.[51]

Sustainability, in this context, consists of a country's ability to maintain its workforce (and workforce strategy) during the duration of its nuclear program—10 to 15 years to first reactor startup and decades more of operation.[52] Threats to sustainability include short-term planning at the expense of long-term success, poor coordination among stakeholders, insufficient willingness or ability to invest in workforce development, and lack of public outreach.[53] Countries that depend more on foreign expertise may face a particular sustainability challenge if non-native workers depart without a plan in place to replace them or transfer their knowledge to other workers who remain.

Embarking countries should start with a workforce assessment that examines the existing workforce and enabling resources and put together a workforce development plan to be carried out by a NEPIO, as defined by the IAEA. The IAEA identifies this as a critical first step, to be taken even before any decision is made regarding launching a nuclear program. A clear identification of the challenges ahead together with a national strategy for addressing these challenges will help ensure that all stakeholders are aligned and allow the embarking country to prepare for recruiting foreign talent, forging a domestic pipeline of skilled workers, or undertaking a combination of both.

The IAEA outlines responsibilities for all three, core nuclear "organizations"—NEPIO, regulator, and O/O (or multiple O/Os)—in workforce development. The NEPIO's most important responsibilities are to coordinate across stakeholders and set an overarching national strategy, which the IAEA deems critical for embarking countries. All three organizations must also consider their own staffing and need for engagement with external experts. The NEPIO and O/O are also responsible for cultivating relationships with vendor countries and firms. Both may also fund or implement training programs or other initiatives to spur domestic workforce development, including apprenticeships, partnerships with existing labor organizations, and private sector training models.

NEPIOs, regulators, and O/Os are by no means the only stakeholders engaged in workforce development. Universities, technical schools, and other educational institutions are essential and can develop nuclear education programs either on their own or with the assistance of the government and other nuclear implementing organizations.[54] An embarking country may supplement its existing educational system with a national or regional nuclear training center.[55] Given that workforce training is best conducted through applied practice, constructing and operating a research reactor that is not intended for commercial purposes could be a valuable educational resource. Initially, hands-on training could be provided through an academic or private-sector-led fellowship program to other countries with such facilities, with the option to phase in a country or region's own research reactor for training purposes at a later date, depending on the country's larger policy objectives. Beyond understanding how to operate a nuclear reactor including all facets of the fuel cycle, it is imperative that experience is built to manage in-country construction. Even if initial construction of a new local build is fully outsourced, such local capabilities can ensure efficient resource use at the very least, and the basis for long-term construction know-how. Embarking countries can look to embed junior construction managers in projects currently underway around the world to gain these critical experiences. Countries with advanced and expanding nuclear energy programs should, as a matter of policy, assist embarking countries to build their workforce capacity, including by welcoming their nationals as contributing members of nuclear project teams.

Other entities in the nuclear energy ecosystem (including contractor firms, entities involved in fuel cycle operations, grid operators, companies, and institutions engaged in R&D) may also be a part of a broader workforce development strategy, whether on a coordinated or decentralized basis. The NEPIO should also ensure that additional government entities (e.g., foreign policy and education ministries) as well as non-governmental entities (e.g., unions, local communities) are included in workforce planning.

The first roles within a country's nuclear program will be regulatory in nature, with a focus on effectively overseeing the siting and licensing process. Given the expertise needed for these roles, embarking countries may opt to seek foreign talent at this juncture, either as advisors, trainers, or early hires. Alternatively, this is also the point where a domestic workforce development program needs to bear fruit, as the various entities within the domestic nuclear regulatory environment will require dozens if not hundreds of qualified experts to fill key roles. Crucially, given that there will likely be extensive interactions with foreign entities and skillsets, language training must go hand-in-hand with technical skill development to ensure complete and enduring knowledge transfer.

With respect to NLBs, workforce considerations are typically baked into the agreements struck between an embarking country and a vendor country. An embarking country could opt for a turnkey contract that relies on the vendor to supply labor up to the point of plant commissioning, a BOO contract that relies on foreign labor even through operation, an arrangement that requires domestic labor be used during design and construction, or none of the above. These decisions may need to be made before bids are submitted, at the solicitation stage, so as to give vendors the opportunity to tailor their bids to the embarking country's stated workforce goals.

Beyond the first build, a country may choose to have its supplier continue operating the plant or may choose to transition to a partial or wholly domestic workforce. This transition could happen several years into operation, providing an opportunity for domestic employees of the O/O to train in real time with their vendor country counterparts. During this period, an embarking country may also decide to continue foreign training and education partnerships or pursue new ones.

The process repeats anew when additional reactors or projects are contracted—with the caveat that, at this point, the embarking country will have had both the opportunity to gain experience from its first project and further time to develop a domestic pipeline of talent (if desired).

7.4 International Cooperation and Technology Development

A cross-cutting consideration for nuclear infrastructure development in embarking countries is the role of international or regional cooperation beyond the kinds of bilateral agreements that are already routine. Some embarking countries have begun looking to their neighbors to assist in workforce development—an example is Bangladesh's cooperation with India.[56] Existing regional partnerships could be leveraged to support joint workforce development. Multiple embarking countries could also share scarce human resources, such as through an ITSO (discussed in Chapter 3) that can sponsor regulator development or a regional nuclear training center.[57]

CHAPTER 8

Application of the Playbook: Illustrations

As shown in Figure 1 within Chapter 1, the six dimensions of the playbook stack together as a cohesive set creating a unified lens through which embarking countries could view the options available to them in standing up their civilian nuclear fleet. Also described within Chapter 1 is the idea that the options described in this playbook could be applicable to countries that already have a civilian fleet and maybe looking to expand their respective aggregate nuclear capacity. In this way, the playbook offers the building blocks to country-specific pathways. This chapter offers illustrations of the playbook in use, applied each to a representative embarking country and a country looking to expand its civilian nuclear capacity given limited experience. These illustrations are not meant to be prescriptive, but rather to illustrate the application of the playbook in two different settings.

8.1 Embarking Country Playbook Application Illustration

Country A is a lower-middle income economy with a strong agricultural sector and rich deposits of rare minerals, and primarily relies on imported fossil fuels. Country A's ability to industrialize and increase its Human Development Index is hampered by lack of access to reliable energy sources. Country A has a Comprehensive Safeguard Agreement (but not an AP) with the IAEA and operates a 1-MWth research reactor, an accelerator facility, and two irradiation facilities. It has a small number of individuals with experience in research reactor operation and nuclear materials management. Country A has limited experience in deployment of thermal power stations, primarily by state-owned enterprises. As part of its broader national energy and economic development policy, Country A is seeking to deploy Gen III+ SMRs to support the expansion of mining operations, establish industry for materials processing, and increase electricity access for its population. Two of its neighboring states are similarly interested in SMRs.

Table 3: Illustration of the Playbook implemented in an embarking country scenario

Dimension	Implementation
Project Execution & Capacity Building	• Establish a group of potential industrial off-takers (mining, processing, agriculture, etc.) to include companies in Country A and neighboring states. • Working with established, seasoned nuclear industry expertise, most of which from foreign entities, establish an integrated development organization (IDO) with initial government funded capital (provided by Country A and its interested neighbors) to develop an orderbook of SMRs based on an agreement with the off-take group. • IDO to conduct a technoeconomic study to determine technologies best suited to deliver nuclear capacity to meet Country A's industrial requirements and requirements of industry in neighboring states. • Select SMR technology based on factors that include suitability for off-take group applications, industry expertise and experience with identical or similar designs, potential for modularity compatibility of licensing, and deployment of reference plant timeline with off-take needs. • Form partnerships with other companies implementing the selected technology in other countries to share costs and achieve supply chain savings and share experience. • The IDO is to engage third parties with recent or current experience delivering successful projects to fill experience gaps.
Regulatory System Development	• Establish an independent regulator that incorporates existing Country A experience in regulating nuclear materials and activities. • Implement the IAEA "Milestones on the Development of National Infrastructure for Nuclear Power" (NG-G-3.1). • Enact policies and legal structure for a new organization within the government framework. • Establish licensing structure that allows for acceptance of designs certified by competent national regulators, including DACs, while providing for licensing of construction and operation activities to be conducted by Country A regulator. • Establish agreements with regulators in countries deploying the same SMR design, including participation in licensing reviews and job shadowing. • Support the establishment of the ITSO; engage with ITSO to fill gaps in expertise required for reviews of construction and operating licenses.
Project Bankability & Finance	• Require the SMR projects to incorporate IPD mechanisms. • Arrange for a delivery model where the portfolio of power stations constructed and operated in Country A are by an experienced entity, with Country A having slight majority ownership share initially in such facilities. • Provide pooled sovereign guarantees with interested neighboring countries and Country A to investors and export financiers, including a financial backstop for project overruns (especially for the first project(s) to be deployed). • Arrange for long-term PPAs with off-takers and consider any credit enhancements needed for said off-takers. • Support establishment of IBNI and efforts to change policies of existing MDBs/MIBs.
Nonproliferation & Nuclear Security	• Incorporate security and safeguards planning early in the project development timeline. • Sign the AP and ensure that selected SMR designs have incorporated robust plans for safeguards. • Adopt a once-through fuel cycle and opt to procure fuel from the international market.
Spent Nuclear Fuel Management	• Incorporate waste disposal planning early in the project development timeline. • Enter into agreements with neighboring states to develop interim storage and permanent disposal of spent fuel.
Workforce Development	• Through secondment agreements: (1) engage Country A nationals with backgrounds in thermal power station development and nuclear materials in positions at the IDO that correspond to their skill set; and (2) embed junior managers in nuclear project development organizations abroad. • Enter into agreements with neighboring states to set up a regional training center and share workforce across borders and projects, providing an experience continuum.

8.2 Country with Limited Nuclear Energy Experience Playbook Application Illustration

Country B is a high-income economy with a strong industrial sector—steel and cement production and machine building. As a coastal country, Country B also has a budding shipbuilding sector. Country B has one nuclear reactor, nearing 40 years of operation, which satisfies 7% of its energy demand. Country B has also invested significantly in renewables, but more than 65% of its current electricity generation comes from fossil fuels—coal and imported natural gas. Country B's industry has had to cut back production due to recent natural gas shortages; energy prices have also soared. Country B is party to all key IAEA safety, safeguards, and security agreements, including the AP. It has a nuclear engineering program at its top technical university. It also has strong engineering and some supply chain capabilities (but no capability to supply nuclear steam supply system components). Country B does not have any fuel cycle facilities. It has significant experience in deployment of thermal and renewable assets by both state-owned and private enterprises. To meet its national decarbonization and energy security goals, Country B is seeking to expand its nuclear capacity, considering both large reactors and SMRs. Four other states in the region are interested in building new nuclear capacity.

Table 4: Illustration of the Playbook implemented in the scenario of a country with limited nuclear energy experience

Dimension	Implementation
Project Execution & Capacity Building	• Set up a non-profit cooperative organization composed of heavy energy off-takers that will invest in new nuclear construction in exchange for reliable cost-effective electricity and heat. The organization will be an IDO responsible for full-scope development of new nuclear capacity in Country B. Facilitate membership in the IDO by industry in neighboring states. • IDO to conduct a technoeconomic study to determine technologies best suited to deliver nuclear capacity to meet Country B's industrial requirements and requirements of industry in neighboring states. • Based on the results of the study, form collaborative agreement or joint venture with companies considering similar technology options to conduct a joint or coordinated procurement to further enhance orderbook. • If SMRs are chosen as a technology to be deployed, analyze the potential to building up shipbuilding capabilities to support deployment of offshore SMRs. • Use non-nuclear project construction project development expertise to support IDO activities; engage owner's engineer experienced in the nuclear sector to enhance capabilities.
Regulatory System Development	• Conduct an assessment to determine gaps in regulatory capabilities required to license new reactors (whether large or SMRs, based on the results of the technoeconomic study conducted by the IDO). • Support establishing the ITSO; engage with ITSO, as needed, to fill identified gaps in expertise required for reviews of construction and operating licenses. • Amend licensing regime (if needed) to allow for acceptance of designs certified by competent national regulators (including DACs). • Establish agreements with regulators in countries deploying the same design(s), including participation in licensing reviews and job shadowing.
Project Bankability & Finance	• Identify financing need outside of IDO capacity and potential sources of equity / debt (e.g., sovereign investment, export credit agency support) that could fill that need. Engage external financial sources early in project development process. • Ensure that projects incorporate IPD mechanisms. • Provide pooled sovereign guarantees with interested neighboring countries and Country B to investors and export financiers, including a financial backstop for project overruns (especially for the first project(s) to be deployed). • Support establishment of IBNI and efforts to change policies of existing MDBs/MIBs.

(table continued)

Dimension	Implementation
Nonproliferation & Nuclear Security	• Incorporate security and safeguards planning early in the project development timeline. • Ensure that any selected reactor designs, including any SMR designs, have incorporated robust plans for safeguards. • Adopt a once-through fuel cycle and opt to procure fuel from the international market.
Spent Nuclear Fuel Management	• Incorporate waste disposal planning early in the project development timeline. • Enter into agreements with other states in the region to develop interim storage and permanent disposal of spent fuel.
Workforce Development	• Identify areas for supply chain growth in Country B and engage with regional states operating or considering nuclear on opportunities to establish regional supply chain. • Embed junior managers in nuclear project development organizations and supply chain companies overseas. • Enter into collaborative agreements with Class A shipyards overseas to train Country B shipyard personnel in successful shipyard delivery mechanisms that could be used in the offshore nuclear sector.

Endnotes

[1] The IEA World Energy Outlook estimates electricity demand will increase by 150%, from 28,000 TWh in 2021 to 73,000 TWh in 2050 under the net-zero scenario. This includes conservative estimates of population growth and continued limits to energy access in developing countries. IEA, *World Energy Outlook 2022*, at 44 (2022), https://iea.blob.core.windows.net/assets/830fe099-5530-48f2-a7c1-11f35d510983/WorldEnergyOutlook2022.pdf

[2] Recent analysis suggests that even these studies have vastly underestimated likely future energy demand, especially in the developing world. A recent paper analyzed the level of energy demand growth in Africa and South Asia contained in the Intergovernmental Panel on Climate Change scenarios and found that these scenarios essentially freeze per capita consumption in those regions at current levels or even a decrease. See generally Tejal Kanitkar et al., *Equity Assessment of Global Mitigation Pathways in the IPCC Sixth Assessment Report* (2022), https://osf.io/p46ty

[3] Jesse D. Jenkins, Max Luke, and Samuel Thernstrom, *Getting to Zero Carbon Emissions in the Electric Power Sector, Joule* 2.12 (2018): 2498-2510, https://www.cell.com/joule/pdf/S2542-4351(18)30562-2.pdf

[4] Seaver Wang, Zeke Hausfather, Steven Davis, Juzel Lloyd, Erik B. Olson, Lauren Liebermann, Guido D. Núñez-Mujica, and Jameson McBride. *Future Demand for Electricity Generation Materials under Different Climate Mitigation Scenarios. Joule* 7, no. 2 (2023): 309–332.

[5] U.S. Department of Energy (DOE), *Pathways to Commercial Liftoff: Advanced Nuclear* 11 (2023), https://liftoff.energy.gov/wp-content/uploads/2023/03/20230320-Liftoff-Advanced-Nuclear-vPUB-0329-Update.pdf

[6] IEA, *Nuclear Power and Secure Energy Transitions* (2022), https://iea.blob.core.windows.net/assets/016228e1-42bd-4ca7-bad9-a227c4a40b04/NuclearPowerandSecureEnergyTransitions.pdf.

[7] Organisation for Economic Co-operation and Development, Nuclear Energy Agency, *Meeting Climate Change Targets: The Role of Nuclear Energy* 16 (2022), https://www.oecd-nea.org/jcms/pl_69396/meeting-climate-change-targets-the-role-of-nuclear-energy.

[8] See Potential Energy, *The World Wants New Nuclear* (May 2023), http://thirdway.imgix.net/The-World-Wants-New-Nuclear.pdf. See also Pew Research Center, "Growing Share of Americans Support More Nuclear Power (August 18, 2023), https://www.pewresearch.org/short-reads/2023/08/18/growing-share-of-americans-favor-more-nuclear-power/ In some cases, self-identified members of environmental organizations are more supportive of nuclear energy than the general public. See The World Wants New Nuclear, p. 11. [au: is this the correct "New Nuclear" resource? Chicago style doesn't use "op. cit." and prefers short cites instead.]

[9] World Nuclear Association, *Financing Nuclear Energy* (2020), https://world-nuclear.org/information-library/economic-aspects/financing-nuclear-energy.aspx.

[10] Energy Technologies Institute, *Nuclear Cost Drivers Project: Full Technical Report* (2020), https://www.lucidcatalyst.com/_files/ugd/2fed7a_917857d4f3544323a84f163e5e904c23.pdf; DOE, *Pathways to Commercial Liftoff: Advanced Nuclear.*

[11] Although many embarking countries have some talented nuclear engineers who studied at the best engineering programs in the world and have returned home to head up the burgeoning nuclear program, these are usually just a handful of individuals and insufficient to staff a nuclear regulatory body. Furthermore, these limited resources cannot just be dedicated to the regulator, as individuals with requisite nuclear technical or industry experience will typically be needed to staff the project development company. Developing domestic human resources requires establishing nuclear engineering programs (a decadal undertaking) or sending a significant number of candidates to overseas programs—and there is no guarantee that the candidates will come back.

[12] Harmonizing regulatory approaches would yield several benefits in addition to those discussed in earlier sections. It would reduce uncertainty, leading to cost savings in constructing and deploying both large and small reactors. It would also streamline international trade by enabling developers to adhere to a unified global standard, mitigating the complexities of varying requirements across different countries, not only ensuring enhanced safety and security of reactors worldwide but also aiding newcomer and resource-limited nations in collaborating effectively and implementing top-tier safety measures. Additionally, harmonization drives efficient research and development collaboration, preventing redundant efforts and promoting knowledge exchange. Finally, consistent and inclusive regulatory approaches are pivotal for fostering public trust and acceptance of nuclear power, which are crucial for their successful deployment.

[13] This proposal emerged from a discussion process that involved dozens of interviews with experts from various organizations, including the IAEA, the Nuclear Energy Agency (NEA), heads and former heads of nuclear regulatory bodies, representatives of nuclear programs in other embarking countries, representatives of vendor country governments, technical support organizations, and suppliers.

[14] See World Nuclear Association, *Aviation Licensing and Lifetime Management—What Can Nuclear Learn?* https://www.world-nuclear.org/uploadedfiles/org/wna/publications/working_group_reports/cordelaviationreport.pdf

[15] See https://nuclearbank-io-sag.org/

[16] W.R. Stewart, K. Shirvan, *Capital Cost Evaluation of Advanced Water-Cooled Reactor Designs With Consideration of Uncertainty and Risk, Center for Advanced Nuclear Energy Systems*, MIT, MIT-ANP-TR-194, June 2022, https://canes.mit.edu/capital-cost-evaluation-advanced-water-cooled-reactor-designs-consideration-uncertainty-and-risk

[17] OECD Nuclear Energy Agency, *Unlocking Reductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders*, 2020, https://www.oecd-nea.org/jcms/pl_30653/unlocking-reductions-in-the-construction-costs-of-nuclear?details=true.

[18] U.S. Government Accountability Office, *DOE Should Institutionalize Oversight Plans for Demonstrations of New Reactor Types* (GAO-22-105394), Reissued with revisions on Sept. 15, 2022, https://www.gao.gov/products/gao-22-105394.

[19] DOE, *Pathways to Commercial Liftoff: Advanced Nuclear.*

[20] The American Institute of Architects, *Integrated Project Delivery: A Guide* (2007), https://info.aia.org/SiteObjects/files/IPD_Guide_2007.pdf.

[21] See https://www.legislation.gov.uk/ukpga/2022/15/contents/enacted.

[22] For a comprehensive overview of the regulated asset base model, please refer to *Regulatory Trends, New Nuclear RAB Funding Model* (July 2022), https://www.nortonrosefulbright.com/en/knowledge/publications/55726950/nuclear-energy---briefing-8-july-2022.

[23] By contrast, nuclear plants can expect to be more competitive in markets that are structured to allow generators to capture value for providing firm, dispatchable capacity.

[24] World Economic Forum, *Blended Finance: How to Accelerate Sustainable Development*, World Economic Forum (April 3, 2023), https://www.weforum.org/agenda/2023/04/blended-finance-financial-intermediation-can-accelerate-sustainable-development/

[25] IAEA, *Climate Change and Nuclear Power 2022 Securing Clean Energy for Climate Resilience* (2022).

[26] CPI, *Blended Finance in Clean Energy: Experiences and Opportunities—Green Bank Network* (Climate Policy Initiative, 2018), https://greenbanknetwork.org/portfolio/blended-finance-in-clean-energy/.

[27] Alvaro Mendez and David Patrick Houghton, *The Role of Multilateral Development Banks as Norm Entrepreneurs, Sustainability Mdpi* 3, no. 12 (2020): 972–93, https://doi.org/10.3390/su12030972.

[28] IAEA, Climate Change and Nuclear Power.

[29] World Nuclear Association, *Financing Nuclear Energy*.

[30] The IAEA defines LEU as enriched uranium containing less than 20% of the isotope U^{235}. For safeguards purposes, the IAEA does not make a distinction between standard assay LEU and HALEU.

[31] The IAEA classifies HEU and plutonium as direct use materials, meaning that they can be used for the manufacture of a nuclear weapon. LEU is not considered suitable for a nuclear weapon. See https://www.iaea.org/sites/default/files/iaea_safeguards_glossary.pdf.

[32] NEA and IAEA, *Uranium 2020: Resources, Production and Demand* (2020), https://www.oecd-nea.org/jcms/pl_52718/uranium-2020-resources-production-and-demand.

[33] TRISO stands for tristructural isotropic particle fuel. For more information, see *TRISO Fuel—Fuel with Its Own "Containment,"* https://www.ncbj.gov.pl/en/aktualnosci/triso-fuel-fuel-its-own-containment.

[34] Policy of the United Arab Emirates on the Evaluation and Potential Development of Peaceful Nuclear Energy, https://www.enec.gov.ae/doc/uae-peaceful-nuclear-energy-policy-5722278a2952f.pdf.

[35] Ernest J. Moniz, *Nuclear Non-Proliferation: Steps for the 21st Century* (November 5, 2019), https://www.hoover.org/research/nuclear-non-proliferation-steps-21st-century.

[36] IAEA, *Nuclear Security Recommendations on Physical Protection of Nuclear Material and Nuclear Facilities* (INFCIRC/225/Revision 5), https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1481_web.pdf.

[37] IAEA, *Additional Protocol*, https://www.iaea.org/topics/additional-protocol.

[38] *Disposition of High-Level Waste and Spent Nuclear Fuel: The Continuing Societal and Technical Challenges*, (Washington, DC: The National Academies Press, 2001), https://doi.org/10.17226/10119.

[39] Blue Ribbon Commission on America's Nuclear Future, *Report to the Secretary of Energy* (January 2012), https://www.energy.gov/ne/articles/blue-ribbon-commission-americas-nuclear-future-report-secretary-energy.

[40] IAEA, "Storage of Spent Nuclear Fuel," *IAEA Safety Standards Series*, no. SSG-15 (Rev. 1), https://www-pub.iaea.org/MTCD/Publications/PDF/P1882_web.pdf.

[41] *Milestones in the Development of a National Infrastructure for Nuclear Power*, Nuclear Energy Series, NG-G-3.1 (Rev. 1) (Vienna: IAEA, 2015), https://www.iaea.org/publications/10873/milestones-in-the-development-of-a-national-infrastructure-for-nuclear-power.

[42] *Human Resource Management for New Nuclear Power Programmes*, Nuclear Energy Series, NG-T-3.10 (Rev. 1) (Vienna: IAEA, 2022), https://www.iaea.org/publications/14724/human-resource-management-for-new-nuclear-power-programmes.

[43] OECD and Nuclear Energy Agency, *Nuclear Education and Training: From Concern to Capability*, Nuclear Development (2012), https://doi.org/10.1787/9789264177604-en.

[44] Energy Futures Initiative, *The U.S. Nuclear Energy Enterprise,* EFI Foundation, August 1, 2017, https://efifoundation.org/reports/the-u-s-nuclear-energy-enterprise-a-key-national-security-enabler/.

[45] OECD and Nuclear Energy Agency, *Nuclear Education and Training*.

[46] The taxonomy in this playbook expands OECD's "research reactors" category to include other support elements and adds the "Finance" category.

[47] *Human Resource Management for New Nuclear Power Programmes.*

[48] *Human Resource Management for New Nuclear Power Programmes.*

[49] *Human Resource Management for New Nuclear Power Programmes.*

[50] John Banks, Kevin Massy, and Charles Ebinger, *Human Resource Development in New Nuclear Energy States: Case Studies from the Middle East*, n.d.

[51] Banks, Massy, and Ebinger, Human Resource Development in New Nuclear Energy States.

[52] Banks, Massy, and Ebinger, Human Resource Development in New Nuclear Energy States.

[53] Banks, Massy, and Ebinger, Human Resource Development in New Nuclear Energy States.

[54] For example, in the United States, the Nuclear Engineering Department Heads Organization, among other things, creates a forum for universities to share best practices and tools regarding nuclear power research, workforce development, public engagement, licensing, fuel, and advanced reactor markets.

[55] *Workforce Planning for New Nuclear Power Programmes*, Nuclear Energy Series, NG-T-3.10 (Vienna: IAEA, 2011), https://www.iaea.org/publications/8488/workforce-planning-for-new-nuclear-power-programmes.

[56] World Nuclear Association, *Nuclear Power in Bangladesh*, https://world-nuclear.org/information-library/country-profiles/countries-a-f/bangladesh.aspx.

[57] *Establishing the Framework to Facilitate Licensing of New Nuclear Projects in Embarking Countries*, Clean Air Task Force, https://www.catf.us/resource/establishing-framework-facilitate-licensing-new-nuclear-projects-embarking-countries/.