Global Nexus Initiative
Where Climate, Nuclear, and Security Meet

Advancing Nuclear Innovation

Responding to Climate Change and Strengthening Global Security

June 2019

Nuclear innovation is essential in the 21st century, a period of powerful technological evolution and intensifying global competition. The challenges posed by climate change and to global nuclear security must be addressed in a strong and effective manner. Advanced reactors are an important response to both of these critical issues.

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Overview

Because of their unique features, advanced reactors will pose new challenges for the international non-proliferation and security regimes. There is high confidence that these issues can be effectively resolved.

Advanced nuclear reactors, the smaller, flexible, and innovative nuclear technologies of the future, are rising in importance as the global community grapples with the vital challenges of cutting carbon emissions, supporting the global demand for electric power, and ensuring the continued peaceful use of nuclear energy in the 21st century.

The Global Nexus Initiative is a leader in analyzing the intersection of nuclear power, climate change, and global security. It determined that advanced reactors offer sufficient potential value in providing zero-carbon energy and supporting global economic growth, and that further study was needed of the nuclear safeguards and security requirements for the three major types of advanced reactors: molten salt fuel, TRISO-based fuel, and fast neutron spectrum reactors.

The Value of **Advanced Reactors**:

- **Meet energy demands in underserved areas**
- **Provide carbon-free energy**
- **Address fuel cycle and proliferation concerns**
- **Offer inherent passive safety features**
- **Provide lower-cost production and operational flexibility**

This report is based on a more detailed analysis that can be found on the GNI website.

Five primary results of this assessment:

Supporting Decarbonization

Advanced reactors are an important component of the global strategy to reduce carbon emissions to zero. The most recent report by the IPCC[1] states that limiting the global temperature increase to 1.5° Celsius will prevent the worst impacts of climate change but will require “rapid, far-reaching and unprecedented” action on decarbonization. Advanced Reactors promise: enhanced efficiency and safety, reduced construction time and costs, fuel cycles that can reduce environmental impacts, and a wider variety of sizes and outputs for different locations and applications. All of these attributes, plus the value of producing emission-free electricity in a carbon-constrained world, make advanced reactors attractive energy sources. However, in order to make a timely contribution to meet the energy and climate challenges that the world faces, advanced reactors must move to deployment in the 2025-2030 timeframe.

Preventing Proliferation

There is high confidence that any of the advanced reactor concepts can be safeguarded to prevent nuclear weapons proliferation. The question is how easily and at what cost. The current international safeguards system has been effectively and efficiently implemented for the global fleet of Light Water Reactors (LWRs). The IAEA will need to consider how to best accommodate the unique characteristics of advanced reactor technologies and designs. The reactor designers must, from the early concept stage, be focused on “safeguards by design,” identifying reactor features that will facilitate effective international safeguards and ensure a high level of proliferation prevention and security comparable to LWRs. This will require the adaptation of the international safeguards and security systems for advanced reactors by the international community and the IAEA.

The potential value of advanced reactors is significant as the global community faces new and evolving challenges of the 21st century. To maximize that value, the technology must be secure, proliferation-resistant, and safe.

Strengthening Security

There are characteristics of advanced reactors that can support improved nuclear security and prevent unauthorized radioactive release, including below-ground placement, passive safety features, low operating pressures, and decreased external power dependence. Emerging technologies like artificial intelligence and blockchain may also assist with security and safeguards. There are questions regarding the implications of the remote location of these reactors (because they can support industrial as well as electric power operations). This includes how the siting may impact physical security and critical issues like timely response in the case of a security event.

Fortifying Governance

The international community must ensure from an early point that any race for market share among key geopolitical competitors strengthens nuclear governance rather than weakens it. Advanced reactors must be thoroughly evaluated with respect to both safety and security, as part of an evolved nuclear governance structure. Traditionally, the dominant suppliers of a nuclear technology have had significant influence on these issues. It is not clear at this point which advanced reactors, or which countries, will lead the market competition.

Promoting Public Confidence

There must be political and public confidence in this new class of reactors if they are to effectively contribute to meeting the climate and security challenges the word faces in this century. Nations that are interested in the deployment of these reactors must commit, and be offered adequate international assistance, to increase their capability to safely, securely, and effectively operate them.

These five results are preliminary because there are a number of different reactor designs within the three major technology categories, and the GNI analysis did not examine each unique reactor design. The different sizes and design features of individual reactors may influence and change these preliminary findings.

Importance of Nuclear Power for Climate Change

In order to meet the Paris Climate Change Agreement's emissions reduction objectives, analysis by the Intergovernmental Panel on Climate Change (IPCC) and other experts indicates the need for a near-zero carbon electricity system soon after mid-century.[2] The most recent report by the IPCC[3] states that limiting the global temperature increase to 1.5° Celsius will prevent the worst impacts of climate change, but will require "rapid, far-reaching and unprecedented" action on decarbonization. Reductions of this magnitude require significant and rapid technological advances, including in the four key elements of a climate change response strategy: energy efficiency, renewable energy, carbon capture and storage, and nuclear power.

There is a growing chorus of expert opinion noting that nuclear power remains an important element of the global decarbonization strategy.[4] Yet, very few nations have included nuclear power as a part of their approach to reducing carbon emissions as outlined in their national commitments at the Paris climate agreement meeting.[5]

Advanced reactors promise the following:

- Coolant systems that can enhance efficiency and safety
- Reduced construction time and costs
- Fuel cycles that can reduce environmental impacts
- A wider variety of sizes and outputs for different locations and applications

Beyond electricity generation, there may be a role for next-generation reactors in the desalination of sea water, which would provide a new source of fresh water to countries and regions that need it.

All of these attributes, plus the value of producing emission-free electricity in a carbon-constrained world, make advanced reactors attractive energy sources. However, in order to make a timely contribution to meet the energy and climate challenges that the world faces, advanced reactors must move to deployment in the 2025-2030 timeframe.

All of these attributes, plus the value of producing emission-free electricity in a carbon-constrained world, make advanced reactors attractive energy sources.

If the clean energy benefits that are contributed by the existing reactor fleet decline significantly, there is a considerable risk in assuming that renewable or other zero-carbon energy options will be able to substantially compensate for this reduction by mid-century.[6] In recent cases where nuclear plants have been shut down in the U.S., carbon emissions have grown as the substitute power came primarily from natural gas, while in Germany, lignite, and now imported coal, have been the major replacement sources.[7]

If non-nuclear zero-carbon energy sources and related technologies cannot meet carbon-reduction objectives, then falling back on carbon-emitting sources of power, including natural gas or coal without capture and sequestration, will inevitably mean that aggressive climate targets will be unmet, with the attendant global consequences.[8]

Advanced Nuclear Technologies

For the purposes of this report, advanced reactors have been grouped into three main categories: i) the Molten Salt Fueled Reactors, ii) the TRISO-based Reactors, and iii) Fast Reactors.

Molten Salt Fueled Reactors

In molten salt fueled reactors, the fuel consists of fissile materials dissolved in a salt, a mixture that becomes liquid during operation. In general, the design has no fuel units such as fuel rods or assemblies, and the fissile element (uranium or thorium) is mixed with the coolant. Molten salt fueled reactors operate with a uranium fuel enrichment up to (but less than) 20% or thorium-based fuel. In a reactor with thorium-based fuel, ^{232}Th in the initial fuel inventory is converted during operation to the fissile isotope ^{233}U, which is then consumed as fuel.

Molten salt fueled reactors are typically refueled online, allowing for extended, continuous reactor operation. Molten salt fueled reactor designs can range in size from 10s of MWe to 100s of MWe. Removal of unwanted fission by-products and the addition of fresh fuel enables the reactor to run for long periods without major refueling outages. Molten salt fueled reactors can be either thermal reactors, burning the fuel, or fast reactors which may, but do not have to, produce more new fissile material than they consume in operation. The salt is solid at room temperature, but a molten liquid during the operation of the reactor.

Molten salt fueled reactors are typically refueled online, allowing for extended, continuous reactor operation.

TRISO-Fueled Reactors

Tristructural-**iso**tropic (TRISO)-fueled reactors operate at high temperature, using small, uniform microspheres of uranium oxycarbide coated with several layers of pyrocarbon and silicon carbide that are dispersed into a) graphite pebbles (e.g., billiard-ball sized) or b) prismatic, hexagonal graphite fuel blocks in which the TRISO fuel particles are dispersed into a graphite block matrix. The reactor uses graphite as moderator. The fuel is designed not to crack due to the stresses from very high temperatures, which will prevent release of fission products or actinides during accident conditions, an improved safety feature. Some designs are helium-cooled, and some are molten fluoride salt-cooled designs. TRISO-fueled reactors can range in size from 10s of MWe to 100s of MWe.

Pebble-bed TRISO-fueled reactors are refueled online. Used pebbles are taken out of the core, and unirradiated pebbles or pebbles that have not reached the desired burnup are added to the core. The reactor is shut down periodically (about every 6-10 years) for replacement of in-core graphite structures. Prismatic designs will require regular refueling outages every 1 to 3 years.

The fuel is designed not to crack due to the stresses from very high temperatures.

Fast Reactors

Fast reactors use a fast neutron spectrum that can enable high fuel utilization, operational flexibility, and fuel recycling. Fast reactors can use liquid metal, gas coolants,[9] or salt coolants. Liquid metal reactors are typically designed to operate at low, near-atmospheric pressure and high temperature (~500-800°C).

Lead-cooled fast reactors utilize either molten lead or a lead-bismuth mixture as the coolant, which are relatively inert in relation to water or air but are highly corrosive, requiring more robust piping or vessel materials. Lead-cooled designs typically use uranium metal or nitride fuels.

Sodium-cooled fast reactors have several hundred reactor-years of operational experience and the benefit of oxygen-free/low-corrosion operation. However, the chemical volatility of sodium requires a sealed coolant system. Sodium-cooled reactors typically use uranium oxide or metal fuel.

There are several varieties of fast reactors. One specific type is a **Gas Fast Reactor (GFR)**, which is helium-cooled, with the coolant under high pressure and high temperature, about 850°C. It uses uranium fuel in silicon carbide fuel rods. Some fast reactors are being designed to operate for an estimated period of 10 to 40 years without refueling.

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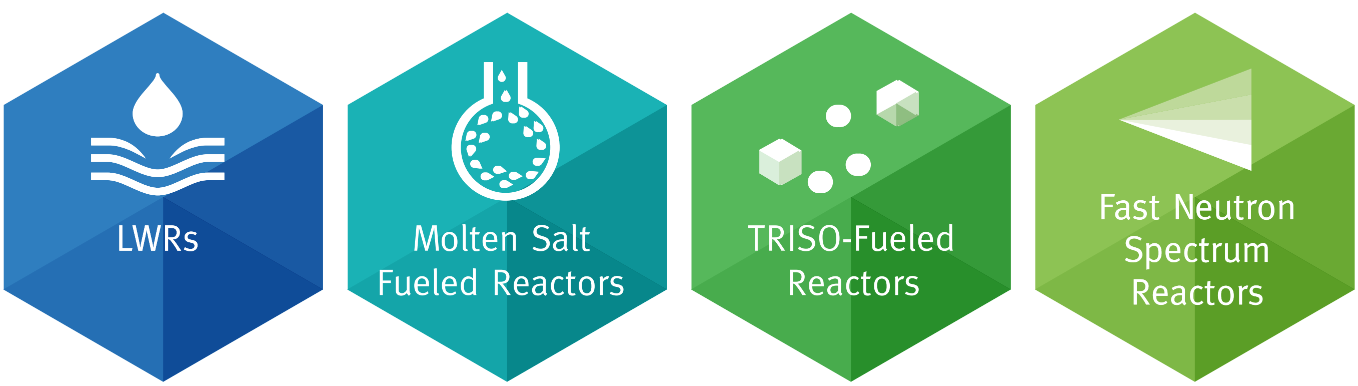
Preliminary Assessment of Safeguarding Advanced Nuclear Reactors

The peaceful use of nuclear energy has been globally important for over 60 years. It has resulted in 452 nuclear reactor units in 32 countries, most of them in Europe, North America, East Asia, and South Asia. Most of them are LWR units that may produce up to 1650 MW of electricity. This has significantly contributed to, and accelerated, economic development in a number of countries. But nuclear technology can be dual use – peaceful or weaponized – and an extensive and effective international safeguards regime, implemented by the International Atomic Energy Agency, has been established to contain the potential proliferation of nuclear weapons. Because of their unique features, advanced reactors do not easily fit into the existing national regulatory or international governance regimes and, in particular, they pose new challenges for the safeguards system.

There is high confidence that any of the advanced reactor concepts can be safeguarded to prevent nuclear weapons proliferation.

Reactor Types



Advanced reactors present new challenges for international safeguards because of their fuel types, coolants, and configurations.

Non-Proliferation and Advanced Reactors

The IAEA can apply safeguards at any type of nuclear facility. However, the human, institutional, and related effort required, and the expense, will depend on the type of facility and whether the nuclear material is available in bulk form or as items. There is a direct relationship between non-proliferation and the ease of applying effective safeguards. This report has evaluated the safeguarding of advanced reactors based on a comparison with the processes and approaches for safeguarding traditional LWRs. For the assessment of advanced reactor technology, this analysis uses a two-part analysis:

1. Comparing elements of "LWR safeguards" with the relevant characteristics of each type of advanced reactor technology.
2. Assessing whether safeguarding the advanced technology is likely to require the same, somewhat more, or significantly more safeguards effort compared with the application of IAEA safeguards at LWRs.

The following evaluation is relevant for the three design groups, recognizing that there are variations among them in the specific designs that are being developed around the world.

Light Water Reactor (LWR) Safeguards

- **Item Facility:** An "item facility" is where all nuclear material is kept in item form and remains unaltered during its time in the facility. This allows for accurate item counting and identification. An example is reactor fuel.
- **Fresh Fuel:** The fresh fuel for an LWR contains low enriched uranium (LEU), around 4-5%.
- **Source Data:** Source data will provide detailed information on the unirradiated fuel and will be available after irradiation, including the burn-up and post-irradiation isotopic composition that is assigned to each fuel assembly.
- **Refueling:** LWRs are refueled during outage periods, during which the inventory of nuclear material in the reactor and storage areas can be verified.
- **All Nuclear Material Is Verifiable:** Nuclear material for LWRs is verified by visual inspection, non-destructive assay (NDA) measurements, and containment and surveillance (C&S) methods.

Assessment of Advanced Reactor Safeguards

LWR Safeguards	Item Facility	Fresh Fuel	Source Data	Refueling	All Nuclear Material Verifiable
Molten Salt Fueled Reactors	●	✓	●	●	●
TRISO-Fueled Reactors	●	✓	●	●	●
Fast Neutron Spectrum Reactors	✓	●	✓	✓	✓

✓ Indicates relative compatibility with current IAEA safeguard measures for LWR.

● Indicates that IAEA safeguards may require considerably more effort than for an LWR.

Molten Salt Fueled Reactors

● **Item Facility:** Fuel is in liquid form and cannot be safeguarded as an item facility. These reactors are likely to be subject to safeguards as a bulk material handling facility.

✓ **Fresh Fuel:** The fuel contains uranium, with enrichment $<20\%$ ^{235}U.

● **Source Data:** Incoming fuel will be well characterized. The post-irradiation fuel composition likely will have to be determined through calculation or measurement, and this process may be more challenging if the fuel is removed in batches.

● **Refueling:** Online.

● **All Nuclear Material Is Verifiable:** It is assumed that all parts of the reactor, the flow of fuel, and potential extract possibilities can be monitored by C&S methods. However, additional measurements may be required.

Further study required:

- Further study of various design models will be required, particularly to understand the size of the individual reactor, its need for refueling, the duration of the operating cycle, and whether the reactor could become more like an item facility.

TRISO-Fueled Reactors

Item Facility: The fuel consists of unidentifiable fuel particles. The microspheres are dispersed in either graphite pebbles or prisms.

Fresh Fuel: Uranium oxycarbide (enrichment <20% ^{235}U) in graphite pebbles or hexagonal prisms.

Source Data: Source data after irradiation may not be able to be assigned to an individual pebble.

Refueling: Online or during outage (prisms). Pebbles will be identical but potentially not identifiable when moving into or out of the reactor during online refueling.

All Nuclear Material Is Verifiable: It is assumed that all points in the flow of pebbles will be possible to monitor with C&S methods.

Further study required:

- Further analysis with access to more detailed information on the fuel for specific reactor designs will be required (e.g. information related to the feed of pebbles during online refueling and how this flow can be measured).

Fast Neutron Spectrum Reactors

Item Facility: Fuel assemblies are similar to those in an LWR

Fresh Fuel: The potential presence of separated plutonium in unirradiated fuel is a higher proliferation risk than those that contain LEU.

Source Data: Source data available for each unit, as for LWR fuel.

Refueling: During outage. Some very long operating periods.

All Nuclear Material Is Verifiable: Yes, through visual inspection, NDA, and C&S methods.

Further study required:

- Individual reactor designs: clarification regarding quantities of fresh fuel normally in storage, size of reactor core, and individual fuel elements in various designs.

Safeguards Conclusions

1

All the advanced reactor types can be safeguarded, but the approaches will differ from LWRs and both the IAEA and reactor designers will need to work together to ensure cost-efficient and operationally effective "safeguards by design."

2

None of the advanced reactor design categories can be safeguarded in the same manner as an LEU-fueled LWR.

Pebble-bed and molten salt fueled reactors offer new challenges in verifying items in the reactor and fuel cycle. Fast reactors are closer to the LWR model but present some unique problems and have the added complication of the potential for separated plutonium.

3

Both the IAEA and the reactor designers should take steps in the design phase to facilitate effective international safeguards.

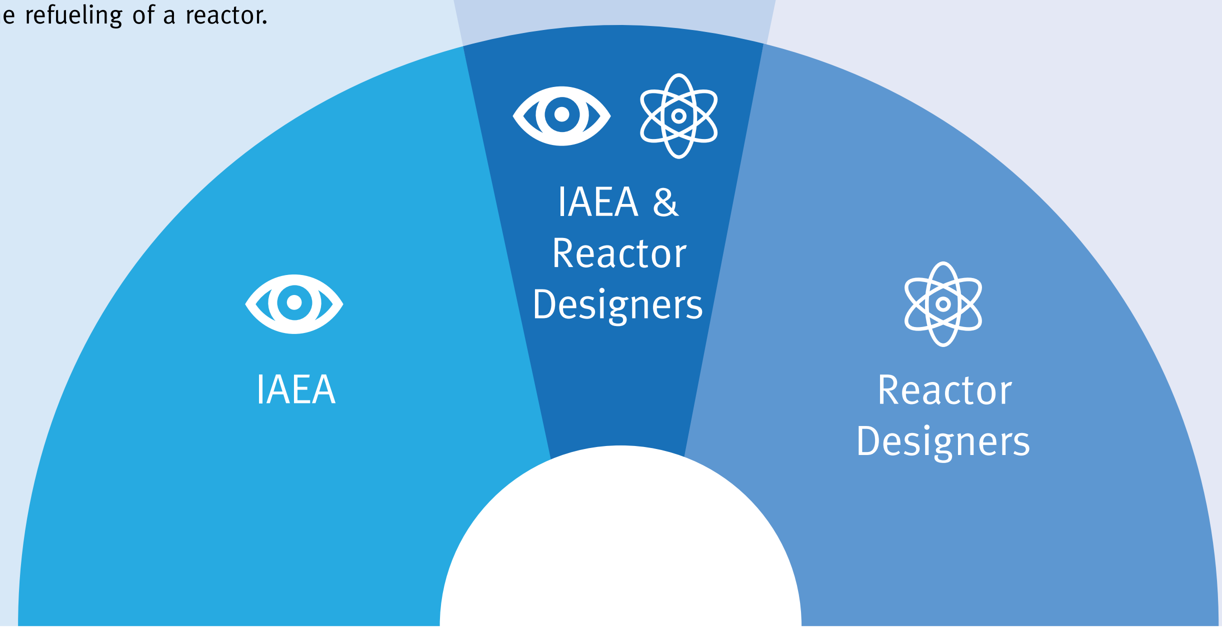
Safeguards Recommendations

The IAEA can safeguard all kinds of nuclear facilities, including advanced reactors. However, the human, institutional, and financial resources required will be a measure of how easily they can be implemented. The following three recommendations are drawn from the evaluation:

The IAEA should recognize that advanced reactor technologies represent new safeguards challenges and that it is important to accelerate its work to identify and adapt to potential technical problems that may impact safeguards implementation. The Agency should identify whether more effective verification tools will be required and start working on new safeguards approaches that could be implemented for the new types of reactors, including those with long-life cores. These could include new C&S techniques and non-destructive measurement of enrichment and nuclear material quantities in process-related circumstances, such as online refueling of a reactor.

The IAEA and the designers of advanced technology reactors should initiate, at an early date, an interactive process through which the safeguards system can be explained and safeguards-challenging elements of the technology can be identified. Steps should be taken to facilitate international safeguards in the design phase of the reactor.

The reactor designers should review their designs considering the efficient, well established IAEA safeguards system for LWR reactors. Such review should focus on the possibility of turning the advanced reactor into an item facility, recognizing that the definition of an item may need to evolve in new and untraditional ways.



Nuclear Security and Advanced Reactors

Advanced nuclear reactors will be subject to security measures that are defined in the international legal framework, including IAEA recommendations and guidelines, and by the regulations of individual nations. There are a number of nuclear security challenges that are applicable to all nuclear reactors and some that are specific to advanced reactors.

A primary concern for all reactors is the physical protection of all nuclear materials, unirradiated and irradiated in storage and in transport.

Nuclear security also extends to protection of facilities from acts of sabotage, including insider and outsider threats, terrorism and cyber attack, and the potential security threats posed by new and emerging technologies.

For advanced reactors, specific challenges may include the specific location and siting of the reactor, including how remote the area is where it is deployed, whether it is built above ground or below ground, and how prepared the nation in which it is deployed is for nuclear operations and emergencies.

There are three types of security challenges for nuclear reactors: a hostile outside attack, nuclear terrorism resulting from illicit access to nuclear weapons materials, and insider sabotage. These plus new technological challenges must be effectively addressed.

Physical Protection

Advanced reactors of the three types addressed in this document typically contain uranium-based fuel with an enrichment up to 20%. This material would be Category 2 or 3 according to the IAEA definition. This would also apply to designs that use thorium-based fuel. After irradiation, the spent fuel will be treated as Category 2. The fast reactor group is the only type of advanced reactor design that presents a Category 1 nuclear material concern if the reactor uses separated plutonium in the fresh fuel. The risk of theft of weapons-usable material directly depends on the quantity of material, which will vary with the size of the reactor and the operating cycle. Therefore, the specific technical characteristics of individual reactors and the operational approach to their fuel supply will be important in assessing and addressing this concern.

Facility Sabotage and Nuclear Terrorism

Nuclear facilities are required to be protected against acts of sabotage and nuclear terrorism that may result in unacceptable radiological consequences. A particular concern is centered on the vital areas which would be critical for reactor safety. Historically, the threat has been an attack from outside the facility. But, in recent years, there has been significant concern about the potential for insiders or employees of the facility — acting alone or supporting outsiders — to sabotage the facility.

Advanced reactors offer the potential of limiting the impacts of facility sabotage or attack and the resulting radiation release concerns because they are designed with characteristics that are likely to reduce the risk of the dispersal of radioactivity:

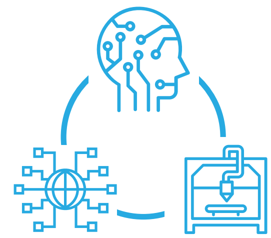
- Passive safety features that automatically respond and move the reactor into a safe state.
- No external power dependence, which would reduce the risk of cutting the power supply for the circulation of the reactor coolant.
- Low operating pressure that can reduce the dispersal of radioactivity in most designs.

All three primary groups of advanced reactor designs have passive safety systems, which significantly lowers the risk of accidents caused by a safety failure or acts of sabotage.

Cyber and Emerging Technologies

Advanced reactors are being introduced into an environment where emerging technologies are creating new security challenges. Cybersecurity is a major concern for the existing global nuclear reactor fleet and may cause problems for advanced reactors. There is not a global approach to cybersecurity in the civil nuclear sector.

Rapidly advancing technologies include artificial intelligence, additive manufacturing, and blockchain. The benefits and challenges of each of these technologies need to be explored in more detail, but some may contribute to greater nuclear security. For example, artificial intelligence may be configured to prevent insider threats through surveillance and may help with the physical protection of facilities without requiring excessive security personnel. Blockchain holds the promise of potentially being applicable in cataloging small and numerous fuel pellets as they enter and exit a reactor, as is the case for TRISO-fueled reactors.



Reactor Location and Siting

The three major advanced reactor designs can be deployed in remote and arid locations. They may be sited below or above ground or at sea level. These unique characteristics may have some inherent security value but also can raise questions. A small, remotely located reactor would have to have a certain level of protection from outside attack and a rigorous vetting process for the operations staff to minimize the potential for insider sabotage. It therefore will be important to consider how a particular reactor would be sited and then to develop various options for physical protection of the plant and its fuel. A further concern is that any country considering the deployment of an advanced reactor develop an effective nuclear governance infrastructure, including an educational system, workforce, and regulatory capacity to safely and effectively operate the reactor.

Security Conclusions

Further analysis of the security vulnerabilities based on additional updated and technical information is required to determine with clarity the specific security challenges posed by advanced reactors. The different technologies, size of the cores, and location for the reactor are examples of parameters that may shed further clarity on the assessment. However, as a preliminary assessment, the following points are relevant:

1

Molten Salt Fueled Reactors

Molten Salt Fueled Reactor designs appear to be the least vulnerable from the nuclear security perspective, with a low risk for theft of nuclear material and of dispersal of radioactivity. It must be noted, however, that the size of the reactor is a critical consideration and may impact this initial assessment.

2

TRISO-Fueled Reactors

It has been demonstrated that the microspheres in the pebbles or prisms are extremely resistant to change under high temperatures and will contain the nuclear material and fission products, reducing the risk of the dispersal of actinides or fission products. TRISO-based Reactors use extensive passive safety features including no dependency on offsite power or any pumping capacity during accident conditions. During accident conditions, cooling is achieved passively through the graphite and the vessel. There are several reactor designs with TRISO fuel, and the potential impact of the different designs will require additional evaluation.

3

Fast Neutron Spectrum Reactors

While the metal-cooled reactors will operate around atmospheric pressure, the helium-cooled reactor will require high operating pressure. Size of fast reactors can vary considerably, which makes an overall group assessment more complex. The overall assessment in such a case could point to having a relatively low risk of accident, with low risk of dispersal of radioactivity. However, fast reactors may have fresh fuel containing separated plutonium, a Category 1 material that requires strong physical protection and other security measures during transport and storage. Category 1 material is a potential security risk, being attractive for theft for weapons purposes. This risk is mitigated when the fuel is loaded into the reactor.

Security Recommendations

1

Below-Ground Deployment

The security benefits of reactors installed below ground should be clearly demonstrated.

2

Sabotage

Further information will be required regarding both the general reactor design and the technical specifications, to reliably assess the vulnerability of specific advanced reactors to an act of sabotage.

3

Cybersecurity

Intensified and confidential discussions should be encouraged and organized among key nuclear nations, regulators, and cybersecurity professionals. While there are national security and sensitivity concerns at the national level, the consequences of a serious nuclear cyber attack would negatively reverberate across the globe.

4

Emerging Technologies

A more thorough evaluation of the benefits, challenges, and implications of rapidly emerging technologies including artificial intelligence, additive manufacturing, and blockchain, needs to be conducted in relation to advanced reactors, and the civil nuclear sector more generally. Similar to cybersecurity, this is an assessment that may be done at the national level but that would also benefit from circumscribed international collaboration.

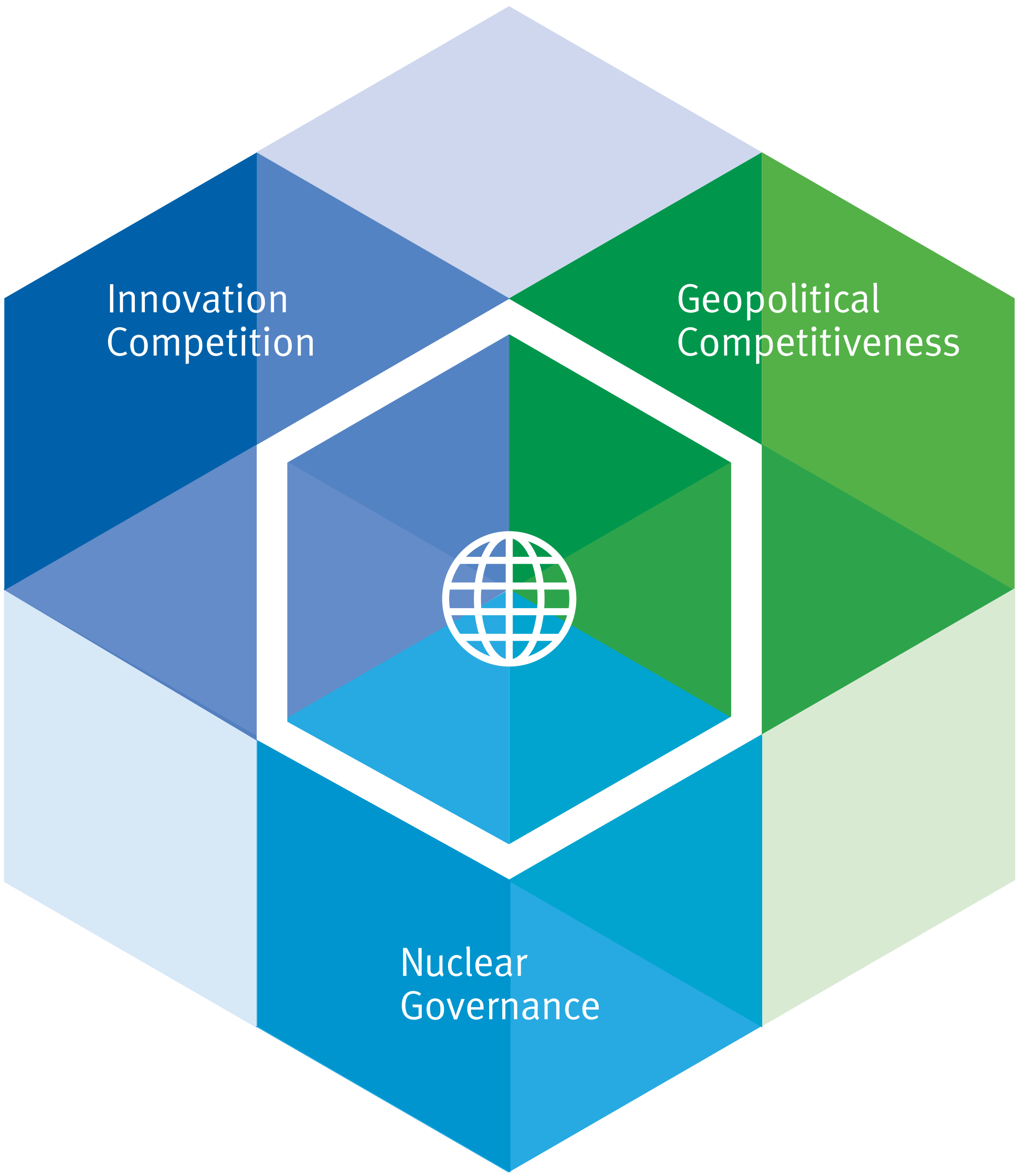
5

Working Group

Representatives from the reactor designer community, IAEA, and other experts and authorities should assemble to further assess the security challenges and benefits of advanced reactors.

Nuclear Geopolitics, Governance, and Advanced Reactor Innovation

The future of advanced reactors cannot be divorced from the critical issues associated with the intensifying geopolitical competition among large powers, particularly the U.S., Russia, and China and their allies; the evolution of nuclear supplier arrangements; and the future of nuclear governance.



Innovation Competition

A critical element of geopolitical competition is the race for technological dominance and global influence in the 21st century. Advanced reactors cut across both of those key challenges. **Several countries are focused on developing advanced reactors, including the U.S., Canada, South Korea, U.K, France, Russia and China.** While many of the underlying advanced reactor technologies are not new and have been tested over the past 70 years, the deployment of these technologies has not been widespread, and the specific designs of the new reactors are different than in the past. There are several challenges that result from this.[10]

One is the lack of a developed regulatory system and regulator experience. This is a challenge for all nations.

Also, as these reactors move through the design and development phase it will be important to have well developed test beds to demonstrate the technology.

Technology innovation will be the major global competition of the 21st century. Energy technologies are one of the key battlegrounds.

In this area, Russia and China have shown an advantage. Fast reactors have operated in Russia for decades, and the testing of these technologies is not in question on its territory. China also has an interest in fast reactors and is moving toward the deployment of a small high-temperature gas-cooled pebble-bed reactor. But it also is focused on molten salt technologies, committing $3.3 billion to a molten salt demonstration facility in the Gobi Desert.

The potential market for advanced reactors is also a key issue. The supply of reactors entails considerably more than just the transfer of technology. The relationship between supplier and recipient nation can last up to a century through the contract and decommissioning stages. This offers the supplier nation significant influence over the purchaser and influence in the region.

Geopolitical Competitiveness

Both Russia and China have intimately tied their nuclear export strategy to their geopolitical ambitions and objectives, and their companies are state-financed. OECD countries face restrictions on using financing as an incentive for reactor sales and limits on the repayment of credit. Companies in OECD countries also must comply with strict export control laws.

At present, Russia controls 50% of the reactor construction and fuel market.[11]
Russia offers a build, own, operate model that will lend nations funds for the reactor, operate it for them, and take back the spent fuel from it. That is a very attractive deal for a newcomer nuclear nation. Russia's ROSATOM has a presence in 44 countries and is building reactors in half a dozen of them, including Turkey, Bangladesh, and India.

China is using its One Belt One Road initiative to influence Eurasia's economics and trade, and 65 nations are engaged with the program. China also has a "Made in China 2025" initiative that is designed to dominate new technologies, including robotics, artificial intelligence, aviation, and energy. By the mid-2020s China is projected to be the largest domestic nuclear fleet operator in the world, surpassing the U.S. China is also deeply involved in the nuclear modernization efforts in the U.K. This will provide China with a strategic nuclear foothold in Europe, provide additional construction and operating experience outside its borders in a high-regulation mature nuclear country, sustain a hot production line for its nuclear industry, and improve its positioning as a dominant nuclear supplier.

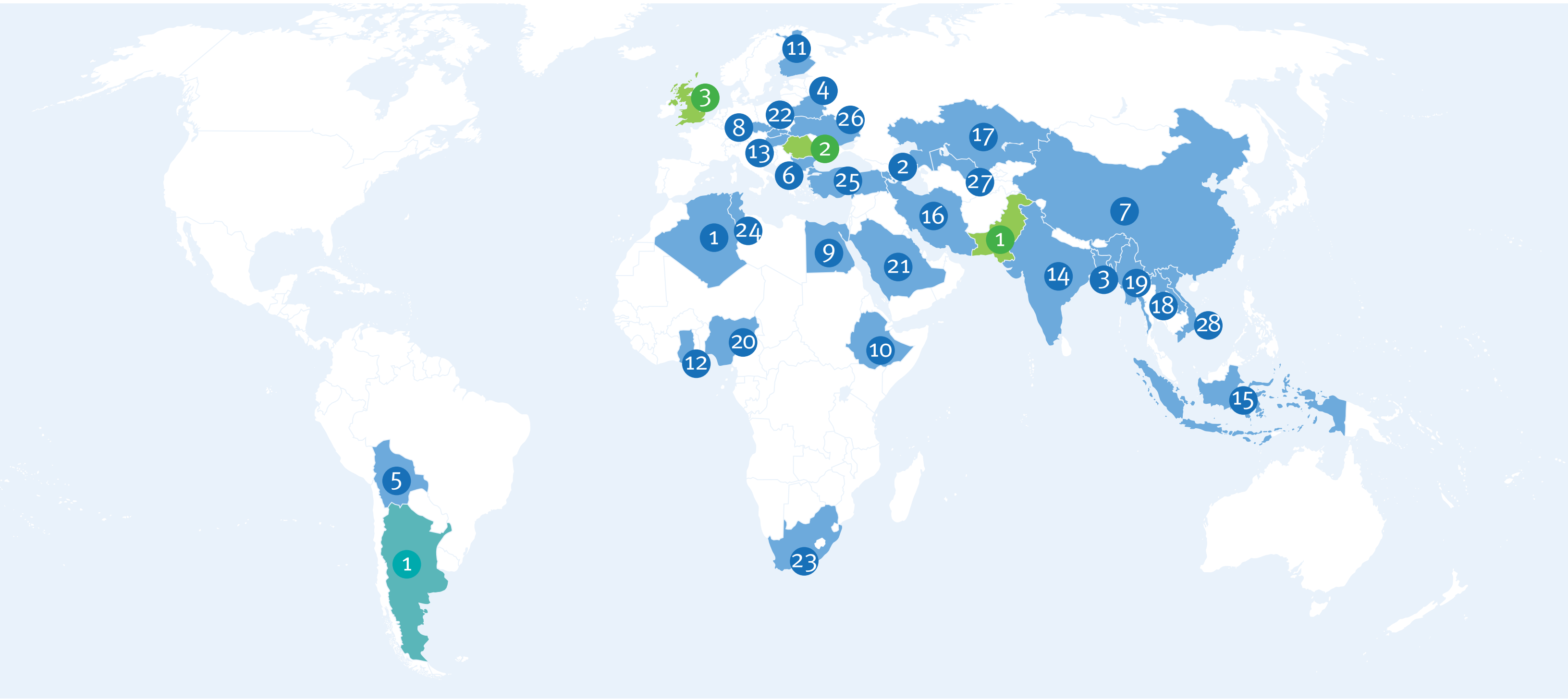
Russia's control of reactor construction and fuel market:

Nuclear Governance

It is important to note that during the history of the nuclear era, the nations dominating nuclear supply have exercised an outsized influence on the nuclear governance regime. The U.S., once the world's dominant nuclear supplier, used its influence to strengthen nuclear governance and global security.[12] It is unclear in the current nuclear power market whether nuclear suppliers will replicate the practices of the U.S. and continue improving the IAEA safeguards and security systems to adapt to new technical and political challenges.

As the advanced reactor competition plays out in this century, it is essential to keep competitive supplier countries from boosting their marketability by racing to the bottom on nuclear safeguards and security.

Russian and Chinese LWR Export Targets



Nuclear Export Status:

- ⚛ Operating
- ⚒ Under construction
- 📄 Contracted
- ⇥ Ordered
- ⊗ Deal canceled
- ☑ Broad agreements or memorandums of understanding

Russia

1. Algeria ☑
2. Armenia 📄
3. Bangladesh ⚒
4. Belarus ⚒
5. Bolivia ☑
6. Bulgaria* ⊗
7. China ⚛ ⚒ ⇥
8. Czech Rep. ☑
9. Egypt ⇥
10. Ethiopia ☑
11. Finland 📄
12. Ghana ☑
13. Hungary ⇥
14. India ⚛ ⚒ 📄 ⇥
15. Indonesia ☑
16. Iran ⚛ 📄
17. Kazakhstan ☑
18. Laos ☑
19. Myanmar ☑
20. Nigeria ☑
21. Saudi Arabia ☑
22. Slovakia ⚒
23. South Africa ☑
24. Tunisia ☑
25. Turkey ⚒
26. Ukraine ⚛ ⚒
27. Uzbekistan ⇥
28. Vietnam ⊗

China

1. Pakistan ⚛ ⚒
2. Romania ⇥
3. U.K.** 📄

Both

1. Argentina*** ☑

* Bulgaria set to revive the canceled nuclear plant. New ROSATOM offer has followed suit.

** Financing and technical support for Hinkley C.

*** Chinese technical delegation to visit Argentina to meet with local suppliers.

Source: IAEA PRIS, WNA Reactor Database

Nuclear Governance Recommendations

Advanced reactors are not yet ready for deployment but likely will be within a decade. This will create a major technological competition among large and powerful geopolitical rivals. It is essential that an effective governance structure for these reactors be developed in advance of their deployment and that it be subject to continuous improvement.

A lack of public confidence in the safety, security, and safeguarding of advanced reactors will significantly impact public acceptance and the willingness of nations and companies to invest in and deploy these technologies. There are two suggestions for steps that can be taken in these areas:

1

Support Nuclear Newcomers

There is a need to significantly strengthen the support that is provided to countries considering nuclear power for the first time. The IAEA has a number of programs in place to assist nations with preparation for the deployment of LWRs, but even with that support there is a need to further develop and sustain the educational, training, regulatory, and emergency response capabilities in these nations. The situation becomes even more complex because not even advanced nuclear nations have deployed or operated these reactors as part of their nuclear fleet. This argues for an IAEA Plus process that would bring supplier nations, the purchasing countries, and the IAEA into a deeper discussion of how to ensure the long-term safety, security, and proliferation resistance of these reactors.

2

Create a New Nuclear Alliance

The evolution of nuclear technology supply is beginning to tilt heavily in the direction of state-backed companies in authoritarian nations - Russia and China. If they become the dominant suppliers of the 21st century, it will have a number of potentially significant implications. It may relegate the U.S. and its allies like France, Japan, and South Korea to subcontractor status or may effectively knock them out of the nuclear supply business. One option is for traditional nuclear allied nations to band together to create a Next Generation Nuclear Alliance.

This will require the U.S. and its allies to think about how to collaborate rather than compete against one another in the global nuclear market. This will be a very difficult, complex process, but the changes in the international environment require that the idea be seriously considered.

One way to think about it is that some nations are better at the hardware of nuclear power – hot production and supply lines – and others are better at the software – design, governance, operations, regulation, and education. But this combination of attributes will be very attractive to nations seeking nuclear power. This new alliance does not need to exclude Russia and China, but how it could incorporate them will be a major challenge for all sides.

This alliance could take the following actions:

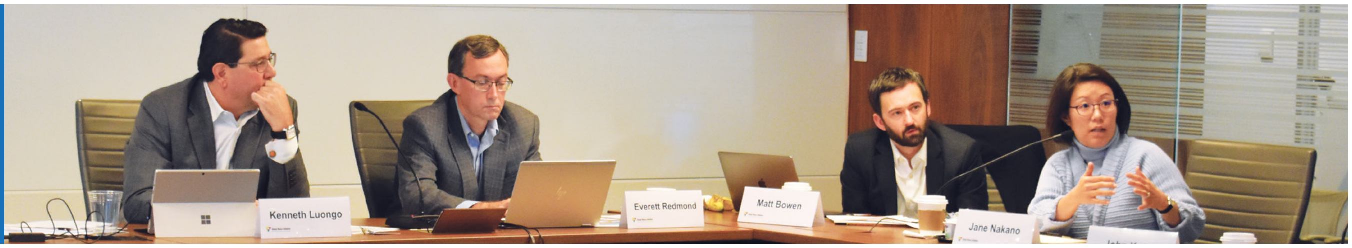
- Develop the nuclear governance and regulatory regime for advanced reactors within the next 3 to 5 years and present it to the IAEA for consideration.
- Collaborate on advanced reactor design, development, and demonstrations.
- Support and supplement the IAEA's work to prepare newcomer nuclear nations by providing funding and experts for education and training to prepare the market and support advanced reactor deployment and operations.
- Consider pooling contributions from national export financing institutions to support alliance member and third country nuclear projects.
- Expand outreach to the investment community to draw together private and public funding for technology innovation and project development.
- Focus on the socially responsible contributions that nuclear power can make in the 21st century and ensure that the governance system is continuously improved to support those objectives.

Working Group Members

We gratefully acknowledge the members of the GNI working group, a distinguished panel of 16 experts from the nuclear industry, environmental, diplomatic, and energy communities, and global security organizations with decades of first-hand management and policymaking experience on these critical issues.

- Dr. Todd Allen, Senior Visiting Fellow, University of Wisconsin and Third Way (U.S.)
- Amb. John Bernhard, Ambassador to the IAEA from Denmark (retired) (Denmark)
- Amb. Kenneth Brill, Ambassador to the IAEA from the U.S. (retired) (U.S.)
- Armond Cohen, Co-founder and Executive Director, Clean Air Task Force (U.S.)
- Kirsty Gogan, Co-founder and Global Director, Energy for Humanity (U.K.)
- Caroline Jorant, President, SDRI Consulting; Former Director for Non-Proliferation and International Institutions, AREVA (France)
- Jessica Lovering, Director of Energy, The Breakthrough Institute (U.S.)

Above: GNI Working Group members met for a series of workshops in Washington, D.C. from 2017-2018.



- Kenneth N. Luongo, President, Partnership for Global Security; Former Senior Advisor to the U.S. Secretary of Energy for Nonproliferation Policy (U.S.)
- Melissa Mann, President, URENCO USA, Inc. (U.S.)
- Dr. Richard Meserve, Senior of Counsel, Covington and Burling; Former U.S. Nuclear Regulatory Commission Chairman (U.S.)
- Jane Nakano, Senior Fellow, Energy and National Security Program; Center for Strategic and International Studies (U.S.)
- Dr. Anita Nilsson, President, AN & Associates; Former Director of Nuclear Security at the IAEA (Sweden)
- Dr. Everett L. Redmond II, Senior Technical Advisor, New Reactors and Advanced Technology, Nuclear Energy Institute (U.S.)
- Richard Rosenzweig, Former Chief Operating Officer, Natsource; Former Chief of Staff, U.S. Department of Energy
- John Stewart, Director of Policy and Research, Canadian Nuclear Association (Canada)
- Dr. Tatsujiro Suzuki, Professor, Director of Research for Nuclear Weapons Abolition, Nagasaki University; Former Vice Chair of the Atomic Energy Commission of Japan (Japan)

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Above: Guest experts attended each workshop to provide insights on key issues.

Second row, far right: Armond Cohen, Co-founder and Executive Director, Clean Air Task Force. The GNI Working Group is indebted to Armond for suggesting the analysis in this report.

Endnotes

1 "SPECIAL REPORT Global Warming of 1.5 ºC." The Intergovernmental Panel on Climate Change. Accessed March 29, 2019. https://www.ipcc.ch/sr15/.

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5 The countries most prominently identifying nuclear power as part of their Paris commitment were China and India.

6 The following projects highlight differing opinions on the subject - "The Solutions Project." The Solutions Project. Accessed March 29, 2019. https://thesolutionsproject.org/ ; Jacobson, Mark Z., et al. "100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World." Joule 1, no. 1 (September 6, 2017): pp. 108-21. Accessed March 29, 2019. https://www.cell.com/joule/fulltext/S2542-4351(17)30012-0 ; POWERING EARTH 2050: Is California's 100% Renewable Strategy Globally Viable? Directed by UCLA IoES. YouTube. February 24, 2016. Accessed March 29, 2019. https://www.youtube.com/channel/UC_iW_KvXMd7-hJb8yrDgI3A.

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Global Nexus Initiative Results

Since its formation in 2015, GNI has produced a series of policy papers on the intersection of nuclear power, climate, and security issues based on workshops and discussions with dozens of experts from around the globe. These reports have identified critical issues, developed innovative approaches, and formulated clear recommendations for action.

Nuclear Power for the Next Generation: Addressing Energy, Climate and Security Challenges (May 2017) In a major report summarizing the first two years of its work, GNI concludes that it will be extremely difficult, if not impossible, to meet the goals of the Paris Climate Agreement without a significant contribution from nuclear power, and it will be daunting to deploy nuclear on the scale needed and with the public confidence required unless significant changes are made in the way the technology is brought to market and governed.

Evolving Nuclear Governance for a New Era (April 2017) The global nuclear governance system is facing a series of new challenges that require effective responses. GNI calls for a strengthening of the system through realistic continuous improvement, a demonstrated commitment to norms and standards by nuclear suppliers and users, and a greater appreciation of nuclear power as a geopolitical tool.

A Framework for Advanced Nuclear Reactor Development: Policy and Issues (September 2016) The next generation of nuclear reactors are at a critical crossroads. GNI explains that near-term demonstration projects; advanced licensing procedures; and enhanced safety, security, and safeguards measures are critical if the next generation of reactors are to inspire public confidence, enable commercial success, and meaningfully contribute to climate goals.

The Role and Responsibility of Nuclear Power in a Carbon Constrained World (December 2015) Achieving the international community's goal of limiting global temperature increases requires a significant transformation in the way the world produces and consumes energy. In this report, GNI urges policymakers to recognize the contribution of nuclear power to reducing global carbon emissions.

For more information on these reports and GNI's accomplishments, please visit **www.globalnexusinitiative.org.**

www.globalnexusinitiative.org

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Formed in 2015, the Global Nexus Initiative (GNI) brings together for the first time leading experts from the nuclear industry, nuclear security, diplomatic, and environmental communities to examine the complex challenges posed by the intersection of climate change, energy demand, and global security. GNI is co-sponsored by the Partnership for Global Security and the Nuclear Energy Institute.

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