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2023 Regional Workshop on Nuclear Energy and Nonproliferation:

Insights, Policy Recommendations, and Featured Papers

NTI
BUILDING A SAFER WORLD

Contents

About the Nuclear Threat Initiative-Emirates Nuclear Energy Corporation Partnership

In October 2022, the Nuclear Threat Initiative (NTI) and Emirates Nuclear Energy Corporation (ENEC) commenced a collaborative project, "Building a Cooperative Approach to the Future of Nuclear Energy Development and Nonproliferation." The project brings together experts from the United States and across the Middle East for workshops to examine existing standards in nuclear energy development and identify new cooperative fuel cycle strategies that support the global expansion of nuclear energy in a responsible, sustainable, secure, and transparent manner. NTI thanks ENEC for its support for this important work, including the publication of this report.

Overview

Nuclear energy is high on the global agenda; a growing number of government leaders and energy and climate experts recognize it as a critical part of the solution for managing climate change and meeting future energy demands. At the United Nations' COP28 climate change conference in Dubai in December 2023, 25 countries committed to tripling nuclear energy by 2050. In March 2024, the International Atomic Energy Agency (IAEA) and Belgium built on this progress by hosting the Nuclear Energy Summit in Brussels, the first head-of-state gathering dedicated to nuclear energy. Dozens of countries are considering or already pursuing nuclear energy, including several in the Middle East. However, nuclear energy expansion is still modest globally and it is unclear whether it will live up to its full potential to address climate threats and support economic development.

Geopolitics continues to play a significant role in nuclear energy's expansion. Russia—a major supplier of nuclear materials and fuel—is entrenched in its war with Ukraine, and is occupying Europe's largest nuclear power plant as part of its offensive. The U.S. ban on Russian uranium imports combined with fears that additional western sanctions could be applied to Russian fuel and enrichment services have put a spotlight on the importance of energy security and reliable nuclear supply chains.

Nuclear proliferation concerns remain ever-present, with several countries seeking or advancing sensitive fuel cycle technologies that can be used peacefully or for nuclear weapons purposes. As nuclear energy expands—and as new nuclear technologies are developed and deployed—nonproliferation and nuclear security practices will need to adapt to keep pace. The world needs an approach to nuclear energy deployment that ensures that achieving energy security does not erode global security. Indeed, strong nonproliferation practices can help pave the way for expediting and successfully expanding nuclear energy.

It is in this global context that the Nuclear Threat Initiative (NTI) and the Emirates Nuclear Energy Corporation (ENEC) held their annual workshop on nuclear energy and nonproliferation in Abu Dhabi in October 2023, titled, "Facilitating the Responsible Expansion of Nuclear Energy." More than 40 experts from the United States and Middle Eastern countries participated in this workshop, which catalyzed a discussion on how countries in the Middle East region and the international community can cooperate on nuclear energy in a way that bolsters nonproliferation and nuclear security standards and practices.

The three papers in this report were presented by their respective authors at the workshop in Abu Dhabi. They examine:

1. Options for regional collaboration on nuclear fuel fabrication and spent fuel management;
2. Options for regional cooperation on nuclear security; and
3. Pathways and principles for the efficient, sustainable, and responsible expansion of nuclear energy development.

Based on the papers, presentations, and discussion during the workshop, NTI has identified the following key insights and recommendations.[1]

Key Insights

- 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 safe and secure nuclear technologies. To succeed, nations must rethink how to build, regulate, and finance nuclear technology. A new system will need to deliver standardized products rather than costly and risky one-off multi-decade projects.
- Although countries in the Middle East are taking different approaches to nuclear energy and have differing energy needs, opportunities abound for collaboration in the region that can help achieve nuclear energy goals and meaningfully enhance nonproliferation. Areas of potential collaboration include the nuclear fuel cycle, the nuclear supply chain, and nuclear security.
- The United Arab Emirates, as a country that successfully and efficiently stood up its own nuclear energy program and that maintains the highest standards of safeguards and nonproliferation, has an important leadership role to play in the expansion of nuclear energy in the region and globally.
- For nuclear to be scaled successfully and responsibly, governments must make a firm decision to develop nuclear energy, make such development a national priority, and engage all relevant domestic parties. “Nuclear” cannot just keeping talking to “nuclear”; governments and industry need to build support across a broad coalition. Young people and groups focused on related issues (e.g., climate change and electricity access) are key audiences and stakeholders who need to be engaged.
- The discussion on scaling nuclear energy needs to pivot from the “what” to the “how”—and start addressing the mechanics of global nuclear energy development. This includes project execution, supply chain management, financing, regulatory development, nonproliferation, and workforce development.
- As nuclear energy expands—and as new nuclear technologies are developed and deployed—nonproliferation and nuclear security capacity must expand in parallel, and best practices and standards must evolve at the same pace. Ignoring or deprioritizing these critical issues will compromise the entire nuclear energy enterprise.
- Many reactor technologies are under development—including more than 70 designs for small modular reactors (SMR) and other advanced reactors—that could serve a variety of useful purposes in the region. From a nonproliferation and security standpoint, these technologies are not created equally. Light water, low enriched uranium (LEU)-fueled reactors have strong nonproliferation benefits. However, reactor designs that rely on plutonium fuel, incorporate reprocessing technologies, or both, introduce proliferation and security risks because plutonium can be directly used in nuclear weapons.

[1] NTI’s analysis and recommendations are NTI’s alone, and do not necessarily reflect the opinions of the paper authors, workshop participants, or ENEC.

Recommendations

Embarking countries can take a range of actions to ensure responsible, sustainable, and effective development of nuclear energy, including:

- Adopt best practice project management, assembling multi-off-taker buyer consortia that can generate large orderbook demand, create multilateral agreements for international transfer of design certifications, adopt a once-through fuel cycle and work with certified designs and proven entities, and develop workforce assessment strategy.
- Weigh nonproliferation and nuclear security criteria equally alongside other factors when developing their nuclear programs and deciding on reactor technologies. For example, countries should avoid reactors that require plutonium fuel, given that plutonium can be directly used in nuclear weapons. The Middle East region can set a positive example as it explores SMR technology by making safety, security, and nonproliferation important criteria for selection.

Over the longer term, all countries across the globe should take additional steps to expedite the safe and secure scaling of nuclear energy, including by creating new institutions and partnerships, such as:

- Public-private global partnerships to provide integrated project delivery
- An international technical support organization to assist embarking countries with licensing and regulation
- A multilateral International Bank for Nuclear Infrastructure
- Regional nuclear training centers to enhance workforce development.

Countries should further explore opportunities for regional collaboration in a number of areas:

- Embarking countries should also consider a regional approach to reactor technology selection. Banding together could not only ensure strong consideration for nonproliferation factors, but it would also create the demand necessary to drive down costs and dilute financial risks.
- All countries should further explore collaboration on aspects of the fuel cycle in ways that can provide economic, energy, and nonproliferation benefits. For example, countries could explore the potential advantages of a regional fuel fabrication capability or spent nuclear fuel facility and the conditions needed for success.
- All countries should consider options for enhancing collaboration on regional nuclear security. For example, they could work to establish a center of excellence on nuclear security, strengthen nuclear security governance, or cooperate on specific projects such as nuclear security considerations around small modular reactors.

Middle Eastern Nuclear Fuel Services Collaboration

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and
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What Can Be Done to Secure the Nuclear Fuel Cycle in the Middle East?

Four nuclear power plants (NPPs) exist in the Middle East either under construction or in operation in Iran (IR), United Arab Emirates (UAE), Egypt (EG), and Turkey (TU) with a total gross electrical capacity of 16,100 MWe (see Table 1). Two types of pressurized water reactors (PWRs) are being built: one based on U.S. and Korean technology, and the other based on Russian technology. Furthermore, the Russian design, known as VVER (Water-Moderated, Water-Cooled Energy Reactor), has two variants: the "Generation 2" VVER-1000, built and being built in Iran, and the "Generation 3" VVER-1200. A Generation 3+ PWR, the VVER-1300, is under development. The Republic of Korea has built four Advanced Pressurized Reactors (APR-1400) in the UAE, based on the Palo Verde NPP System-80 design in the United States. (Because of data access, Palo Verde is the reference plant in this analysis.)

Fuel for these plants is available from the nuclear steam system (reactor and steam generator) suppliers (e.g., Rosatom for the VVERs), with even more market options emerging. For example, to diversify fuel supply, particularly for European and Ukrainian VVERs, the European Union is financing a consortium led by Westinghouse to develop the capacity to produce all variants of PWR fuel in the EU. A similar scheme could also be considered in the Middle East (see World Nuclear News (WNN, 2024)).

Table 1. Nuclear Power Plants in Operation and Under Construction in the Middle East

MS*	Station Name	Therm†	Gross§	Net‡	Type	Years**	Cons	Crit	Oper††
IR	BUSHEHR-1	3,000	1,000	915	VVER-1000	15.3	Jan-96	May-11	Sep-13
UAE	BARAKAH-1	3,983	1,417	1,310	APR-1400	8.0	Jul-12	Jul-20	Apr-21
UAE	BARAKAH-2	3,983	1,417	1,310	APR-1400	8.4	Apr-13	Aug-21	Mar-22
UAE	BARAKAH-3	3,983	1,417	1,310	APR-1400	8.0	Sep-14	Sep-22	Feb-23
UAE	BARAKAH-4	3,983	1,417	1,310	APR-1400	8.5	Jul-15	May-24	Oct-24

MS*	Station Name	Therm†	Gross§	Net‡	Type	Years**	Cons	Crit	Oper††
TU	AKKUYU-1	3,200	1,200	1,114	VVER-1200	8.9	Apr-18	Feb-27	Nov-27
IR	BUSHEHR-2	3,012	1,057	974	VVER-1000	8.9	Sep-19	Aug-28	May-29
TU	AKKUYU-2	3,200	1,200	1,114	VVER-1200	8.9	Apr-20	Mar-29	Dec-29
TU	AKKUYU-3	3,200	1,200	1,114	VVER-1200	8.9	Mar-21	Feb-30	Nov-30
EG	ELDABAA-1	3,200	1,194	1,109	VVER-1200	8.9	Jul-22	Jun-31	Mar-32
TU	AKKUYU-4	3,200	1,200	1,114	VVER-1200	8.9	Jul-22	Jun-31	Mar-32
EG	ELDABAA-2	3,200	1,194	1,109	VVER-1200	8.9	Nov-22	Oct-31	Jul-32
EG	ELDABAA-3	3,200	1,194	1,109	VVER-1200	8.9	May-23	Mar-32	Dec-32
	TOTAL	**44,344**	**16,107**	**14,912**					

* IAEA Member State.

† Thermal size, MWth.

§ Electricity generating size, Mwe.

‡ Subtracts plant's electricity consumption, Mwe.

** The difference between **Cons** (construction start date of first base mat concrete) and **Crit** (first criticality date), where dates in italic are projections.

†† Commercial operation date or projection.

Source: IAEA (2024). Incomplete VVER-1200s are assumed to take 8.9 years to criticality and another nine months to commercial operation; this is the time it took to build and commission Belarusian-2, a VVER-1200. Also, see Associated Press (2024).

Kraftwerk Union of Germany (KWU) started two PWRs at Bushehr, Iran, in May 1975, but suspended construction in January 1979 in a dispute over the lack of Iranian payments for the plants (Public Intelligence, 2010). Rosatom (a Russian state-owned enterprise) restarted construction in January 1996 to complete Bushehr as a VVER-1000, which began commercial operation in September 2013. The current Middle Eastern NPP growth consists of eight PWRs on which construction began in the last five years, located in three countries. According to the World Nuclear Association (WNA) (2023), "About 30 countries are considering, planning, or starting nuclear power programmes..." In the Middle East, these countries include Saudi Arabia and Jordan.

One problem with operating a nuclear power plant is assuring a continuous supply of nuclear fuel over its lifetime. This is particularly worrisome for countries that are ordering their first NPP. The typical one gigawatt (GW) PWR consumes 20–30 MT (metric tons) per year of uranium oxide (UO2) in fuel rods containing less than 5 percent fissionable uranium, U^{235}. Fresh fuel (in about one-third of the assemblies) is replaced in a PWR every 12 to 24 months.

The production of low enriched uranium (LEU) nuclear fuel involves (1) uranium oxide (U_3O_8) procurement, (2) U_3O_8 conversion to uranium hexafluoride (UF_6) and enrichment to increase the concentration of U^{235}, and (3) the reconversion of the enriched UF_6 to uranium oxide (UO_2) and fabrication into fuel.

On the other hand, there is a discharge of about 20–30 MT of heavy metal (MTHM, fission products and isotopes of uranium and transuranic elements) from the PWR that must be managed until disposal. Thus, owning an NPP implies two related issues: (1) how to secure the nuclear fuel input, and (2) how to manage the Spent Nuclear Fuel (SNF) output. (Although SNF can be reprocessed, we do not explicitly consider the cost of it here (see Wood, Rothwell, Daly and Weimar, 2014.)

First, although an abundance of uranium exists, not all countries can develop low-cost uranium resources; thus, they must rely on foreign suppliers (Rothwell, 1980). Second, commercial uranium enrichment is viewed as a sensitive nuclear technology and the international community has developed guidelines to restrict its transfer due to the ability to use enriching technologies to produce highly enriched uranium (HEU) for nuclear weapons. Hence, most countries must rely on a few foreign sources of enrichment services (Rothwell, 2009). Third, commercial nuclear fuel fabrication is a competitive, technical, international industry (Rothwell, 2010). The high entry costs and high technical sophistication of fuel fabrication facilities results in market concentration, and a large fraction of fabricated PWR fuel is exported from a few countries (see next section).

The cost of acquiring nuclear fuel involves the costs of many physical and contractual stages. Table 2 provides stage-by-stage costs for the two PWR designs in the Middle East: the APR-1400 and the VVER-1200. For example, to supply fuel to the four APR1400s at Barakah Nuclear Power Plant, the Emirates Nuclear Energy Corporation (ENEC) signed contracts with Orano and Techsnabexport (Tenex of Rosatom) to supply uranium concentrates, conversion, and enrichment services. To diversify supply, there are contracts with Uranium One and Rio Tinto to provide natural uranium, ConverDyn to provide conversion services, and URENCO to provide enrichment services. The enriched uranium is delivered to KEPCO Nuclear Fuels for manufacturing fuel assemblies (Power Technology, 2020). More recently, ENEC CEO His Excellency Mohamed Al Hammadi said, “With a significant positive shift in many nations to include civil nuclear energy as part of their energy mix, security of supply for fuel is paramount” (NEI, 2024).

The cost of these fuel assemblies (in Table 2) is calculated assuming the price of UF_6 is $111/kg, including the cost of U_3O_8 (e.g., $95/kg) and the conversion of UO_2 to UF_6 (e.g., $16/kg), according to WNA (2022). These calculations assume an enrichment of 4.5 percent and a burnup of 50 GWd/MTU (GW days of heat / metric tons of uranium (Al Saadi and Yi, 2015).

Table 2. “Front-End” Nuclear Fuel Costs from WNA for the APR 1400 and VVER 1200

					APR	APR	VVER	VVER
PWR Fuel Costs	**WNA**	**WNA**	**WNA**	**WNA**	**1400**	**1400**	**1200**	**1200**
WNA (2022)	**kg**	**$/kg**	**2021**	**%**	**MT**	**k$-2021**	**MT**	**k$-2021**
Uranium (U3O8)	8.9	$94.60	$842	50.6%	242.598	$23,000	194.907	$18,500
Conversion	7.5	$16.00	$120	7.2%	242.598	$4,000	194.907	$3,000
Enrichment (SWU)	7.3	$55.00	$402	24.1%	224.873	$12,000	180.666	$10,000
Fuel Fabrication	1.0	$300.00	$300	18.0%	29.707	$9,000	23.867	$7,000
Total Fuel Cost		**$1,663**	**100.0%**		**$48,000**		**$38,500**	
MTHM per year per GWe				**22.677**		**21.697**		
Fuel Cost per MWh					**$4.66**		**$4.46**	

Note: There is rounding in dollar amounts.

Source: Prices from WNA (2022).

Slight differences in the thermal to electricity efficiency (33 percent for the APR-1400 and 34 percent for the VVER-1200) between the two PWR designs lead to a small difference in fuel costs per MWh of fuel produced ($4.66/kg vs. $4.46/kg). More important is that these costs are quite low compared to the costs that would result from a country operating its own fabrication facility.

At the back end of the fuel cycle, the four units at Barakah discharge about 120 MTHM each year, which is stored in on-site fuel pools. *Each* of the four fuel pools has a capacity of 20 years of discharge, or total room for about 600 MTHM. It is anticipated that after 20 years the SNF will be moved from the fuel pools and stored in on-site dry-cask storage, or possibly in an off-site centralized dry storage facility. An off-site facility could be cheaper and could facilitate the moving of SNF to a disposal site. Should Middle Eastern countries build on-site or off-site SNF storage?

This paper addresses (1) whether new entrants in the commercial nuclear power industry could compete with established fuel fabricators, and (2) whether new entrants could manage their SNF at competitive costs. However, since July 2015 in the Middle East, construction has started only on Rosatom's VVERs. This portends future use of Russian nuclear fuel service markets in the Middle East.

See Egypt's El Dabaa NPP (NEI, 2022) and Turkey's Akkuyu NPP (Alkis and Gergiieva, 2023).

The International Nuclear Fuel Fabrication Market

To address these issues, this paper models the costs of LWR (light water reactor) nuclear fuel—in particular, the extent to which fuel fabrication and SNF storage exhibit economies of scale (i.e., that larger plants (with high fixed costs) can produce at lower average cost than smaller plants).

Although PWR fuel is functionally similar across many PWR designs, fuel designs themselves are highly tailored to meet individual reactor specifications and achieve optimal fuel performance. They thus contain many elements of proprietary technology and tacit knowledge. This includes the manufacturing processes that produce fuel components. Thus, modeling these costs cannot be based on detailed facility descriptions and production data. WNA (2021) explains,

> Fuel fabrication services are not procured in the same way as, for example, uranium enrichment is bought. Nuclear fuel assemblies are highly engineered products, made to each customer's individual specifications...Most main fuel fabricators are also reactor vendors (or owned by them), and they usually supply the initial cores and early reloads for reactors built to their own designs. However, the market for LWR fuel has become increasingly competitive and for most fuel types there are now several competing suppliers...Currently, fuel fabrication capacity for all types of LWR fuel throughout the world considerably exceeds the demand.

To circumvent this lack of cost data, this paper is based on "reverse cost engineering," which builds a top-down model (based on GIF/EMWG, 2009; Rothwell, 2010 and 2016) to mimic observable information about industry prices in publicly available data.

Table 3 identifies participants in the international commercial LWR LEU nuclear fuel fabrication industry. The largest share of fabrication capacity, 31 percent, in 2008 was held by the French group Framatome (formerly Areva), including one-quarter of the U.S. capacity, but its share dropped to 21 percent in 2021 (see WNA, 2021 for other reactor type fuel fabricators).

Table 3. International Commercial LEU Fuel Fabrication Capacity

						IAEA 2008	WNA 2021
Country	**ID**	**Open**	**Current Operating Firm**	**Location**	**Type**	**MTU/yr**	**MTU/yr**
Belgium	BE	1961	FBFC International (Areva)	Dessel	BWR* + PWR†	400§	0
Brazil	BR	1982	FEC (Indústrias Nucleares do Brasil)	Resende	PWR	250§	400
China	CN	1993	China National Nuclear Corporation (CNNC)	Yibin	PWR	100	800
China	CN	2018	China Baotou Nuclear Fuel (CBNF)	Baotou	PWR (AP1000)‡	0	400
China	CN	2017	China Northern Nuclear Fuel Corp. (CNNFC)	Baotou	HALEU fuels	0	200
France	FR	1979	FBFC (Framatome, CERCA 1962–1977)+2008 add	Romans-sur-Isere	PWR	1,380	1,400

					IAEA 2008	WNA 2021	
Country	ID	Open	Current Operating Firm	Location	Type	MTU/ yr	MTU/ yr
Germany	DE	1979	Advanced Nuclear Fuels (Framatome)	Lingen	BWR + PWR	650	650
India	IN	1974	DAE Nuclear Fuel Complex (NFC)	Hyderabad	BWR	25	48
Japan	JP	1980	Nuclear Fuel Industry Ltd.	Tokai	BWR	250**	250
Japan	JP	1972	Nuclear Fuel Industry Ltd.	Kumatori	PWR	383**	284
Japan	JP	1972	Mitsubishi Nuclear Fuel Co. (MNF/MHI)	Tokai	PWR	440	440
Japan	JP	1970	Japan Nuclear Fuel (Global Nuclear Fuel, GNF)	Yokosuka	BWR	750**	630
Kazakhstan	KZ	2021	Ust Kamenogorsk (Ulba Metallurgical Plant, UMP)	Ulba	PWR	0	200
Korea (ROK)	KR	1989	Korea Nuclear Fuel Co. (KNFC, KEPCO)	Daejon	PWR	400	700
Russia	RU	1996	JSC TVEL	Elektrostal	VVER + LWGR††	620	1,560
Russia	RU	1949	JSC TVEL	Novosibirsk	VVER	1,000	1,200
Spain	ES	1985	ENUSA (Fabrica de Combustibles)	Juzbado	BWR + PWR	300	500
Sweden	SE	1971	Westinghouse Electric Sweden (in 1999: BNFL)	Västerås	BWR + PWR	600	600
United Kingdom	UK	1996	Westinghouse Electric UK (in 1999: BNFL)	Springfields	PWR + AGR§§	330	860
United States	US	1982	Framatome (in 1999: Fram+Cogema)	Lynchburg, VA	PWR	400	0
United States	US	1970	Framatome (in 1999: Siemens)	Richland, WA	BWR + PWR	700	1,200
United States	US	1982	Global Nuclear Fuel (GNF=GE+Toshiba+Hitachi)	Wilmington, NC	BWR	1,200	1,000
United States	US	1986	Westinghouse-Toshiba Group (in 1999: West.)	Columbia, SC	PWR	1,150	2,154
			Total Commercial Fuel Assembly Manufacturing Capacity (MTU/year)			**11,328**	**15,476**

* Boiling water reactor.
† Pressurized water reactor.
§ Data from the operating firm or from NEA/OECD.
‡ AP1000 is a Westinghouse Advanced Passive PWR.
** Implies same source for MTU/year as in Rothwell (2010, Table 3).
†† Light water graphite reactor.
§§ Advanced gas reactor; other reactor types identified in the text.
Source: IAEA (2002, p.4), updated with WNA (2021).

Scenarios for Nuclear Fuel Fabrication and Interim Spent Fuel Storage Services

Given that all NPPs in operation or under construction in the Middle East are PWRs (which includes VVERs) and many of the LWR SMR options available in the near future will be PWRs, we forecast generic PWR fuel costs in Appendix 1. Little information on VVER fabrication costs or prices exists; we assume that the *scale* economies are similar to non-VVER PWRs.

We compare the minimum costs for three fuel fabrication scenarios: (1) a "non-cooperative" scenario where a country with 1 to 4 GWs of PWRs fabricates its own nuclear fuel with a fuel fabrication facility with capacities of 30 MTU to 120 MTU/year; (2) a "cooperative" scenario, where fuel is fabricated in a regional facility capable of assembling 480 MTU/year (e.g., four countries with 4 GW apiece); and (3) a "competitive" scenario where fuel is fabricated internationally for a fleet size of 32 GW with a capacity of 960 MTU/year (see GIF/EMWG, 2007, p. 23: "Fleet size: Size or capacity of the same type of plant for sizing support facilities such as fuel fabrication or reprocessing plants. It has been standardized to a 32-GWe capacity.")

Parallel with these three fuel fabrication scenarios are three interim SNF storage scenarios: (1) a "non-cooperative" scenario with on-site dry (canister and cask) storage with a potential capacity of less than 6,000 MTU (4 x 30 MTU x 50 years); (2) a "cooperative" scenario with a regional consolidated interim storage facility (CISF) with a potential capacity of 24,000 MTU (16 units); and (3) an international "competitive" market scenario involving a CISF (including "take-back" interim storage) with a potential for 48,000 MTU.

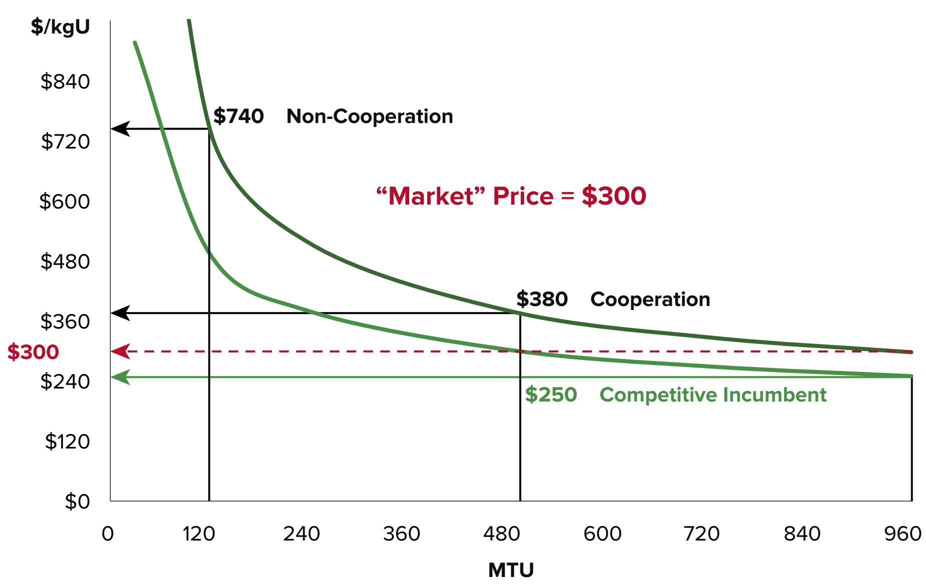
The next two sections consider the cost of nuclear fuel fabrication and the cost of SNF storage alternatives. The final section summarizes our findings and presents our policy recommendations.

Costs of Nuclear Fuel Fabrication Alternatives

If there is a competitive market in PWR fuel fabrication, the long-run price should be approximately equal to the levelized (long-run) average cost (AC), where levelizing assumes a competitive rate of return on investment. Here, capital costs are levelized over lifetime output, expressed in mid-2021 dollars (USD) per kilogram of uranium oxide. The structures and equipment costs are modeled as a function of nominal capacity, "SIZE," measured in MTU per year.

Nuclear fuel fabrication costs as functions of facility size are proposed in Appendix 1. With these cost forecasting equations, Table A1.2 in the Appendix presents nuclear fuel fabrication costs for generic plants between 120 and 1,440 MTU (similar to facilities in Table 3). Figure 1 plots these estimated levelized AC for various capacities for two alternatives: (1) where incumbent nuclear fuel fabricators add capacity to their fabrication lines, and (2) where a new-entrant attempts to produce for internal national or international markets. The cost equations are shown in Figure 1 where new entrants must pay a licensing fee of $100M to produce nuclear fuel.

Figure 1. Scale Economies in Average Cost at Nuclear Fuel Fabrication Facilities



The cost of "non-cooperative new-entrant" fuel fabrication is twice as much as "cooperative new-entrant," and "cooperative new-entrant" fuel is one-third more expensive than "competitive-incumbent" fuel. These forecasts show increasing returns to scale: a steady decline in levelized average costs for the entire range of capacities. Increasing returns to scale arise from the high set-up costs (e.g., licensing the plant and its fuel) that must be levelized over lifetime output. For example, if all APR1400 and VVER1200 fuel could be fabricated at a single Middle Eastern facility with a capacity of 480 MTU per year, a subsidy of approximately $80/kgU would be required over what might be available in an international competitive market ($300/kgU). This could increase the cost of fuel fabrication for an APR1400 by ($80 x 29.707 =) $2,380/kg, and increase in the total fuel cost of a APR1400 by about 5 percent. We return to the implication of these results after discussing SNF storage.

The Cost of Interim Spent Nuclear Fuel Dry Storage

This section discusses the cost of providing (1) non-cooperative on-site dry SNF storage after PWR discharge and before disposal (1,500 to 6,000 MTHM for 1 to 4 units), (2) cooperative off-site dry storage in a regional facility (6,000 to 24,000 MTHM for 4 to 16 units), and (3) competitive off-site dry storage in an international facility (at least 48,000 MTHM for 32 units).

In general, as at the Palo Verde site (3 x 1,400 MWe), SNF cools in a pool of borated water for "four to seven years before it's loaded, in groups of 24 assemblies, into 20-foot concrete casks stored onsite" (Gerbis, 2017). Because none of the current fuel pools can hold a lifetime of SNF, at some point older fuel must be removed. The issue is whether to provide on-site storage for the lifetime discharge or move it directly to a centralized facility. Appendix 2 models the cost of on-site and off-site dry storage. (Rothwell (2021) concludes that off-site wet storage is more expensive to build and maintain than dry storage, so off-site wet storage will not be considered here.) Furthermore, we do not consider the implications or the cost of SNF disposal in a deep geologic repository (DGR), although this would be a good candidate for regional collaboration and an excellent topic for further study, given the lessons learned from the construction of a DGR in Finland.

On-Site Spent Nuclear Fuel Dry Storage

In the United States in the 1990s, many fuel pools were beginning to approach their licensed capacities. In response to this situation, the Department of Energy, in cooperation with industrial partners, developed and evaluated dry storage technologies for spent fuel (McKinnon and DeLoach, 1993). These technologies were then licensed by the United States Nuclear Regulatory Commission (U.S. NRC), and NPP owner/operators began developing plans to move older SNF out of pools and into dry casks for storage at NPP sites, now referred to by the U.S. NRC as Interim Spent Fuel Storage Installations (ISFSIs).

In assessing GE-Hitachi's 2015 proposal to build an advanced boiling water reactor (ABWR) in the UK, the UK Office of Nuclear Regulation (ONR, 2017, p. 3) described the steps to populating an on-site ISFSI. Hitachi-GE's proposed strategy for managing the UK ABWR SNF consists of the following steps (see, e.g., www.youtube.com/watch?v=mILvWNgggfU).

- When decay heat has fallen sufficiently, SNF assemblies are loaded into a multi-purpose cask (MPC) within a transfer cask, inside the fuel pool.
- Once loaded, the MPC and transfer cask are lifted onto a cask stand outside the fuel pool and the MPC internals are dried, pressurized with an inert gas, and fitted with a lid that is welded to the MPC.
- The MPC and cask are moved from the fuel pool building on a cask transporter to a storage area.
- The MPC is removed from the transfer cask and placed inside a large concrete overpack on a concrete pad that might be placed in an underground or above ground structure.
- When a CISF or DGR is available, the MPCs can be moved and stored at the CISF or re-packaged into containers and placed in the DGR.

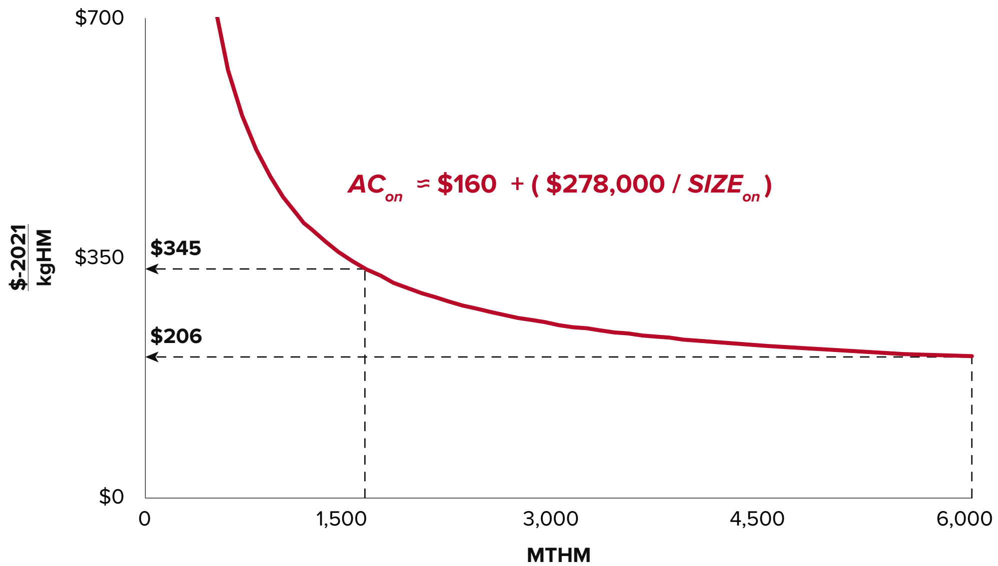
As shown in Appendix 2, annual average cost per kilogram of heavy metal (kgHM) of on-site dry storage is given by Equation 1 (repeated in Appendix 2 as Equation A2.5):

Equation 1	$ACon \approx \$160 + (\$278{,}000 / SIZE_{on})$

where AC_{on} per kgHM is the average cost of on-site dry storage when the NPP is not operating or actively being decommissioned and the storage site requires its own staff, and $SIZE_{on}$ is the storage capacity. However, there is generally a limit to the size of the on-site facility according to its site license (e.g., 1,500 to 6,000 MTU). A single GW PWR at a site would only generate at most 1,500 MTU during its life.

The cumulative MTHM grows until (at least) six years after shutdown of the NPP, when it is assumed that the fuel pool has been emptied. Costs are approximately $345/kgHM for 1,500 MTHM for on-site storage without an NPP staff to operate the ISFSI. Figure 2 presents these values for on-site dry storage facilities from 500 to 6,000 MTHM in capacity. Evaluate Figure 2 in the context of Feiveson, Mian, Ramana, and von Hippel (2011, p. 124): "Compared to spent fuel pools, casks being completely passive, require much less attention and are relatively cheap, costing $100–200 per kilogram of uranium [$135/kg to $270/kg in 2021 dollars] in the fuel."

Figure 2. Estimated Average Cost of an On-site Dry Storage Facility



Source: Equation 1.

Off-Site Spent Nuclear Fuel Dry Storage: Regional and International

About a dozen dry-cask CISFs are in operation, being built, or planned in countries with NPPs (see Table 4). The U.S. NRC licensed the first private CISF in the United States in 2006: Private Fuel Services (PFS) LLC on the Goshute's Skull Valley Indian Reservation in Toole County, Utah. Appendix 2 relies on the cost analysis in PFS (1997) to develop Equation 2, below. Regarding the two proposed privately owned U.S. facilities, the license application for the Holtec CISF in Lea County, New Mexico, was submitted to the U.S. NRC in 2017 (see WNN, 2023a). In June 2018, Waste Control Specialists' (WCS) created a joint venture with Orano USA (Interim Storage Partners LLC) to construct a storage facility in Andrews County, Texas (see WNN, 2023b).

Building on cost aspects of on-site dry storage, Appendix 2 models off-site dry storage updating Rothwell (2021). Appendix 2 shows that the average cost of off-site dry storage per kgHM (AC_{off}), can be approximated by a function of the maximum amount that can be stored on-site (*maxMT*). This approximation is given by Equation 2(repeated in Appendix 2 as Equation A2.13):

Equation 2	$AC_{off} \approx$ \$54.2 + \$767,000 / *maxMT*

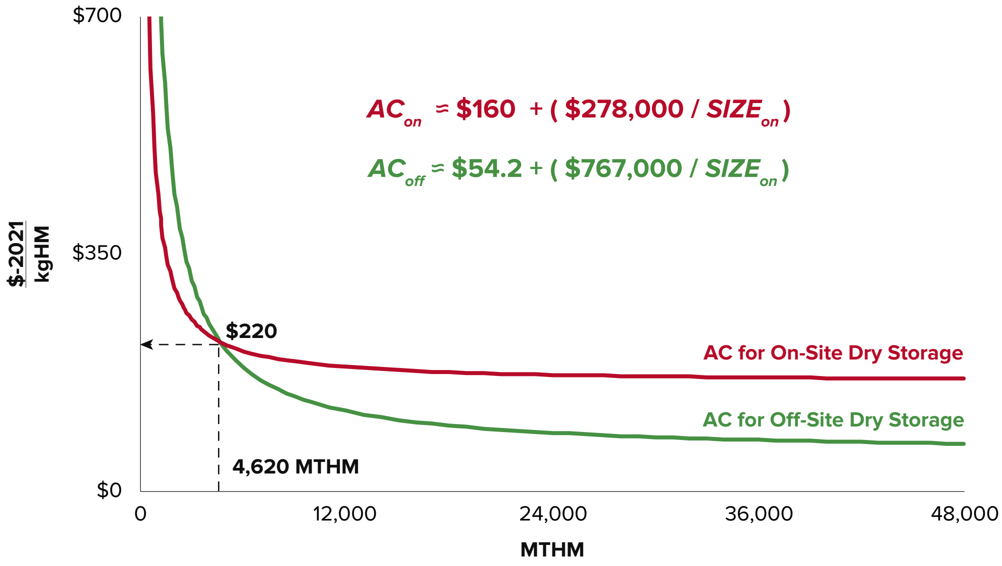
Figure 3 shows the dilemma facing the new NPP owner/operator: with a capacity of above about 4,620 MTHM, the cost of on-site dry storage installation is greater than for an off-site facility. The dilemma is whether the owner/operator of 3 or 4 GWs of new PWR capacity should build an on-site facility to store a lifetime supply of SNF until the end of NPP decommissioning or invest in a collaborative off-site facility that can be expanded to hold the region's SNF (see Waste Control Specialists, 2024 for design of WSC's low-level and high-level radioactive waste facility in Texas).

Table 4. Examples of Consolidated Interim Dry Storage Facilities (CISFs)

Country	Facility Name: ISFSI not at a commercial NPP	Facility Status	Capacity MTHM	Oper. Start
Switzerland	ZWIBEZ (near Beznau NPP)	In operation	600	2010
Germany	Ahaus Central SFSF, TBL-A	In operation	3,960	1997
Germany	Gorleben Central SFSF, TBL-G	In operation	3,800	1995
Japan	Recyclable Fuel Storage Centre, Mutsu	Construction	5,000	?
Korea	Consolidated PWR Fuel Storage Facility	Construction	12,000	?
Korea	Consolidated CANDU Fuel Storage Facility	In operation	6,250	1992
Russia	Mining and Chemical Complex Site	In operation	8,130	2011
U.S.-New Mexico	Holtec International CISF in Lea County	Approved	8,680+	?
U.S.-Texas	WSC/Interim Storage Partners CISF in Andrews County	App in 2018	40,000	?
U.S.-Utah	Private Fuel Storage CISF, license approved	Deferred	40,000	?

Note: This list does not include U.S. Department of Energy (DOE) national laboratory facilities.
Source: IAEA (2023).

Figure 3. Interim Storage Average Costs On-Site and Off-Site



Source: Equation 1 and Equation 2.

Summary and Policy Implications

To summarize the per kilogram cost of the three fuel fabrication scenarios: The cost of “non-cooperative new-entrant” fuel fabrication is much greater than international “competitive-incumbent” fuel, hence requiring subsidies to pay for nuclear fuel fabrication security but providing technology development benefits. The “cooperative new-entrant” fuel is one-third more expensive than internationally supplied fuel. However, the additional total nuclear fuel cost (~5 percent) could be absorbed by a state-owned nuclear utility as payment for the cost of nuclear fuel security.

Although it might be difficult to compete in international markets, the ENEC announced in late January 2024, “As part of examining a range of options, we have entered into the tendering for a domestic fuel assembly fabrication facility… dedicated to the industrial fabrication of fuel assemblies from their various components” (NEI, 2024). There is an opportunity to use this facility to supply multiple reactor sites across the region, which would have clear economic and strategic benefits over simply using the facility for domestic needs only.

On the back end of the nuclear fuel cycle, NPP owner/operators in the Middle East must decide whether they should invest in a consolidated facility before their fuel pools reach their limited capacity and *before* they make investments in national SNF management facilities. For example, the UAE has a decade to consider building a CISF near its Barakah NPP that could also accept SNF from other countries in the Middle East. Operations at the CISF could begin with the direct transport of casks from the fuel pool buildings at Barakah on a transporter to the CISF without an initial requirement of a canister-to-cask (C2C) building (although a hot cell might be required to handle failed fuel rods). An expandable CISF is the cheapest long-run alternative and provides for expansion into the SNF storage management market. The sooner a country starts on such a plan, the sooner its neighbors can collaborate on regional interim storage (and possible disposal).

With its early lead in the construction and operation of large-scale PWRs in the Middle East, the UAE has become the leader of its region’s nuclear power industry. In requesting proposals to construct a nuclear fuel fabrication facility, the UAE is taking steps reminiscent of the Republic of Korea’s plan to become an international supplier of nuclear energy systems (e.g., integrated pressurized water reactor (iPWR) SMRs).

Although much of the back end of nuclear fuel services is limited to very early entrants, because of the complexities of building DGRs, interim SNF management has low barriers of entry and provides a secure path toward high technology, economic development, and diversification. This could be an attractive option, particularly in combination with a regional supplier role for fuel fabrication at the front end of the fuel cycle.

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Appendix 1: Modeling Nuclear Fuel Fabrication Cost[1]

There are four nuclear fuel (NF) fabrication cost components: labor costs (L), hardware costs (H), other variable costs (VC), and Total Capital Investment Costs (TCIC, as defined in GIF-EMWG 2007, including licensing fees, etc.) that must be amortized over the life of the NF facility. Given that all NPPs in operation or under construction in the Middle East are PWRs (including VVERs) and many of the LWR SMR options available in the near future are small PWRs, this appendix estimates PWR fuel costs. This analysis is based on Rothwell (2010), as Idaho National Laboratory (2017, p. D1-21) notes, “Scaling factors are not relevant for [LWR UO2 Pelletized Fuel Fabrication]… New capacity would probably be added at an existing site. A recent American Nuclear Society (ANS) paper by Rothwell [Rothwell 2010] discusses the scaling issue.”

First, we estimate the annual average labor bill for NF fabrication. This is done by examining the number of employees working at light water reactor (LWR) NF fabrication facilities. Staff sizes are estimated from publicly available data from LWR fuel fabrication plants. Of the 20 plants operating in 2006, employee data could only be found for half of them, as reported in Rothwell (2010, Table 2).

Two of these 10 plants (in Belgium and in Lynchburg, Virginia) were closed after 2006. Furthermore, the source of employee data for the Japanese plants (i.e., half of the remaining eight plants) have not been published since 2013 (JNES, 2013).

Table A1.1 presents the changes to data in Rothwell (2010, Table 2) in LWR NF fabrication facilities. In each case, the capital-to-labor ratio increased from 2006 to 2021. (Note: GE-Hitachi employment grew 30 percent in 2022 to about 1,000 employees in anticipation of building fuel fabrication capacity for the GE-Hitachi SMR, the BWRX-300, and capacity to fabricate High-Assay Low Enriched Uranium (HALEU), fuel for the Natrium advanced reactor, SC&A, 2023.)

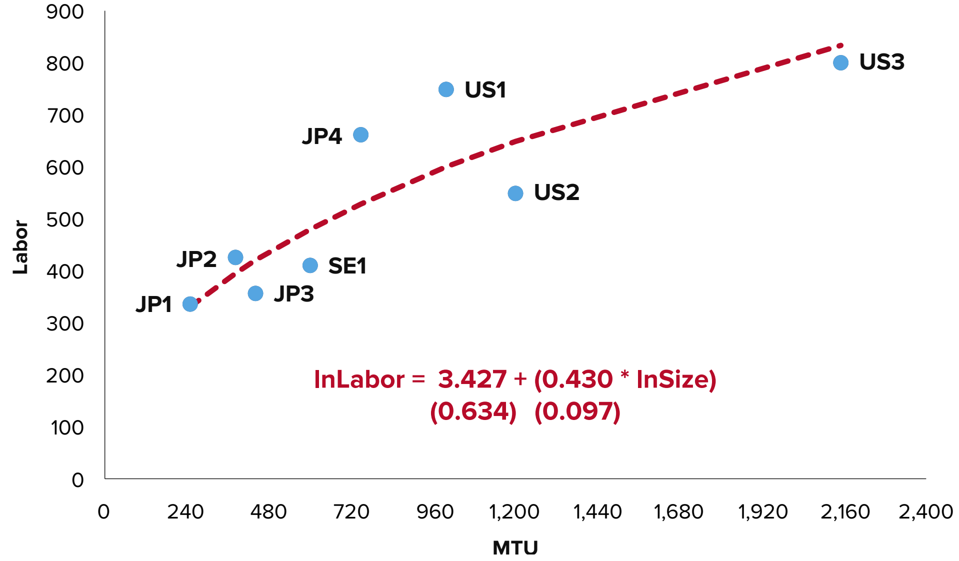
One issue in building regional NF fabrication facilities is whether plants can be built at a competitive scale (i.e., whether small plants can produce fuel at competitive costs (on scale economies; see Rothwell, 1986). To assess whether there are scale economies in fuel fabrication labor, an Ordinary Least Squares analysis was performed with the data from Rothwell (2010, Table 2), updated with information from Table A1.1, and presented in Figure A1.1.

Table A1.1. Labor at Fuel Fabrication Facilities in the United States, 2006 vs. 2021

		MTU/year	Labor	MTU/year	Labor	
Owner	**Location**	**2006**	**2006**	**2021**	**2021**	**Source**
GE-Hitachi	Wilmington (US1)	1,200	900	1,000	750	Growjo.com (2023)
Framatome	Richland (US2)	700	625	1,200	550	Framatome (2019)
Westinghouse	Columbia (US3)	1,150	1,059	2,154	800	Westinghouse (2023)

[1] This text borrows words liberally from Rothwell (2010); all dollar values and some quantities have been updated.

Figure A1.1. Labor Requirements at Nuclear Fuel Fabrication Facilities, 240–2,400 MTU



Sources: Table A1.1 and Rothwell (2010, Table 3).

The proposed model is well estimated. The constant (3.427 in Equation A1.1) is significantly different from zero and the "elasticity" coefficient (0.430) is significantly different from one in the log-on-log function. Scale economies in labor should not be rejected. As portrayed with the dashed line in Figure A1.1, Equation A1.1 is a reasonable equation to estimate labor requirements at LEU fuel fabrication facilities, where SIZE is the size of the facility in MTU.

Equation A1.1	ln Labor =	3.43	*	(ln SIZE ^	0.43)	
			(0.63)			(0.10)
Equation A1.2	Labor =	332	+	(SIZE *	0.24)	
			(70)			(0.07)

Equation A1.1 is used to estimate the number of employees and the labor cost at a typical PWR fuel fabrication facility (1) the fully burdened average 2022 annual salary is $131,000 from Nunn (2022), (2) the plant capacity is between 120 and 1,440 MTU/year, and (3) the capacity factor is 70 percent, given the downtime between producing fuel rods for different PWRs (see annual labor bills in Table A1.2).

Second, to estimate NF hardware costs, assume that PWR hardware costs are proportional to PWR hardware weight. Rothwell (2010) estimated a hardware cost for PWRs at $22/kgU in 2008 dollars. Changes in the price of zirconium (see USGS, 2021) from which fuel rods are made (e.g., Zircalloy) are more representative of changes in hardware costs than Producer Price Indexes. Although other NF costs have decreased due to technology development, zirconium has increased in price by 60 percent between 2008 and 2019 (the last year of USGS data). Therefore, the price of PWR hardware is assumed to be **$35/kgU** in 2021 dollars.

Third, other variable costs (those that vary with annual output and plant size) include general and administrative expenses, materials and supplies, property taxes and insurance, and equipment replacement. Following Judkins and Olsen (1979), these costs include:

(1.1) general and administrative expenses, equal to **$15/kgU**, when updated to 2021 dollars, (1.2) direct and indirect materials and supplies, equal to **$10/kgU**, updated to 2021 dollars, (2.1) property taxes and property insurance, equal to 3 percent of the TCIC per year, and

(2.2) equipment replacement charge, equal to 3 percent of the TCIC per year (up from 1 percent).

Because taxes, insurance, and equipment replacement are proportions of the TCIC, these are added to the capital cost per kilogram of uranium or heavy metal.

Fourth, following from Idaho National Laboratory (2017, D1-25):

> No information was available on the costs of constructing or operating new LEU fabrication plants. Such historical information would be proprietary in a highly competitive industry. It is likely that if new U.S. production capacity is needed, it will be added by reopening existing lines, constructing additional process lines, or going to additional shift operations at existing facilities. An educated guess is that a new fabrication line of 200 to 300 MTHM/yr capacity would cost over $100 million (2004$) in an existing building.

Based on Rothwell (2010, Table 3), TCIC (including a $100M licensing fee, up from $67M in 2008 USD in Rothwell, 2010) plus. Furthermore, capital-related charges including:

(1) a return on TCIC, assumed to be a pre-tax rate of 10% real (less than the 15 percent assumed in Judkins and Olsen, 1979, p. 17), and a 30-year debt (Judkins and Olsen assume 20 years); and

(2) an annual contribution to the decommissioning of the plant, assumed to be one-third of TCIC, with a return on decommissioning funds of ~0 percent real, i.e., the cost of decommissioning is assumed to be escalating at a rate similar to the appropriate discount rate.

The cost estimations using G4ECONS-FCF (GIF-EMWG, 2009) are in Table A1.2. These results can be summarized in the following two equations for (1) a competitive incumbent in the international NF fabrication market and (2) a cooperative regional entrant:

Equation A1.3	$AC_{fab\text{-}incumbent} = \$245 + (20{,}800 / SIZE)$
Equation A1.4	$AC_{fab\text{-}entrant} = \$262 + (48{,}000 / SIZE)$

For example,

- if SIZE = 1,000 MTU, then $AC_{fab\text{-}incumbent}$ = $266 and $AC_{fab\text{-}entrant}$ = $310, or
- if SIZE = 480 MTU, then $AC_{fab\text{-}incumbent}$ = $288 and $AC_{fab\text{-}entrant}$ = $362, or
- if SIZE = 120 MTU, then $AC_{fab\text{-}incumbent}$ = $418 and $AC_{fab\text{-}entrant}$ = $662.

Also, if $300/kg is the international competitive market price, profits above the competitive cost of capital are available for producers with average costs less than $300/kg. Average cost can be less than $300/kg due to scale economies from (1) declining average labor requirements and (2) declining average fixed costs. Of course, these are approximations that must be verified and validated for a specific case.

Table A1.2. Costs of a Generic PWR Fuel Fabrication Facility

Plant Capacity per year	MTU	120	240	480	720	960	1,000	1,440
Capacity Factor	%	70	70	70	70	70	70	70
Capacity x Capacity Factor	MTU/yr	84	168	336	504	672	700	1,008
Investment (TCIC)	$M	$140	$180	$260	$340	$420	$433	$580
Annual Fixed Expenses								
Cost of Capital (pre-tax)	%/year	10%	10%	10%	10%	10%	10%	10%
Plant Life	years	30	30	30	30	30	30	30
Capital Recovery Factor	%/year	10.61%	10.61%	10.61%	10.61%	10.61%	10.61%	10.61%
Annual Capital Charge	$M	$14.85	$19.1	$27.6	$36.1	$44.6	$46.0	$61.5
Decontamination and decommissioning (D&D) Cost	$M	$47	$60	$87	$113	$140	$144	$193
D&D Fund Rate of Return	%/year	0%	0%	0%	0%	0%	0%	0%
Time before D&D	years	30	30	30	30	30	30	30
Annual D&D Charge	$M	$1.53	$1.97	$2.85	$3.72	$4.60	$4.75	$6.35
Annual Variable Expenses								
PWR Hardware (H)	$M	$2.940	$5.88	$11.76	$17.64	$23.52	$24.50	$35.28
Labor (L, number of employees)	#	241	325	438	521	589	589	702
Annual Salary (Fully Burden)	k 2023 $	$131	$131	$131	$131	$131	$131	$131
Annual Labor Bill (at $131,000)	$M	$31.59	$42.55	$57.32	$68.24	$77.22	$77.22	$91.93
Other Variable Expenses								
Supplies and G&A	$M	$3.00	$6.00	$12.00	$18.00	$24.00	$25.00	$36.00
Property Taxes and Insurance	$M	$4.20	$5.40	$7.80	$10.20	$12.60	$13.00	$17.40
Equipment Replacement	$M	$4.20	$5.40	$7.80	$10.20	$12.60	$13.00	$17.40
Average (Levelized) Costs								
Capital Cost	$/kg	$177	$114	$82	$72	$66	$66	$61
Labor Cost	$/kg	$376	$253	$171	$135	$115	$110	$91
Other Variable Expenses	$/kg	$136	$100	$82	$76	$73	$73	$70
PWR Hardware	$/kg	$35	$35	$35	$35	$35	$35	$35
Decommissioning	$/kg	$18	$12	$8	$7	$7	$7	$6
Average PWR Cost (LAC)	$/kg	$742	$514	$378	$326	$296	$291	$264
Incumbent PWR Cost (LAC)	$/kg	$494	$379	$302	$269	$250	$246	$228
Plant Capacity Per Year	MTU	120	240	480	720	960	1,000	1,440

Source: Authors' calculations using G4ECONS-FCF (GIF-EMWG, 2009) software.

Appendix 2. The Cost of Interim Spent Nuclear Fuel Dry Storage[2]

On-Site Dry Storage

According to IAEA (2020), the SNF storage capacity of fuel pools at an APR1400 is equivalent to 20 years of full-power operation with 1,740 m^3 of capacity (or approximately 12m x 12m x 12m). The APR1400 is based on the Republic of Korea experience with the OPR1000, which is based on the Combustion Engineering (CE) System-80+, which was modeled after the CE System-80 design constructed as three units at Palo Verde (Arizona, USA). Each System-80 unit of 3,937 MWth has 241 fuel assemblies with 236 fuel rods per assembly. According to U.S NRC (2017) in their negotiations with Arizona Public Utilities for license extension, the fuel pools are limited to “no more than 1,329 fuel assemblies,” i.e., if one-third of the fuel is replaced every 18 months, Palo Verde’s fuel pools are limited to 16 refuelings or about 25 years of full-power operation. The VVER1200 has a standard fuel pool of 1,800 m^3 (see Titan-2 Holding, 2016, where Titan 2 is a primary contractor on Akkuyu and El Dabaa). The remainder of Section A2.1 provides a cost estimate for building, populating, and operating an on-site ISFSI.

Rothwell (2021) shows that (after updating from 2017 to 2021 dollars):

Equation A2.1	AC_{on} = (**$**30M + $160,000 x $SIZE_{on}$ + $7.44M x 33.333) / $SIZE_{on}$

where

- AC_{on} is the average cost of on-site dry storage if the NPP is not operating or not being actively decommissioned;
- $30M (see estimate of $23.7M in Entergy Corp., 2014) represents fixed one-time costs that are independent of the number of casks on the site storing up to 2,000 MTHM;
- $160,000 is the incremental escalated (variable) capital cost for an additional MTHM from Entergy (2014);
- $SIZE_{on}$ is the size of the facility in MTHM;
- $7.44M/year is the projected annual operating costs for staffing, security, insurance, various fees (see PNNL, 2011, p. 4-24); and
- 33.333 is equal to a perpetuity of annual expenditures using a 3% discount rate.

We assume that Equation (A2.1) is an appropriate benchmark for estimating average on-site dry storage costs. Furthermore,

Equation A2.2	AC_{on} = (**$**30M + $160,000 x $SIZE_{on}$ + $248M) / $SIZE_{on}$
Equation A2.3	AC_{on} = ($160,000 x $SIZE_{on}$ + $278M) / $SIZE_{on}$
Equation A2.4	AC_{on} **0** = $160,000 + ($278M / $SIZE_{on}$) per MTHM
Equation A2.5*	AC_{on} **0** = $160 + ($278,000 / $SIZE_{on}$) per kgHM

* Equation A2.5 was used to produce Figure 2 in the text. Of course, these equations are approximations that must be verified and validated for a specific case.

[2] This text borrows words liberally from Rothwell (2021); all dollar values and some quantities have been updated.

Off-Site Dry Storage

The first CISF to submit a construction and operating license application to the US NRC was Private Fuel Services LLC in Utah. PFS (1997) presents a clear picture of what is involved in building and operating a CISF for 40 years. (The project was cancelled over local opposition.)

Building on the analysis of on-site dry storage, the remainder of this Appendix models off-site dry storage updating Rothwell (2021), based in part on PFS (1997), where the C2C building would have a maximum handling capacity of 4,000 MTHM (*maxHM* = 4,000) per year with a total facility storage capacity of 40,000 MTHM (*maxMT* = 40,000). This implies that the facility will be engaged in MTHM handling for 10 years to load the facility and 10 years to unload the facility with a facility life of 20 to 40 years. Here, it is assumed that the *maxHM* is one-tenth the total facility capacity (*maxMT*) to 40,000 MTHM. For MTHM capacities above 40,000 MTHM the *maxHM* is limited to 5,000 MTHM per year. This implies that 100,000 MTHM would require 20 years to load and 20 years to unload. (Although the costs of unloading the facility are included in the calculations here, the SNF cannot be unloaded until a repository is available, thus the present value could be different than calculated here, which is why a perpetuity is assumed.) The cost of the facility is approximately **$90M** (fixed set-up costs) plus **$20,000****maxHM*** (updated to 2021 dollars): ($90M + $20,000 x 4,000 = $170M).

Also, costs of the storage pad and overpack casks depend on *maxMT*, the maximum capacity of the facility. Assume the cost per MTHM of the storage pad is equal to the storage pad cost at an on-site facility, **$1,560/MTHM**, updated from $1,300/MTHM in Rothwell (2021). Regarding the cost of cask overpacks, updating the cost of overpack casks is about **$5,640/MTHM**. Furthermore, governments and industry must account for indirect costs, owners' costs (primarily licensing and other fees and studies), and contingency (assuming Interest During Construction has been included in the construction cost estimates). If these "indirect and other costs" increase the direct construction costs by the same percentage as in ORNL (2011), that is, **1.92**, then the total capital investment cost of off-site dry storage ($TCIC_{off}$) could be

Equation A2.6	$TCIC_{off} \approx [\$90M + (\$20{,}000 \times maxHM) + (\$1{,}560 + \$5{,}640) \times maxMT] \times 1.92$

For example, if *maxHM* is 4,000 MTHM and *maxMT* is 40,000 MTHM, then $TCIC_{off}$ is approximately $880M, or $22,000/MTHM. This construction capital cost estimate is comparable, when updated to 2021 USD, with those in Bunn et al. (2001) and Macfarlane (2001).

PFS (1997, pp. 1–7) discusses decommissioning costs: "The cost for decommissioning each storage cask is estimated at $17,000." Updating these values to 2021 USD implies that the D&D of casks would be about $290/MTHM (each overpack cask holds 10 MTHM). Furthermore, following Macfarlane (2001, p. 1382), D&D costs are about 15% of direct costs, i.e., $90M x 1.15% = $104M (= $104M x 1.92 ≈ **$200M**) discounted at a rate of 0% under the assumption that D&D costs escalate at the same rate as the rate of return on D&D funds). Adding these D&D costs to Equation (A2.6) and multiplying through by the "indirect and other costs" rate of 1.92 yields

Equation A2.7	$TCIC_{off} \approx \$200M + (\$42{,}000 \times maxHM) + (\$14{,}400 \times maxMT)$

where $20,000 x 1.92 ≈ $42,000 and ($1,560 + $5,640 + $290) x 1.92 ≈ $14,400.

Regarding operation and maintenance (O&M) costs associated with C2C handling, they are calculated in Rothwell (2021). Updating these costs to 2021 USD, O&M costs would be about $17M for administration and security personnel, and an additional $17,600/MTHM for personnel during years of loading and unloading fuel. (See organization chart for a private fuel storage facility (PFSF) in NEA, 2018, Annex E, where contractors do the loading and unloading.) The number of years of loading and unloading is determined by the size of the C2C building.

Equation A2.8	$TC_{off} \approx \$200M + (\$42{,}000 \times maxHM) + (\$14{,}400) \times maxMT + (\$17M \times 33.333) + (\$17{,}600 \times maxMT \times 2)$

where the last "x 2" accounts for the personnel cost of moving SNF both (1) *in* and (2) *out* of the facility. This simplifies to

Equation A2.9	$TC_{off} \approx \$767M + (\$42{,}000 \times maxHM) + (\$50{,}000 \times maxMT)$

Dividing through by the maximum size of the facility, yields average off-site dry storage costs:

Equation A2.10	$AC_{off} \approx \$767M/ maxMT + (\$42{,}000 \times maxHM / \text{maxMT}) + \$50{,}000$

If we set *maxHM* equal to *maxMT* /10, then

Equation A2.11	$AC_{off} \approx \$767M/ maxMT + \$4{,}200 + \$50{,}000$
Equation A2.12	$AC_{off} \approx \$54{,}200 + \$767M/ maxMT$ per MTHM
Equation A2.13*	$AC_{off} \approx \$54.2 + \$767{,}000 / maxMT$ per kgHM

* Equation A2.13 was used to produce Figure 3 in the text. Of course, these equations are approximations that must be verified and validated for a specific case.

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Models for Regional Cooperation on Nuclear Security

Kelsey Davenport

The Middle East is experiencing a resurgence of interest in nuclear power. The United Arab Emirates (UAE) embarked on an ambitious nuclear energy program in 2007 and now has four operating reactors with plans to build four additional reactors in the coming years.[1] Turkey's first large-scale nuclear reactor began operating in 2023 at Akkuyu and three more units are planned for the site. In September 2023, Turkey announced it was negotiating a Chinese bid to build another multi-reactor site.[2] Construction on three reactors in Egypt is underway at El Dabaa and a fourth unit was licensed for construction in August 2023.[3] The first reactor is estimated to begin producing electricity in 2028. Iran operates one power reactor at Bushehr, with three additional units under construction and plans for a second multi-reactor facility at Darkhovin.[4] Saudi Arabia is bidding out two large reactors and investing in a South Korean company working on small modular reactors (SMRs). Jordan has also expressed interest in SMRs and signed cooperation agreements with several companies developing SMR designs. Jordan aims to begin operating units for power generation and desalination by 2031.[5] There are also 14 research reactors in nine states in the Middle East.[6]

Beyond these programs, the Arab League created the Arab Atomic Energy Agency (AAEA) in 1989 to promote the development of nuclear technologies and help coordinate nuclear-related activities. Fourteen states have joined the AAEA, which developed a 10-year plan from 2021–2030 to advance its objectives.[7] This plan, alongside a feasibility study commissioned by the Gulf Cooperation Council to examine options for regional nuclear power among its members, suggests additional states in the region will move forward with nuclear programs in the coming years.

Although civil nuclear programs offer significant benefits, more facilities with nuclear materials also create new security risks. Whereas nuclear safety and safeguards have long-established and broadly accepted governance practices, nuclear security is applied less consistently and best practices are still under development in response to new and evolving threats, such as cyberattacks. Despite consensus that an act of nuclear terrorism would have global consequences, some states still perceive certain nuclear security requirements and recommendations as overly burdensome and designed to hinder the establishment of civil nuclear programs.[8]

Closing the gaps in the nuclear security architecture and strengthening implementation offer an opportunity for collaborative, regional efforts, particularly in the Middle East where interest in nuclear energy is expanding and states are facing pressures to build the necessary capacities for operating and sustaining facilities. Not only does strengthening nuclear security enhance national security, but when pursued region-wide, it provides greater assurance that neighboring states are protected against the theft of materials and sabotage of nuclear facilities. This is a particularly critical benefit in an area like the Persian Gulf, where the geographic proximity of reactors to neighboring states and shared, highly trafficked transit routes compound the regional consequences of any act of nuclear terrorism.

This paper outlines a range of potential collaborative regional nuclear security projects for the Middle East. The recommendations are not intended to be a prescriptive approach to comprehensively addressing gaps in the region's nuclear security architecture, but rather designed to provide a menu of options that states in the region could tailor and pursue based on shared national and regional interests and an evolving threat environment.

Some of the recommended activities are more applicable to states with nuclear facilities and materials, whereas other recommendations would benefit from broader regional involvement, including states without plans for developing nuclear programs. Although some recommended activities are offered by organizations such as the International Atomic Energy Agency (IAEA), a benefit remains in developing regional capacities and forums for expert collaboration in the Middle East. Regional approaches and collaboration can be tailored to address unique threat vectors and create more consistent, sustainable programs and engagement. International organizations, such as the IAEA, also face budget constraints that inhibit the expansion of nuclear security services.

Furthermore, nuclear security cooperation not only provides greater assurance that states are protecting facilities and materials, but it also can pave the way for further technical collaboration and help mitigate proliferation concerns.

What Is Nuclear Security?

The IAEA defines nuclear security as work that "aims to prevent, or detect and respond, to intentional malicious acts involving radioactive substances or directed against facilities or activities where such substances are used."[9]

When compared to safety or safeguards, nuclear security is not as well-established and practices vary significantly by state. In a presentation for the 2020 International Congress on Advances in Nuclear Power, a U.S. National Laboratory report discussed the relationship between safeguards, security, and safety by describing nuclear security as the "least institutionalized, least mandatory, and least consistent" of the three governance practices.[10]

Inconsistency in nuclear security implementation is due to several factors. First, nuclear security emerged after safety and safeguards as an area of concern that required the negotiation of legally binding international standards and concerted national attention. Comparatively, nuclear safeguards are required under the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) and a prerequisite for the majority of state-to-state nuclear cooperation. The Nuclear Safety Convention entered into force in 1996, but even before that a widespread recognition of the importance of nuclear safety existed, including private sector buy-in for institutionalizing best practices. The 2011 Fukushima accident in Japan reinforced consensus regarding the necessity of strong safety practices.

Although general agreement exists regarding the importance of preventing nuclear terrorism, it was not until May 2016 that the first legally binding requirements for the physical protection of nuclear materials entered into force under the 2005 Amended Convention on the Physical Protection of Nuclear Materials (CPPNM). (The original CPPNM did set standards for securing nuclear materials in international transit.) Even the Amended CPPNM, however, does not address nuclear security comprehensively.

Nuclear security was initially less of a priority for the IAEA as well. Nuclear security was not upgraded from department to division status at the agency until 2014, putting it on par with safeguards and technical cooperation. Even now, the IAEA's Nuclear Security Fund still relies on voluntary contributions and much of the IAEA's role is coordination of state-based nuclear security activities.

Second, nuclear security is principally treated as a state responsibility, even though the consequences of an act of nuclear terrorism would have regional, if not global, consequences. Unlike safeguards, which are required by the NPT and implemented by the IAEA, no legally mandated oversight body exists to verify adherence to nuclear security commitments, even the binding commitments made in treaties, such as the Amended CCPNM. As a result, a state's nuclear security reflects the emphasis and resources the government is willing to devote to the issue.

The lack of an implementing body, however, does create an opportunity for state-led collaboration. States have little incentive to collaborate on safeguards, given the NPT requires a safeguards agreement with the IAEA and the agency is mandated to assess compliance. Developing additional safeguards systems would create additional burdens and likely duplicate existing IAEA efforts. On nuclear security, the IAEA can evaluate a state's nuclear security practices against agency guidelines and make recommendations for improvements, but the services are voluntary and are not comprehensive. For example, states can request IAEA missions to review physical protection at a nuclear facility, nuclear security culture, and regulatory frameworks. The agency teams provide feedback, but it is up to the state to implement specific recommendations. Furthermore, the results are not shared, unless the state decides to make public the findings. The lack of required oversight and variation in state emphasis on nuclear security can serve as an incentive and opportunity for regions to devise practices and procedures to provide assurance of strong nuclear security practices.

Third, nuclear security threats vary by country and region. The threats also evolve over time, requiring a continuous review of practices. This creates challenges for sustaining effective nuclear security practices.

Thus, although nuclear security is increasingly perceived as necessary and an indicator of a responsible nuclear actor, there are significant gaps in implementation and emphasis. These gaps, alongside the necessity of continuously updating practices to address new and evolving threats, suggest that well-designed, effective nuclear security collaboration would benefit all states in the region, irrespective of the status of their nuclear programs.

Nuclear Security Threats

Attacks on nuclear facilities are driven by an array of motivations. An analysis of the Nuclear Facilities Attack Database, a project of the National Consortium for the Study of Terrorism and Responses to Terrorism, by Gary Akerman and James Halverson devised four categories for classifying incidents:

1. Attacks aimed at disabling a nuclear facility.
2. Attacks aimed at the theft of nuclear materials.
3. Attacks aimed at sabotaging a nuclear facility (with the intention of radioactive release).
4. Attacks designed to protest the intention or location of a nuclear facility.[11]

Where the first three types of attacks likely have malicious intent, the motivation of protest actions is not necessarily to release radiation or cause harm (although that can be an unintended consequence). For instance, several examples show where activists broke into U.S. facilities to protest nuclear weapons or draw attention to their concerns about nuclear power but did not attempt to damage facilities.[12] Strong nuclear security will protect against protest actions, but the recommendations in this paper are less directly focused on countering this type of attack.

Although the concept of nuclear security and prevention of nuclear terrorism is relatively recent, attacks against facilities date back to the early years of the nuclear age. For example, in 1975 a paramilitary separatist group in France detonated two explosive devices at the Brennilis Nuclear Power Plant. Basque separatists repeatedly attacked the Lemóniz Nuclear Power Plant in Spain while it was under construction in the 1970s and in 1982 an armed faction of the African National Congress attacked the Koeberg Nuclear Power Station in South Africa. No region has been immune from security risks. Although attacks span all regions, there are discernable trends in the types of attacks in particular regions.

For instance, after the fall of the Soviet Union, nuclear facilities in Russia and the former Soviet states were more prone to attacks focused on the theft of nuclear materials.[13] European facilities from the mid-2000s through 2010s experienced a wave of planned attacks focused on malicious sabotage.[14] A survey of attacks (and thwarted attacks) on nuclear sites in the Middle East in the past two decades suggests that attacks typically aimed to maliciously disable or sabotage nuclear facilities. This risk is intensified during periods of inter- or intra-state tensions or violence.

Furthermore, analysis of nuclear security incidents also demonstrates commonalities in attack methodology. Some trends are even discernable across regions. More generally, the Nuclear Facility Attack Database, which includes 80 cases from 1961 to 2014, found that a quarter of the cases included insider involvement. That number jumped to 44 percent for the incidents deemed higher threat.[15]

Specifically in the Middle East, many recent attacks on nuclear facilities have relied on drones or missiles. For example, in 2017 during the civil war in Yemen, the Houthis claimed to have fired a missile at the Barakah Nuclear Power Plant, although the UAE denied the attack;[16] Israel sabotaged an Iranian uranium enrichment facility using explosives during a period of heightened tensions over Iran's nuclear program in 2021; and Hamas claimed to have fired rockets at Dimona, Israel's nuclear complex, following its October 7, 2023 terrorist attack and Israel's subsequent invasion of the Gaza Strip.[17] Although it is likely that all states take drone and missile attacks into account when developing the design basis threat assessments that are instrumental in guiding nuclear security practices, the prevalence of this type of attack underscores a benefit of regional collaboration: states can share best practices and lessons learned for protecting against the type of attack more common in the region.

The Benefits of Nuclear Security Cooperation

Nuclear security is primarily a state responsibility, but the failure to adequately protect nuclear facilities and materials can have devastating regional and global consequences. The consequences of a lapse highlight that states have an interest in encouraging effective nuclear security practices in neighboring states and that a direct national benefit exists in supporting nuclear security at the regional level. National security interests, however, are not the only benefit of supporting nuclear security among neighboring states. Additional benefits include de-escalating concerns about proliferation by providing greater transparency about a state's nuclear intentions and creating opportunities for further regional and international technical nuclear collaboration.

Strong Regional Nuclear Security Is a National Interest

The geographic proximity of nuclear facilities and reactors in the Middle East underscores the regional impact of a lapse in nuclear security. For instance, if an attack on a nuclear reactor or spent fuel pond resulted in a release of radiation, then an adverse impact on health, the environment, and economic activity would happen across the region.[18] The costs of mitigating a nuclear security incident would be compounded by the loss of trade. For example, both the UAE and Iran have built reactors on or near the Persian Gulf Coast. A nuclear incident that disperses radiation in that area would interfere with shipping by closing or limiting transit through the highly trafficked Strait of Hormuz. These effects would extend far beyond the region, given the volume of exports, particularly oil, that transit this waterway.

Furthermore, states will need to coordinate response and mitigation activities to minimize the negative effects of a large-scale radiation release caused by a nuclear security breach. Regional collaboration on nuclear security can build ties between expert and technical communities and provide opportunities for collaborative response training and exercises, ideally facilitating a more effective and timely response in the event of an incident.

Nuclear Security Can Deescalate Regional Nuclear Tensions

The Middle East is experiencing an expansion of interest in nuclear energy, but that interest also drives regional and global concern about the proliferation of nuclear weapons. Cooperative regional security activities are not sufficient to prevent proliferation, but collaboration can provide greater assurances about a state's intentions by enhancing transparency about its nuclear program and providing insights into its trajectory.

Transparency is particularly crucial in the Middle East for building assurances that nuclear programs are peaceful, given the history of proliferation concerns and contemporary threats to develop nuclear weapons. Iran, Iraq, and Libya each pursued illicit nuclear weapons programs in the past, in part by relying on civil nuclear activities as cover for covert actions. Although no evidence exists that any country in the region is currently pursuing nuclear weapons, Iran is enriching uranium to near-weapons-grade levels and no longer implementing the more intrusive safeguards arrangement known as the Additional Protocol. If Tehran were to make the political decision to develop nuclear weapons, it could move quickly to build a small arsenal.

Iran is not the only contemporary proliferation risk. As recently as 2023, Saudi Arabia threatened to build nuclear weapons if Iran does so.[19] In addition to planning two larger nuclear energy reactors, Saudi Arabia is planning to mine uranium and develop enrichment capabilities, which could be used to produce fissile material for weapons.[20] Turkish President Tayyip Erdogan suggested in 2019 that it was unacceptable for countries with nuclear weapons to tell Turkey it cannot develop its own nuclear warheads.[21]

Nuclear security engagement between these states could provide greater insight into the trajectory of their respective nuclear programs and help quell concerns about weaponization. Building ties between experts also creates channels of communication that could be useful to clarify state intentions or deescalate weaponization-related concerns, particularly during periods of escalatory political rhetoric. Collaboration between U.S. and Russian nuclear experts, for instance, played a critical role in devising technical solutions during arms control negotiations after the Cold War.[22] Scientists can also engage outside of the political spotlight, where rhetoric and posturing has less of an effect.

Collaboration on nuclear security can also be a pathway to cooperative safeguards activities. For instance, the Argentinian-Brazil Accounting Control Community (ABACC) includes a system of bilateral inspections and a common nuclear material accountancy framework to verify that the fissile materials in each state are not diverted for weapons purposes. ABACC demonstrates how former adversaries that suspected each other of nuclear weapons ambitions can build relationships by first engaging in technical cooperation at the epistemic level. These collaborative activities and ties between epistemic communities in the two countries were instrumental in laying the groundwork for a bilateral safeguards inspection system when there was political space to deescalate tensions over proliferation.[23]

Nuclear Security Enhances Prospects for Nuclear Cooperation and Expansion

Similar to the role played in supporting nonproliferation efforts, collaborative nuclear security activities enhance the prospects for nuclear technical cooperation, among states in and out of the region. For states looking to expand nuclear research and grow nuclear programs, this is a powerful incentive for collaboration.

In addition to building expertise and ties between epistemic communities that can create opportunities for collaborative nuclear research, a strong record of nuclear security is another indicator that a state is a responsible nuclear actor. This may make a state more attractive for transfers of sensitive technology, particularly from Western states that have been deterred from exporting nuclear technology over regional and geopolitical stability in the past.[24] Establishing confidence in the security of a country's nuclear program could help assuage some of those concerns and open up new opportunities for civil nuclear cooperation.

Characteristics of Effective Multilateral Nuclear Security Collaboration[25]

Several forums exist where states meet to discuss and advance nuclear security. Two of the most notable are the IAEA-hosted International Conference on Nuclear Security (ICONS) meetings, which take place every four years, and the review conferences for the Amended CPPNM, which can take place every five years. Although not the sole focus, nuclear security is discussed in broader nuclear-related forums, such as the NPT Review Conferences, the IAEA General Conference, and the UN First Committee. These bodies may make recommendations for advancing nuclear security, but they are often non-binding and subject to lowest-common-denominator thinking in order to garner consensus support.

Beyond these more formal intergovernmental settings, multilateral voluntary initiatives such as the Global Partnership Against the Spread of Weapons and Materials of Mass Destruction (GP) focus on advancing certain aspects of nuclear security through activities such as resource sharing, developing best practices, and conducting multilateral exercises.

Arguably, the most significant development bringing global attention to the risk posed by nuclear terrorism and strengthening nuclear security occurred during the six-year Nuclear Security Summit process initiated in 2010 by then U.S. President Barack Obama. The Nuclear Security Summits, a head-of-state level effort to strengthen nuclear security, included voluntary national and multilateral commitments by the 53 participating states. Each summit offered an opportunity to review progress on those commitments and pledge further actions. As a result of these activities, nine states eliminated all remaining stockpiles of highly enriched uranium from their territories and 24 states invited IAEA expert missions to review physical protection measures at nuclear facilities. The summits also spurred technological progress on converting research reactors to run on low enriched uranium (LEU) and the development of new fuels for those reactors.[26] Several of the multilateral commitments, known as gift baskets, are now IAEA Information Circulars (INFCIRCs). Any IAEA member state can sign on to the INFCIRCs, but these mechanisms have failed to garner widespread support from non-summit participants.[27]

Several factors contributed to the success of the Nuclear Security Summits. More specifically, certain characteristics within the commitment-making process appeared to contribute to more effective implementation. Four lessons about how to design productive collaborative regional approaches to advance nuclear security emerged from this process and should be taken into consideration when developing such approaches in the Middle East.

First, states are more likely to implement commitments it will benefit from. If a state perceives the outcome of an activity as advancing its own interest, it is more likely to follow through on implementation. The benefits do not necessarily need to be directly related to a state's nuclear security practices; the perception that an activity has an economic or national security-related value will also drive implementation. This finding appears obvious, but commitment-making can be a performative action, particularly if states feel pressure to engage.

Accountability is a second factor. If a state pledges to report progress on implementation or participates in a forum where national and/or multilateral reporting is expected, there will be an incentive for it to follow through. The specific type of accountability appeared less important than strength of the state's buy-in to the agreed-upon process. For example, formal reporting requirements in certain multilateral commitments did not appear to push states to take significantly more action than ad hoc reporting. Multilateralizing commitments also has a positive impact on accountability. The Nuclear Security Summit experience suggests that when states make pledges to take action in connection with other states or international bodies such as the IAEA, they are more likely to follow through than if the commitment were unilateral.

The third factor is high-level political support for the process. President Obama's focus on head-of-state participation at the Nuclear Security Summits demonstrated how political will and peer pressure can be critical to pushing states to make commitments beyond the status quo, and then to follow through on implementing those commitments. By endorsing nuclear security-related activities and prioritizing those efforts, the Middle East's leaders can provide impetus for the commitment-making process.

A fourth factor relates to the necessity of continuous review and improvement of nuclear security practices. Certain activities, such as inviting peer reviews, updating policies on insider threat mitigation, and conducting nuclear security threat assessments should be repeated or reviewed regularly to respond to the changing threat environment and ensure that practices and regulations are up to date. Commitments that build in routinized practice and review provide a greater degree of effectiveness over time and are more likely to spur states to update practices and respond to evolving threats. This is particularly relevant in the Middle East where there is a history of attacks on nuclear facilities and inter-state tensions increase the risk of conflict.

Not every factor needs to be incorporated for nuclear security collaboration to be effective. But taking these lessons into account when designing the structures and processes for collaborative work could improve success and sustainability in a regional context.

Opportunities for Nuclear Security Collaboration in the Middle East[28]

States should determine which approaches best strengthen their nuclear security and meet national and regional needs. As mentioned, activities that have political buy-in and directly benefit national interests have a greater chance of being effectively fulfilled. Although states are the primary actors responsible for nuclear security, cooperative endeavors should also engage existing multilateral groups when appropriate and build on existing collaborative relationships, particularly those that are regionally based. The following options are designed to spur thinking about how regional cooperation can be pursued in the Middle East.

Centers of Excellence

A critical aspect of nuclear security is creating and maintaining a strong nuclear security culture. The IAEA defines nuclear security culture as the "characteristics, attitudes and behavior of individuals, organizations, and institutions which serves as a means to support and enhance nuclear security."[29] Most officials and experts interviewed for this paper raised concerns related to nuclear security culture, particularly related to developing and implementing standards for training and addressing insider threats. As states in the region establish and expand nuclear programs and demands for personnel rise, the pressure to develop and maintain appropriately strong standards for security culture is likely to increase.

One option to help states develop and maintain a robust nuclear security culture would be to establish a regional nuclear security center of excellence or to encourage the development of state-based centers of excellence and create a regional network for collaboration. Centers of excellence have different missions, but they generally provide opportunities for nuclear security-related training and the development of a strong nuclear security culture. This approach could strengthen capacities in the region and create a space for reviewing and testing best practices.

Although centers of excellence pre-date the Nuclear Security Summit process and focus on a range of issues, the concept experienced a renaissance during the summits. More than 15 states—including China, Italy, the Netherlands, and South Korea—committed to developing new centers or expanding existing facilities, often with a focus on strengthening nuclear security culture.[30] Several centers, including Japan's Integrated Support Center for Nuclear Nonproliferation and Nuclear Security and Pakistan's Centre of Excellence for Nuclear Security, were built with the deliberate intention of acting as regional training hubs.[31]

Not all centers of excellence are equally effective and some pledges to develop centers during the Nuclear Security Summit process appear to have been performative. Effective centers appear to share certain characteristics, such as a defined mission, continued political support, and engagement with expert entities, such as the IAEA or the World Institute for Nuclear Security (WINS). Setting up a regional center or a network of centers in the Middle East could draw on the best practices discerned over the past decade and new resources that have emerged to support such centers.

For instance, the flurry of interest surrounding centers of excellence contributed to the IAEA's decision to create the International Network for Nuclear Security Training and Support Centres (NNSC) in 2012. The network provides support to members in areas such as training programs, technical support for nuclear security equipment, and scientific support for further research and analysis in advancing nuclear security efforts. A Middle East-based center could use these resources to maximize effectiveness and capitalize on existing best practices. Engagement with an entity like the IAEA's NNSC network also creates an element of accountability. Annual NNSC meetings provide an opportunity for reviewing and refining practices and can facilitate collaboration with centers.

A center of excellence in the Middle East could benefit nuclear security in a number of ways. Three areas stand out as ripe for a center to address, based on interviews with experts and officials and analysis of the status of nuclear energy programs in the region:

- Developing and offering certified training programs
- Workshopping insider threat mitigation practices
- Guiding use of existing nuclear security-related technologies or developing new ones.

Certified Training Programs

Building certified training capacity would take advantage of the fact that this is a known interest of states that are establishing and expanding nuclear energy programs. For example, the UAE and Saudi Arabia identified capacity building as a promising area for bilateral cooperation in 2021. During that meeting, regulatory agencies in the two countries—the Federal Authority for Nuclear Regulation (FANR) in the UAE and the National Nuclear Regulatory Commission in Saudi Arabia—recommended holding capacity-building workshops.[32] These opportunities are also valuable for states with well-established programs and practices. In a November 2022 interview, Christer Viktorsoon, the head of FANR, explained that the UAE "has strong physical protection" requirements but emphasized the importance of the frequent testing and drills for the security of the Barakah Nuclear Power Plant. He said there could be "great benefit" to introducing cooperation between regulatory agencies in the region.[33]

Furthermore, the Gulf Cooperation Council identified the benefits of regional cooperation for workforce development in a study commissioned in the mid-2000s.[34] The AAEA also identified the development of human resources and the establishment of jointly supported nuclear regulations as key goals in its strategic plan through 2030. The Arab Network of Nuclear Regulators (ANNuR), an initiative founded in 2010 to support the development of regulatory and legislative frameworks among Arab League countries, has supported efforts to develop and share best practices on radiation monitoring. Although the intended function of this work was directed at safety-related practices, developing radiation monitoring and detection capabilities is also relevant to nuclear security.

These studies and limited exchanges on training and culture-related issues suggest cooperation on training is an area where states have already identified collaboration as nationally beneficial and would likely be willing to engage further. Creating a center of excellence that seeks to become a regional training hub could also amplify and support national and multilateral initiatives. A center of excellence-based approach would also allow states to specialize in certain areas. For instance, existing efforts by the UAE's Gulf Nuclear Energy Infrastructure Institute and the Arab League's AAEA to develop shared nuclear security culture standards among Arab League states could use the center for expanded regional engagement.

A regional center may also increase buy-in from states unwilling or unlikely to engage bilaterally or multilaterally due to political tensions. For instance, several groups created among Arab League member states, such as ANNuR and AAEA, are already engaged in multilateral efforts within the region, some of which are relevant to nuclear security. Working with these groups may be politically challenging for states outside of the Arab League, notably Iran and Turkey.[35] However, if these initiatives offer opportunities to collaborate in a more inclusive regional center, additional states could capitalize on the expertise, connections, and existing capacities these groups have developed. A regional center that draws selectively from multilateral initiatives, such as the IAEA and WINS, may use limited resources more efficiently than state-by-state engagement.

Relatedly, a center creates an established, collaborative space for conducting exercises and simulations that provide additional training opportunities. The center could serve as a hub for regional states to conduct exercises in areas such as incident response and mitigation drawing on playbooks established by the Global Initiative to Combat Nuclear Terrorism. These types of collaborations can bolster buy-in from regional states and assist with standardizing practices because the activities are beneficial irrespective of a state's nuclear status.

Insider Threat Mitigation

Insider threat mitigation is a second aspect of nuclear security culture development that could be a key focus for a center. As highlighted previously, nearly half of all attacks on facilities categorized as posing a higher threat in the Nuclear Facilities Attack Database involved insiders.[36] This finding is not surprising—personnel within a facility have intimate knowledge of how it is run and protected. Despite the relationship between insider threats and attacks, it is an area where most states with nuclear materials and facilities can improve. One Middle Eastern official said insider trustworthiness is particularly crucial in the region and must be developed early in the process of establishing a civil nuclear workforce because secular and religious factionalism increases the risk of sabotage.[37]

The Nuclear Threat Initiative's 2023 *Nuclear Security Index* highlighted insider threat mitigation in its recommendations for states with weapons-usable materials and nuclear facilities. Specifically, the *Index* found that the median score for insider threat prevention "hit a record low" since its first edition in 2014. It recommended that states "intensify efforts to establish and strengthen programs aimed at identifying and mitigating insider threats."[38] A center of excellence could focus on implementing recommended actions for insider threat mitigation as described in IAEA INFCIRC/908, which was based on outcomes from the Nuclear Security Summits and circulated to all IAEA member states in 2017. That document includes recommendations for training on protecting against insider threats, establishing trustworthiness programs, and developing evaluative protocols such as psychological and drug testing. A center could provide resources for developing, implementing, and reviewing national regulations and offer workshops and exercises for insider threat prevention as well.

Technology Development

A technology hub is the third possible area of focus for a regional center. Such a hub could train personnel on nuclear security technology and create space for collaboration on new technologies that address regionally specific threats. Opportunities to train on and deploy new technologies would be attractive, according to author interviews. States outside of the region or organizations like the GP could contribute to these services with technical expertise and financial support. China and the United States, for instance, cooperated on establishing a nuclear security center as part of the Nuclear Security Summit process. That center contains a technology training center and a force-on-force training facility, features that could be replicated at a center in the Gulf.

Another model could be to establish several national centers with the deliberate intention to engage in regional collaboration. China, Japan, and South Korea took this approach and established the Asian Regional Network. One of the ideas that motivated the creation of the network was the recognition that each center could specialize and develop certain expertise. Collaborative training and exchanges allow all three states to benefit from the differing thematic focuses. If states in the region prefer a network approach, they could establish shared priorities and coordinate specializations to increase effectiveness and prevent duplication.

Arguably, the Asian Regional Network could be more effective in facilitating collaboration and exchanges. One hindrance to collaboration is that the authorities that established and operate the centers of excellence in each state differ, which complicates exchanges.[39] The Asian Regional Network also demonstrates that different degrees of political will from the participating states can hinder multilateral engagement. If the Middle East looks to develop a networked approach to nationally based centers, encouraging similar authorities to set-up and operate the facilities could overcome these issues and better spur collaboration.

Strengthening Nuclear Security Governance Implementation

Although nuclear security is less institutionalized compared to nuclear safety and safeguards, treaties and guidelines set standards for protecting nuclear materials and facilities. The most relevant treaty is the aforementioned Amended CPPNM. The original treaty, which entered effect in 1987, set standards for the protection of nuclear material in transit. A 2005 amendment to the treaty, which entered into force in 2016, expanded the physical protection requirements to include domestic transport and storage. The first review conference for the amended treaty took place in 2022. The IAEA is the depository for the Amended CPPNM and hosts the review conferences, which provide a critical opportunity to assess implementation of the treaty and the impact of emerging threats on best practices. During the 2022 Review Conference, for instance, several states highlighted the necessity of further action to address risks posed by cyberattacks. The International Convention on the Suppression of Acts of Nuclear Terrorism (ICSANT), which entered into force in 2007, is another relevant treaty. Negotiated at the UN, ICSANT criminalizes nuclear terrorism and includes requirements for international cooperative efforts to prevent and investigate nuclear terrorism.

In addition to those treaties, IAEA member states have developed guidance documents and recommendations for nuclear security practices. One of the most relevant documents is the IAEA's Nuclear Security Recommendations on Physical

Protection of Nuclear Material and Nuclear Facilities, commonly referred to as INFCIRC 225/Revision 5. The recommendations in the INFCIRC 225/Revision 5 were developed by IAEA member states and include guidance on developing and implementing physical protection programs and national regulations. Although some experts argue that INFCIRC 225/Revision 5 is outdated and should be revised, it still provides a critical baseline for establishing nuclear security practices and some states in the Middle East are not yet fully implementing the guidance document.

IAEA member states can also sign on to INFCIRC/869, Strengthening Nuclear Security Implementation. INFCIRC/869 originated as a Nuclear Security Summit multilateral commitment, or gift basket, but is now open for all IAEA member states to join. In addition to committing to the implementation of IAEA nuclear security guidelines, the INFCIRC encourages states to take additional actions to provide assurance of robust nuclear security practices. These areas include taking advantage of IAEA nuclear security services, such as International Physical Protection Advisory Service (IPPAS) Missions, which review a state's legal and regulatory frameworks and compare nuclear security practices to agency guidelines and relevant international instruments, and voluntary initiatives designed to combat nuclear terrorism.

Despite the centrality of these treaties and the consensus nature of the IAEA recommendations, not all states in the Middle East are party to the instruments or fulfill the intention of those treaties and the agency's guidelines. Several options exist for strengthening the implementation of these treaties and guidelines at the regional level.

Host Workshops on Governance Implementation

States party to these treaties and regulations could host workshops aimed at bringing other states in the region into compliance with the legal requirements and guidelines set out in the principal nuclear security guidelines. Even states reluctant to formally ratify or sign to these documents may be willing to take steps to meet their intentions.[40] This could include sharing best practices for updating domestic regulations and introducing new practices that satisfy the treaties and norms. Although the IAEA and other states also offer these types of activities, collaboration at the regional level builds capacities and routinizes collaboration. A series of workshops on INFCIRC 225/Revision 5 or INFCIRC/869, for instance, not only provides an opportunity to expand adherence but also incentivizes states to review and update practices to meet evolving security threats.

Use the Amended CPPNM Review Process to Address Gaps

Another option is for regional states to use the Amended CPPNM review process to advance a shared goal or respond to a gap in the regional nuclear security architecture. States, for instance, could commit ahead of a review conference to develop best practices for cybersecurity and hold workshops or tabletop exercises to test and advance cybersecurity in the region. The review conferences would provide an opportunity for accountability and further engagement on lessons learned, thus incentivizing states to follow through on the commitment. Pursuing collaboration at the regional level would also allow states to consider any regionally specific threat vectors that influence cyber practices and take those activities into account. Even for states not party to the Amended CPPNM, the review conference would add an element of accountability and multilateral support, which can spur more effective and timely collaboration. Given the emphasis officials and experts place on strengthening cybersecurity practices, this area could also be an area of focus for a regional center of excellence.

Strengthen Nuclear Assurances

States in the region could commit to joining and implementing certain assurance activities laid out in INFCIRC/869. In addition to committing states to meet the intention of certain IAEA nuclear security recommendations, states pledge to continuously improve nuclear security systems by taking certain actions. One option in INFCIRC/869 for the states with civil nuclear programs is to commit to requesting IAEA IPPAS missions or follow-up missions. The expert teams that lead IPPAS missions use IAEA guidelines, such as INFCIRC 225/Revision 5, and requirements in the Amended CCPNM as a benchmark for assessing nuclear security practices at an agreed-upon facility. As a result of the Nuclear Security Summit process, during which many states committed to IPPAS missions, the review process is widely accepted as a best practice.

Upon completion of the IPPAS mission, these states could go beyond the INFCIRC/869 recommendations and commit to a workshop to share best practices, redacted IPPAS reports, or both. There are precedents that demonstrate the benefit of both practices; France hosted an international seminar on IPPAS missions in 2013 to inform states about the benefits of establishing IPPAS reviews as a regular practice and discuss recommendations for strengthening those missions.[41] A regionally focused conference in the Middle East would help demonstrate the importance of peer reviews to states that are developing or considering civil nuclear programs. It could also provide an opportunity for states in the region that have welcomed IPPAS reviews, such as the UAE and Iran, to share any best practices. Publicly releasing portions of IPPAS mission reports is gaining traction as a nuclear security best practice that provides transparency and assurances to other states, while balancing the necessary confidentiality to protect sensitive information. In recent years, states including the Netherlands, Finland, and Canada, published certain IPPAS findings to enhance public confidence in their nuclear security.

Specific Project Collaboration

Another model of cooperation is for states to collaborate on addressing threats unique to the region, or improving implementation or establishing new best practices that benefit the group as a whole. The downside of a more ad hoc model is that it can be more challenging to build in continuous review (which may not be necessary for every project) and accountability. An ad hoc approach would need to deliberately create the expectation that states assess and report on their progress from the onset. High-level political support for any agreed-upon project could help drive accountability. Furthermore, ad hoc collaboration can create connections between expert communities and lead to expanded areas of cooperation.

Develop Regionally Driven Best Practices

One option for project-specific collaboration would be for states to set a shared priority based on identified gaps in national nuclear security practices. States in the region could create a working group to address specific topics, with the aim of identifying best practices for regional implementation and holding tabletop exercises or workshops for states to hone practices. Topics discussed above, such as insider threat mitigation and cyber security could be addressed through this model.

Create a Joint Technology Development Incubator

Similarly, states could develop a stand-alone technology development incubator, with a particular focus on refining equipment to address regionally specific threat vectors and environmental challenges. For instance, the UAE's experience working with South Korea in building Barakah Nuclear Power Plant demonstrated regionally specific challenges to building and operating a nuclear facility, such as accounting for heat conditions and dust that did not affect the construction of similar facilities in South Korea.

Synchrotron-light for Experimental Science and Applications in the Middle East (SESAME), an independent lab in Jordan with a third-generation synchrotron-light source, could be a possible model for this type of project. The laboratory was created by states in the Middle East as a research hub and is available for use by scientists in all SESAME member states. Scientists from non-member states can also apply to use the facility. It is governed by a council composed of members and observers and prioritizes support for regionally beneficial scientific and industrial projects. The current membership includes Cyprus, Egypt, Iran, Israel, Jordan, Pakistan, Palestine, and Turkey. Other states in the Middle East, including the UAE and Kuwait, are observers. SESAME could be expanded to include a specific nuclear-security related technology focus, but a better approach may be to build a dedicated facility using a similar approach for membership and governance.

Collaborate on Nuclear Security for SMRs

Another option for a project-specific approach could be a series of regional discussions on nuclear security considerations for small modular reactors (SMRs). Several states in the region are looking into SMRs and planning to deploy the systems once the technology matures. Limits exist on how far states could collaborate on nuclear security in this area because there are more than 60 SMR designs in development globally. However, states could still hold discussions on questions such as how design basis threat approaches would need to be adapted for SMRs and how to adjust security practices from larger-scale reactors to SMRs, given the smaller footprint of SMR technology.

Some states, such as Jordan, are looking into SMRs for power generation in remote areas. The ability to deploy SMRs in a broader range of locations will have security implications. Beginning some of these discussions now could better situate states as they assess reactor designs and assist in incorporating nuclear security considerations for deploying SMRs. These workshops could evolve if or when states begin to construct and operate SMRs to focus on how physical protection and security regulations need to evolve to address changes in the threat environment and respond to unforeseen challenges.

Establish Practices for Investigating Nuclear Attacks

States could also consider collaborating on establishing best practices for investigating attacks on nuclear facilities. International law prohibits targeting nuclear facilities and states party to ICSANT are obligated to share information regarding attacks. However, state and non-state actors are infrequently held accountable for attacks on nuclear facilities and there is no established investigative body for attribution. States in the region could consider holding a series of discussions to develop guidelines for documenting and preserving evidence from attacks on nuclear facilities. This would be most applicable to acts designed to sabotage or damage a facility, rather than investigating the theft of nuclear materials (where work has already been done) or responding to a radiation release. In the latter case, collecting evidence regarding the attack would be a secondary priority to response and mitigation activities.

Attribution for a number of past attacks on nuclear facilities in the Middle East is disputed. Using jointly developed techniques would increase the credibility of any accusation and could preserve evidence for future legal proceedings. The act of investigating and attributing attacks will not deter all state and non-state actors from planning future attacks on facilities, but accountability can be beneficial in rebuilding the norm against targeting nuclear infrastructure.

To further develop this concept, states could consider establishing a special panel of experts available for consultation in the event of an attack on a nuclear facility. This could include experts from participating states and states from other regions. In the event of an attack, states could invite an impartial body to assess evidence and intelligence and, when possible, provide an assessment of attribution. Although the IAEA has assisted in documenting attacks on facilities, most notably attacks on nuclear sites in Ukraine, it does not have the mandate to investigate and attribute attacks. Expanding the IAEA's mission to include attribution risks would politicize the agency and create an additional resource burden. Creating an independent and impartial investigative body with an attribution mandate would provide a beneficial resource for states in the Middle East, particularly given the history of attacks on nuclear facilities in the region.

Some of the project-specific approaches could be incorporated into other models of cooperation. A center of excellence, for instance, could include developing best practices for documenting evidence from an attack on a nuclear facility. Similarly, aspects of governance implementation or certain activities within a center of excellence could be singled out for project-specific regional activities.

Conclusion

Expanding nuclear programs in the Middle East comes with nuclear security risk, but these risks can be mitigated by establishing effective nuclear security practices. Well-designed and executed cooperative regional efforts can spur more effective nuclear security implementation and benefit every state in the region. Given the expected growth in nuclear programs in the Middle East, now is the time to prioritize cooperative efforts to create the necessary capacities and institutions to provide greater assurance that these developing nuclear programs are protected.

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A Global Playbook for Nuclear Energy Development in Embarking Countries: A Summary of the Six Dimensions for Success[1]

Clean Air Task Force, EFI Foundation, and Nuclear Threat Initiative

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 gigawatts per year from now until 2050.

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, the world needs 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. Finally, given that much of this future nuclear 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.

The Clean Air Task Force, the EFI Foundation, and the Nuclear Threat Initiative have developed that comprehensive strategy, the key points of which are summarized in this paper. This "Nuclear Playbook" outlines pathways for the responsible, sustainable, and effective development of new nuclear projects and industries in embarking countries. We call it a "playbook" as an analogy to a sports team's strategy for addressing various dimensions of a 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 that do not currently have a nuclear infrastructure but have plans to implement and deploy nuclear energy in their countries.

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 for embarking countries, but also for 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.

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 playbook also highlights the potential for shared benefits and synergies between embarking countries and existing nuclear energy 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 energy nations as they 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.

The playbook, and its recommendations, are organized around six key dimensions of capability and capacity building that are imperative to any successful nuclear development.

1. 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. 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. This is particularly important in embarking countries. 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.

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.

2. Regulatory System Development: 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 setting up a new regulatory regime involves numerous complex and often highly technical decisions. Building such a system from scratch is a daunting task, even for countries with considerable resources and expertise. 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. International regulatory frameworks can be harmonized to increase licensing efficiencies and regulatory support can be centralized and effectively directed to fill gaps in nuclear licensing capabilities that embarking countries may experience.

What can be done now:

- Create multilateral agreements for international transfer of design certifications.
- Develop in-country regulatory capability, borrowing from global best practices 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; addressing resource constraints; and accelerating nuclear deployment.
- Pursue more extensive global licensing harmonization.

Project Bankability and Finance: New business models need to be considered as new off-takers for nuclear power emerge. 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. Financing mechanisms and institutions that support large orderbooks for a given reactor design, while also supporting appropriate knowledge sharing mechanisms, can help spur deployment.

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.

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. 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, 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.

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 Management: The siting of permanent disposal sites for spent nuclear fuel is an important goal that nuclear energy stakeholders must work toward; in addition, a responsibility exists to safely manage waste in interim storage. 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. Although this process can seem complex, spent nuclear fuel can be managed safely, securely, and economically with appropriate effort, especially if these issues are tackled early in project planning. 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 a 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.

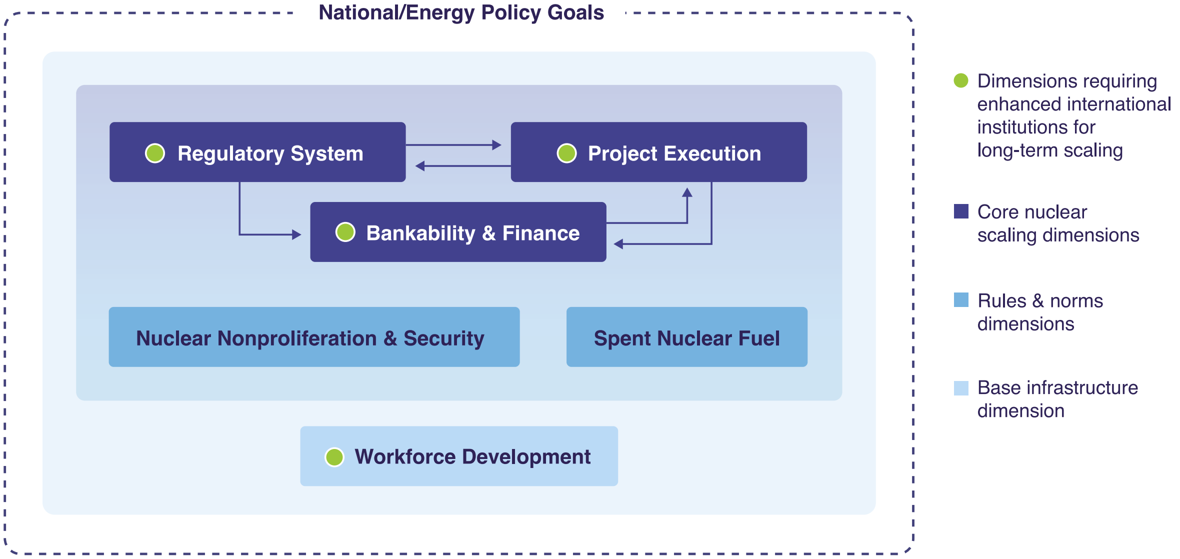
Further options:

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

Workforce Development: Workforce development is foundational to nuclear embarking countries and requires workers with a range of regulatory, management, manufacturing, craftwork, and operations skills. However, nuclear technology's specialized workforce requirements can turn staffing into a choke point for new projects. Embarking countries share global workforce problems and acute constraints particular to new entrants. Supplying talent will likely require a combination of investing in in-country training and recruiting 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.

The sequence of these six dimensions 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 countries cannot efficiently put these pieces in place, 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.

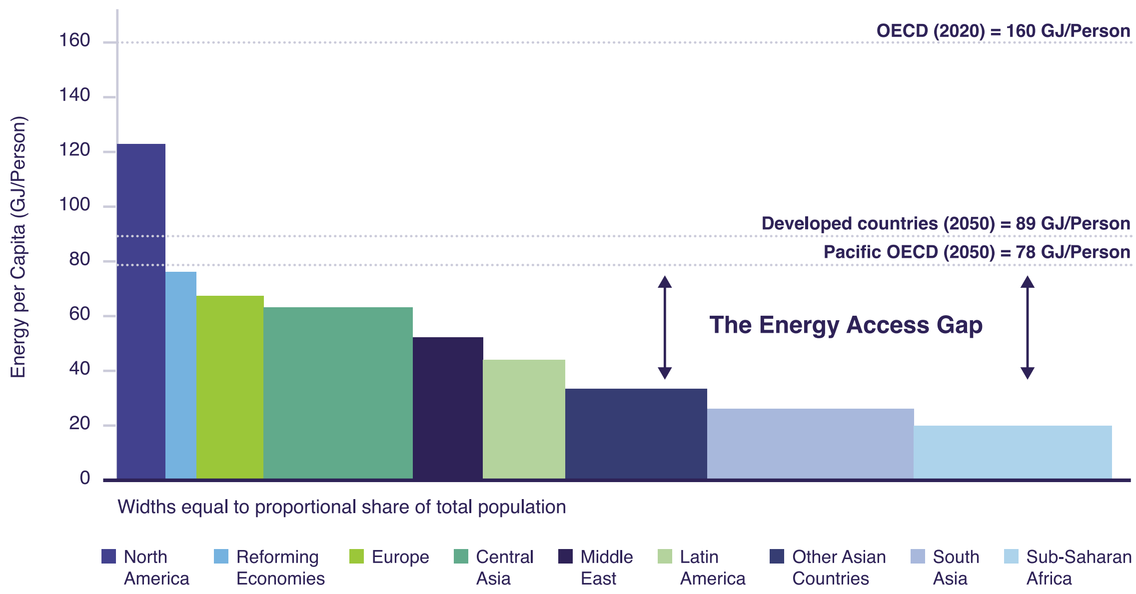
Figure 1. Interrelationships of the Six Dimensions and Where New International Institutions Are Needed to Scale New Nuclear Energy Globally



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 3,000 TWh, by 2050.[2] 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.[3]

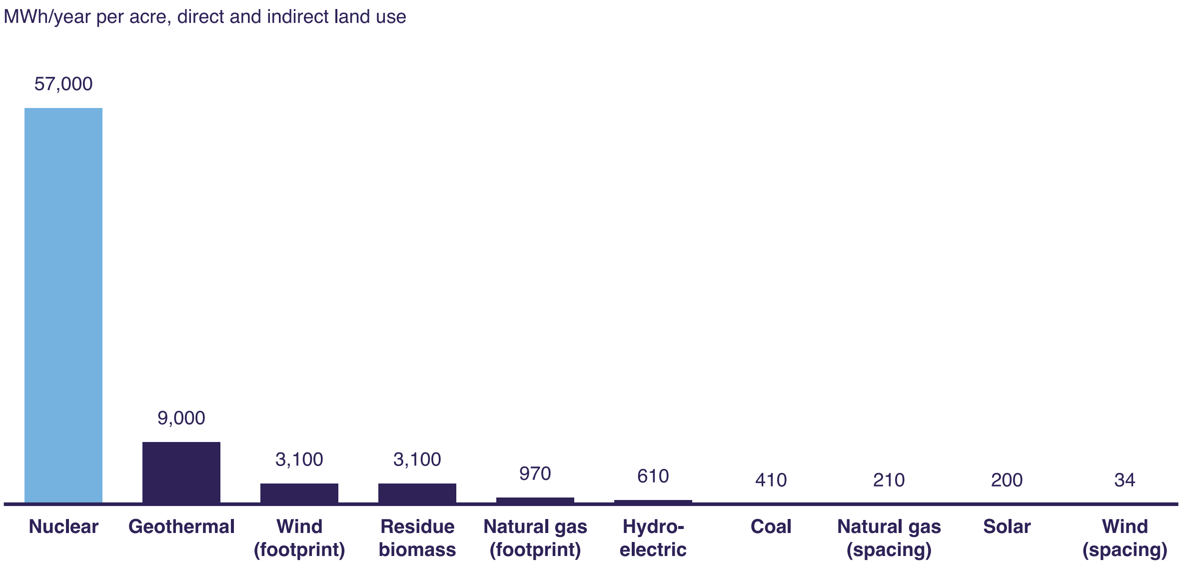
Figure 2: Projected Energy Demand in 2050 by Region in IPCC Scenarios



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, although 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.[4] 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.[5] Both factors are key considerations for the global development of large, critical energy infrastructure.

Figure 3: Land Use Efficiency of Electricity Generating Technologies



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.

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 the 195 countries in the world, only 35 and 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.

Cross-Cutting Themes and Caveats

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

- 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 are heavily influenced by nuclear business and delivery model challenges and regulatory challenges. 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.

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 the 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.

Approaches Benefitting Both Established and Embarking Countries

Although the 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.

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 the playbook 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.

One Size Will Not Fit All

The 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 it will stimulate discussion about which elements might work best where.

The Role of Public Opinion and Public Acceptance

The 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.

Endnotes

[1] This paper is a lightly modified summary of "A Global Playbook for Nuclear Energy Development in Embarking Countries: Six Dimensions of Success," published by CATF, EFI Foundation, and NTI in December 2023, https://www.nti.org/analysis/articles/a-global-playbook-for-nuclear-energy-development-in-embarking-countries-six-dimensions-for-success/.

[2] 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.

[3] 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.

[4] 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.

[5] 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.

[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.

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