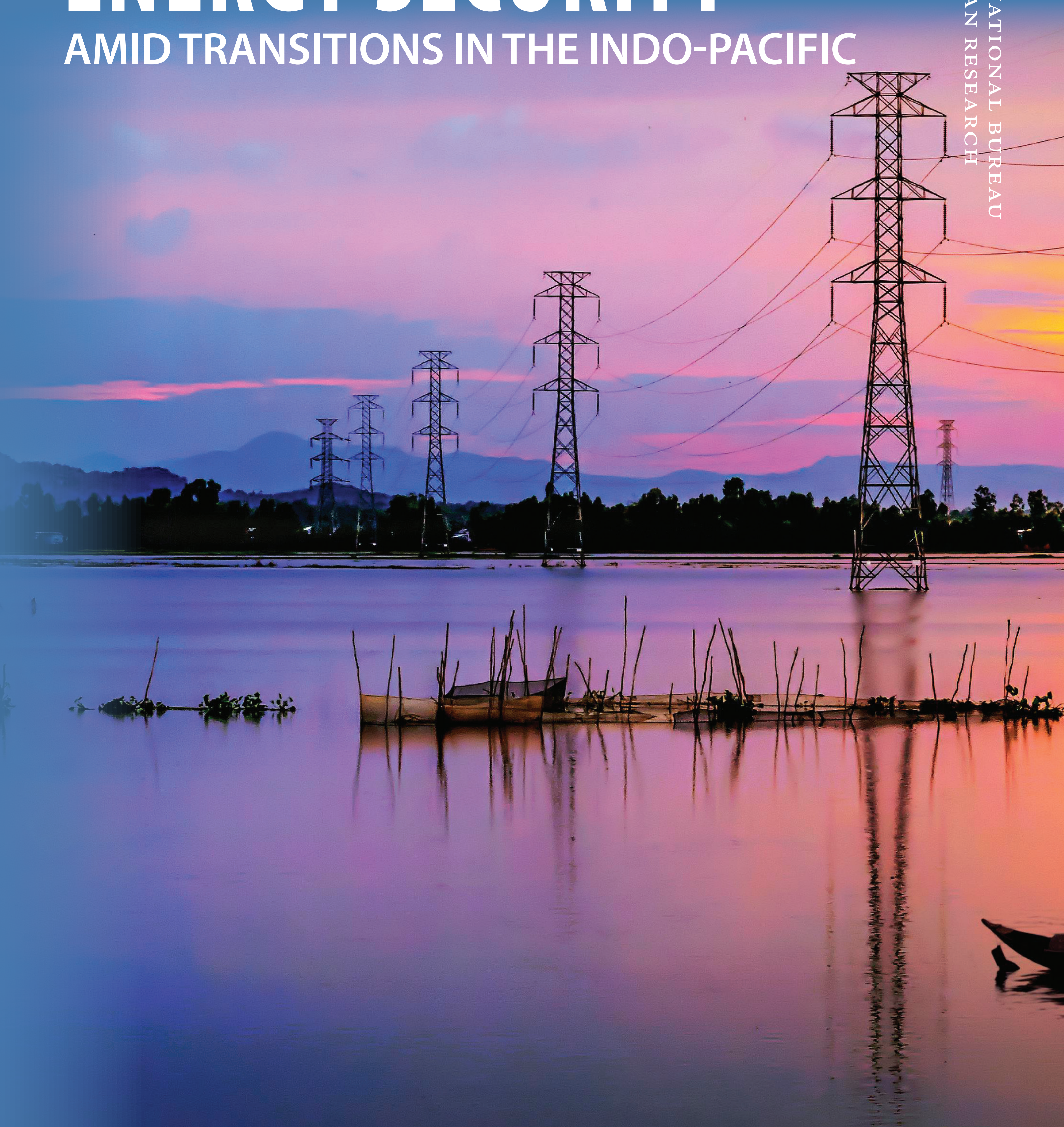
RESTORING ENERGY SECURITY

AMID TRANSITIONS IN THE INDO-PACIFIC



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RESTORING ENERGY SECURITY

amid Transitions in the Indo-Pacific

Kyung-Jin Boo, Fan Dai, Mikkal E. Herberg, and Victor Nian

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FOREWORD

In the wake of Russia's invasion of Ukraine in February 2022, countries around the world suffered oil and gas price shocks, power outages, and other supply chain disruptions due to the geopolitical crisis. The 2023 Energy Security Program analyzed these vulnerabilities and their implications for energy security in the Indo-Pacific. The 2024 Energy Security Program went a step further and analyzed several catalytic clean energy technologies and industry trends that have the potential to strengthen regional energy security while also advancing the clean energy transition. In the near term, technologies and industry developments, such as carbon removal technologies (CRTs) and nuclear power, will allow countries currently relying on imported fossil fuels to decrease their emissions. In the medium term, developments in clean hydrogen and related technologies will enable countries to transition to alternative—including domestic or regionally sourced—energy fuels.

Across the Indo-Pacific, countries and companies are developing a range of technologies and energy industries to enable the transition to low-carbon and more secure energy systems. The 2024 Energy Security Program assessed the most salient of these critical technologies and industries in the region: clean hydrogen, CRT, and nuclear energy technology such as small modular reactors (SMRs). This iteration of the program analyzed the state of the development, deployment, and commercialization of these technologies; policies and market structures enabling their utilization; and the energy security and geopolitical implications of their evolution.

One of the key technological developments for improving energy security in the region is the advancement of a clean hydrogen and ammonia industry. Green and blue hydrogen—that is, hydrogen produced from renewable energy and from natural gas with carbon capture, utilization, and storage (CCUS), respectively—could provide a clean fuel source for energy-intensive heavy industries and hard-to-abate transportation sectors like aviation, marine, and heavy-duty vehicles. It could also contribute critical energy storage and transport capabilities amid the accelerating transition to renewable energy. Nearly every major country in the region is pursuing its own hydrogen strategies as a key tool in its path to net-zero emissions.

Development, deployment, and scaling of CRTs are key to many net-zero strategies of major economies in the near term. CRTs such as CCUS, direct air capture, and enhanced mineralization (or CO_2 mineralization), will be critical for countries with net-zero pledges that have counterproductively reinforced reliance on fossil fuels in the wake of the 2022–23 energy crisis. Bringing these technologies to industrial scale and commercial viability will enable countries to utilize existing fossil fuels—such as liquefied natural gas—and corresponding infrastructure, while concurrently implementing policies to transition to cleaner energy sources.

The expansion of nuclear power generation in developing Asia, along with the potential renaissance of nuclear power among the developed countries in the region, is also an emerging trend for many countries as they seek potential zero-emission energy sources to meet respective climate targets. With some notable exceptions, such as Taiwan, SMRs are gaining traction in most places as public perception of nuclear energy continues to shift toward acceptance.

The technologies that are critical to each of the focus areas of the 2024 Energy Security Program—clean hydrogen, CRTs, and SMRs—have significant implications for both energy and economic security in the Indo-Pacific. Each focus area could broaden the range of energy sources available and reduce the risks of energy shortages and disruptions during the long-term transition to net zero. Not only are these technologies central to the energy transition strategies of all the major countries in the region. There are also dimensions of strategic national competition over which countries might come to dominate the technologies and supply chains for new industries.

To assess the progress of these key technologies and their place in the energy security strategies of key regional countries, the National Bureau of Asian Research (NBR) commissioned essays by three scholars with expertise in these technologies and the Indo-Pacific region. The preliminary results were reviewed and discussed at a virtual workshop on July 24, 2024. Participants included senior representatives from the U.S. government and foreign policymaking communities as well as leading industry and geopolitical experts. Based on feedback from the session, the authors have strengthened their research and findings for this report.

In the first essay, Victor Nian from the Centre for Strategic Energy and Resources in Singapore assesses prospects for the deployment of SMRs in Asia and their role in the region's future energy mix. He concludes that, given their small size and scalability, SMRs "could be an attractive option for the developing ASEAN economies, addressing concerns about a reliable and sustainable electricity supply." Moreover, the passive safety designs could make future plants more "Fukushima-proof."

In the second essay, Fan Dai from the University of California, Berkeley, analyzes the potential role of CCUS technologies in Asia's clean energy transition. The leading countries in this area are the United States and China, reflecting their large fossil fuel industries and the need to find ways to facilitate a transition away from the fossil fuel sector while minimizing the extent of future stranded assets and resources. Nevertheless, CCUS faces significant headwinds in the region, including high costs, unstable energy policy environments in some countries, and geopolitical tensions that make cross-border collaboration on carbon capture, as well as distant storage infrastructure, very difficult.

In the third essay, Kyung-Jin Boo from Seoul National University reviews the role of hydrogen in South Korea's clean energy strategy. He argues that South Korea's strategic investments and policies demonstrate a strong commitment to developing a sustainable hydrogen economy for both climate policy and energy security reasons. But significant challenges still need to be overcome, including high production costs, relatively immature technology, and large investments necessary for hydrogen infrastructure development. He recommends continued government support, international collaboration, and further efforts to advance hydrogen technology.

The 2024 Energy Security Program was made possible by the guidance, contributions, and support of a number of organizations and individuals. We are grateful to Chevron, ConocoPhillips, Freeport-McMoRan, the Japan External Trade Organization, Mitsubishi Heavy Industries, and Monitor Deloitte for their sponsorship of NBR's energy programming. We would also like to thank the many experts who contributed their insights on the energy transitions of China, Japan, India, and Southeast Asian countries, particularly those who attended the workshop. Lastly, working tirelessly behind the scenes to develop the program and refine the policy discussions were NBR's Tom Lutken, Samantha Funez, and Audrey Mossberger.

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Small Modular Reactor Technologies and Floating Nuclear Power Plants for the ASEAN Region

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NOTE: This essay draws on the author's previously published analysis in "Progress in Nuclear Power Technology," in *Encyclopedia of Sustainable Technologies*, ed. Martin A. Abraham (Cambridge: Elsevier, 2017); "The Prospects of Small Modular Reactors in Southeast Asia," *Progress in Nuclear Energy* 98 (2017): 131–42; and "Technology Perspectives from 1950 to 2010 and Policy Implications for the Global Nuclear Power Industry," *Progress in Nuclear Energy* 105 (2018): 83–98.

EXECUTIVE SUMMARY

This essay considers the prospects for the deployment of small modular reactors (SMRs) and floating nuclear power plants (FNPPs) in Southeast Asia and explores their potential role in the region's future energy mix.

MAIN ARGUMENT

Nuclear energy is not new to the Association of Southeast Asian Nations (ASEAN) region. Although there are currently no operating nuclear power plants in any ASEAN country, several have developed and maintained nuclear research or power programs. Indonesia, the Philippines, Thailand, and Vietnam all started working with research reactors in the 1950s and 1960s, and Malaysia started in 1982. Due to concerns over rising energy security and climate objectives, several ASEAN member states are once again interested in developing nuclear energy capabilities. In recent years, the nuclear power industry has made significant progress in terms of both technology and its business model. With their small size and scalability, SMRs and FNPPs could be an attractive option for the developing ASEAN economies, addressing concerns about a reliable and sustainable electricity supply. Given the upfront financial commitment and the negative public perception of traditional large nuclear reactors, SMRs are more financially viable and pose fewer risks. The emergence of FNPPs in this decade likewise represents significant progress in the nuclear power industry by creating a mobile energy bank that could disrupt the traditional approach focused on land-based nuclear power projects.

POLICY IMPLICATIONS

The realization of a sustainable energy future powered by SMRs and FNPPs in the near term is dependent on four critical factors:

- Innovative SMR or FNPP technologies should be advanced as early as possible with cooperation throughout the industrial supply chain.
- Industry standards need to be established for SMR technologies to ensure some degree of compatibility and interoperability for energy production.
- User countries must be committed to adopting and scaling up SMR or FNPP technologies to enjoy the benefits of economies of scale.
- "Green passage" for transportable SMRs and FNPPs is required to facilitate safe and efficient mobility of these technologies for nearshore, offshore, and maritime applications.

Home to around 10% of the world's population, the rapidly growing Association of Southeast Asian Nations (ASEAN) region is shaping many aspects of the global economic and energy outlook.[1] The notion of nuclear energy is not new to this region. Although there is currently no operating nuclear power plant in any ASEAN country, several have developed and maintained nuclear research or power programs since the 1960s.[2] Indonesia, the Philippines, Thailand, and Vietnam all started working with research reactors in the 1950s and 1960s, and Malaysia started in 1982. The Bataan Nuclear Power Plant in the Philippines started construction in response to the 1973 oil crisis and was the first nuclear power plant ever constructed in the ASEAN region, though it was never fueled or operated due to a change in presidential administrations.

In 2013, both the International Energy Agency and the Asian Development Bank projected a dire situation in which Southeast Asia would become a net energy importer around 2030–35.[3] Due to concern over rising energy security and climate objectives, several ASEAN member states are interested in developing nuclear energy capabilities.[4] While no official announcement of confirmed nuclear milestones has been made by any country, a regional prefeasibility study concluded that the five aforementioned member states are the frontrunners to establish nuclear power programs and to commit to nuclear energy.[5]

Vietnam previously expressed explicit interest in building modern commercial nuclear power plants with support from the Russian state nuclear energy corporation Rosatom. An initial four units of Rosatom's VVER-1200 reactors were planned in Ninh Thuan Province, which were to be followed by models from Japan and South Korea in other provinces.[6] However, the plan was eventually deferred indefinitely in 2016 in favor of cheaper alternatives, especially coal.[7] In 2020, there were indications that Vietnam was seeking to revive its plans to develop nuclear power amid dwindling natural resources that could lead to electricity shortages. A draft power plan by the Ministry of Industry and Trade envisaged building nuclear power plants with a capacity of 1,000 megawatts electric (MWe) by 2040 and 5,000 MWe by 2045.[8] The following year, the ministry proposed the development of nuclear energy on a small scale after 2030 in its Power Development Plan 2021–2030.[9]

In 2022 the Philippines became the only ASEAN member state that has declared a civilian nuclear power program. During the campaigning period, then presidential candidate Ferdinand Marcos Jr. indicated his support for the outgoing administration's initiative and his intention

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[1] International Energy Agency (IEA), "Southeast Asia Energy Outlook 2019," October 2019, https://iea.blob.core.windows.net/assets/47552310-d697-498c-b112-d987f36abf34/Southeast_Asia_Energy_Outlook_2019.pdf.

[2] ASEAN Centre for Energy, "Civilian Nuclear Energy," Fact Sheet, 2020, https://aseanenergy.org/publications/civilian-nuclear-energy-factsheet.

[3] IEA, "Southeast Asia Energy Outlook 2013," 2013, https://iea.blob.core.windows.net/assets/a4f224b1-9bee-46c4-8fa5-9ceccbd615b4/SoutheastAsiaEnergyOutlook_WEO2013SpecialReport.pdf; and *Energy Outlook for Asia and the Pacific* (Manilla: Asian Development Bank, 2013), https://www.adb.org/sites/default/files/publication/30429/energy-outlook.pdf.

[4] Victor Nian and S.K. Chou, "The State of Nuclear Power Two Years after Fukushima—the ASEAN Perspective," *Applied Energy* 136 (2014): 838–48.

[5] ASEAN Centre for Energy, "Pre-Feasibility Study on the Establishment of Nuclear Power Plant in ASEAN," Report, May 2, 2018, https://aseanenergy.org/publications/pre-feasibility-study-on-the-establishment-of-nuclear-power-plant-in-asean.

[6] "Nuclear Power In Vietnam," World Nuclear Association, June 10, 2020, https://world-nuclear.org/information-library/country-profiles/countries-t-z/vietnam.aspx.

[7] Karen Mesina, "Vietnam's Nuclear Implosion: Is the Final Decision a Giant Leap Backwards?" Asian Power, November 2016, https://asian-power.com/project/in-focus/vietnams-nuclear-implosion-final-decision-giant-leap-backwards.

[8] "Vietnam Is Seeking a Return to Nuclear Power," Vietnam Insider, July 9, 2020, https://vietnaminsider.vn/vietnam-is-seeking-a-return-to-nuclear-power.

[9] "Vietnam Proposes Developing Nuclear Power on Small Scale," Malaysian National News Agency, March 15, 2022, https://www.bernama.com/en/news.php?id=2062152.

to pursue the program once in power. The Philippines is considering reviving its previously mothballed power plant in Bataan Province, with a potential capacity of 621 MWe, as well as other technologies, including designs for both conventional large-scale reactors and small modular reactors (SMRs). The considerations of SMRs are mainly driven by their enhanced safety, smaller footprint and upfront capital commitment, and modularity with standardization for future cost reductions. Now that Marcos has been elected president, it is likely that the country's nuclear program will move ahead.

Since 2014, Russian vendors have been assisting Indonesia with the development of its indigenous 10 megawatt thermal (MWt) experimental, noncommercial power reactor using high-temperature gas-cooled reactor technology. Here, too, Russia's Rosatom is playing a key role and has undertaken the conceptual design of a high-temperature reactor (HTR). National Nuclear Energy Agency of Indonesia (BATAN) has also signed an agreement with China Nuclear Engineering Corporation (CNEC) on the development of HTR technology with the goal of constructing a small HTR in Kalimantan and Sulawesi beginning in 2027. In August 2015, Rosatom and BATAN signed a cooperation agreement on the construction of floating nuclear power plants (FNPPs) that could be deployed in Gorontalo Province on the island of Sulawesi.[10] ThorCon, a start-up company focusing on the development of molten salt reactors (MSRs) on floating barges, represents the FNPP contender in Indonesia. In 2016, President Joko Widodo declared that a political decision to pursue nuclear power would be made by 2025 should alternative energy sources prove inadequate to meet the country's growing energy demand.[11] Subsequently, in 2019 the International Atomic Energy Agency (IAEA) was invited by the Indonesian government to undertake an Integrated Regulatory Review Service follow-up mission, as Indonesia's New and Renewable Energy Bill was being drafted. The bill is now being discussed as part of the parliament's national legislative program for 2020–24. Most recently, in 2022, Indonesia unveiled the Grand National Energy Strategy as a centerpiece of its G-20 presidency. It envisages that a nuclear power plant could begin operations in 2049 to provide 35,000 MWe by 2060.[12]

In Singapore a 2012 government prefeasibility study concluded that the then available nuclear power technologies were not suitable for deployment in the city-state due to concern over factors such as safety, security, and human resources.[13] However, a 2022 report commissioned by Singapore's Energy Marketing Authority concluded that in one out of the three scenarios proposed, nuclear energy could supply around 10% of the country's electricity needs, with the prospect of the commercialization of SMR technologies being one of the scenario's main drivers.[14] In 2024, Singapore and the United States signed a civil nuclear cooperation agreement, commonly known

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[10] "Nuclear Power In Indonesia," World Nuclear Association, updated April 19, 2024, https://world-nuclear.org/information-library/country-profiles/countries-g-n/indonesia.aspx.

[11] Oleh Safrezi Fitra, "'Jokowi minta peta jalan energi nuklir rampung tahun ini" [Jokowi Requests a Nuclear Energy Roadmap to Be Completed This Year], Katadata.co.id, June 23, 2016.

[12] "Indonesia Breaks Down Scenario to Achieve Carbon Neutrality in G20," Antara News, February 4, 2022, https://en.antaranews.com/news/213469/indonesiabreaks-down-scenario-to-achieve-carbon-neutrality-in-g20.

[13] Ministry of Trade and Industry (Singapore), "Nuclear Energy Pre-feasibility Study," Fact Sheet, October 2012, https://www.mti.gov.sg/-/media/MTI/Newsroom/Parliament-QandAs/2012/10/Second-Minister-S-Iswarans-reply-to-Parliament-Questions-on-nuclear-energy-pre-feasibility-study-in-/pre-fs-factsheet.pdf.

[14] Energy Market Authority (Singapore), "Charting the Energy Transition to 2050: Energy 2050 Committee Report," March 2022, https://www.ema.gov.sg/energy-2050-committee-report.aspx.

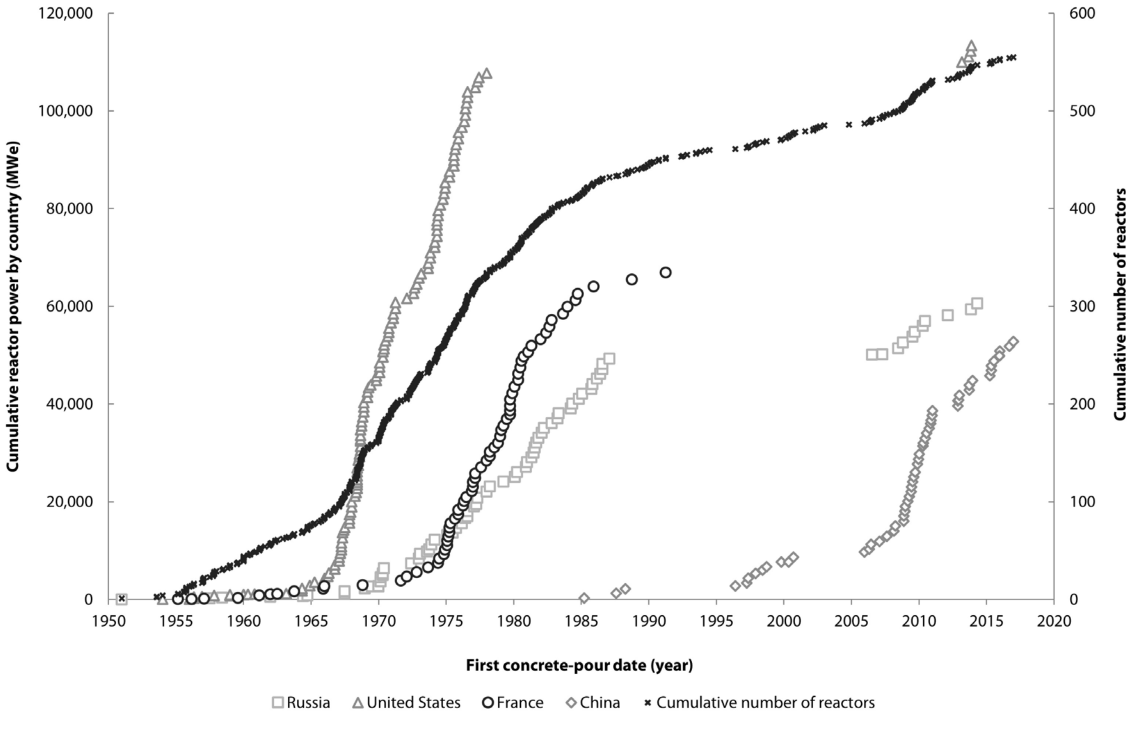
as a "123 Agreement" to enable Singapore's access to U.S. nuclear power technologies, resources, experts, and global partners.[15] However, it is not yet clear which vendors would be considered.

In anticipation and response to the need and plan for nuclear energy development in the ASEAN region, FNPP providers Seaborg, Core Power, and ThorCon have all established their presence to offer FNPPs based on MSR technology. The Centre for Strategic Energy and Resources is currently undertaking an independent cost-benefit analysis of SMRs, including FNPPs, in enabling a greater clean energy ecosystem. The idea is to create an offshore floating multi-utility complex (or an offshore floating clean energy hub) that capitalizes on the enhanced safety and user-centric features of advanced SMRs to power clean energy facilities. The concept aims to help enable private-public partnerships in strategic offshore infrastructure projects that could accelerate national and global energy transitions.

State of Nuclear Power Technology Development

Since the operation of the first nuclear power plant in the 1950s, the world has gone through two development phases in nuclear reactor technologies (see **Figure 1**). The first phase was

FIGURE 1 Trends in the global nuclear reactor market in major nuclear states



SOURCE: Victor Nian, "Technology Perspectives from 1950 to 2010 and Policy Implications for the Global Nuclear Power Industry," *Progress in Nuclear Energy* 105 (2018): 83–98.

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[15] "Joint Statement on the Signing of the United States–Singapore 123 Agreement 31 July 2024," Ministry of Foreign Affairs (Singapore), July 31, 2024, https://www.mfa.gov.sg/Newsroom/Press-Statements-Transcripts-and-Photos/2024/07/20240731--123A-Joint-Agreement.

the development of exploratory Generation I reactors. The second was the rapid scale-up of commercially proven Generation II reactors in the North American and Western European markets. At its peak, nuclear energy supplied nearly 18% of the world's total electricity. Just as the world looked to nuclear as one of the promising energy options, the early success of nuclear energy was plagued by severe accidents, such as Three Mile Island and Chernobyl, as well as other issues, such as cost escalation, completion-time overruns, lawsuits, and negative public perception.[16]

The second phase was also characterized by a shift toward East Asian markets through technology transfer from and strategic partnerships with Western technology vendors. Light-water reactor (LWR) technologies from Westinghouse, Combustion Engineering, General Electric, and OKB Gidropress made important contributions to the globalization of modern nuclear power technologies in the process.[17] Just as the nuclear industry regained momentum toward a "nuclear renaissance" in the 2000s, the incidents at Fukushima Daiichi Nuclear Power Plant in Japan in 2011 caused by a devastating earthquake and tsunami became yet another speed bump for the development of the nuclear energy market.

Driven by the need for safer and more reliable nuclear power technologies to address national energy and climate objectives, the third and fourth phases of development progressed almost in parallel. The third phase is characterized by the development of radically improved Generation III and evolutionary Generation III+ reactor systems featuring more efficient use of uranium fuel, a much longer operational lifespan of 60 years and beyond, and significant improvements in safety (such as passive safety based on gravity or natural convection). The fourth phase is characterized by the development of innovative Generation IV reactor systems with state-of-the-art design of reactor systems and fuel options featuring reactor cores in a liquid state, high operating temperature, and a significantly reduced burden on spent fuel and radioactive waste management.[18]

An important innovative concept from the 1950s re-emerged in the third and fourth phases: the small modular reactor. SMRs are generally defined as reactors having a generating capacity of 300 MWe and below.[19] Since almost all SMRs feature a high level of passive safety or inherent safety designs—now with their smaller size potentially minimizing or avoiding the event of a "thermal run away" (which could lead to a meltdown) inside the reactor core—many observers have suggested that SMRs may help avoid an accident similar to the one that took place in Fukushima.

The benefits of SMRs also go far beyond being a "Fukushima-proof" technology. SMRs are poised to address most of the critical concerns associated with a nuclear power project, including cost, completion time, financing, flexibility, and adaptability to the local power markets.[20] They offer reduced upfront capital cost and are suitable for cogeneration and nonelectric applications such as hydrogen and ammonia production and water desalination. In addition, they offer options for remote regions with less developed infrastructure and the possibility for synergetic hybrid energy systems that combine nuclear and alternative energy sources, such as renewables.

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[16] Victor Nian, "Progress in Nuclear Power Technology," in *Encyclopedia of Sustainable Technologies*, ed. Martin A. Abraham (Cambridge: Elsevier, 2017).

[17] Victor Nian, "Technology Perspectives from 1950 to 2010 and Policy Implications for the Global Nuclear Power Industry," *Progress in Nuclear Energy* 105 (2018): 83–98.

[18] Ibid.

[19] IAEA, "Small Modular Reactors," https://www.iaea.org/topics/small-modular-reactors.

[20] Victor Nian, "The Prospects of Small Modular Reactors in Southeast Asia," *Progress in Nuclear Energy* 98 (2017): 131–42.

Going Small and Floating

Small Modular Reactors

Depending on the nuclear reactor and fuel designs, SMR technologies incorporate similar features to large reactors, such as pressurized water reactors (PWRs), including integral PWRs (iPWRs); sodium-cooled fast-neutron reactors (SFR); lead-cooled fast-neutron reactor (LFR); MSRs; high-temperature gas-cooled reactors (HTRs), including HTR pebble-bed modules (HTR-PMs); and many other types found in the IAEA database.[21] However, SMRs are fundamentally different in size and scale, potentially resulting in much smaller capacity but bringing the benefits of modularity, transportability, and most importantly enhanced safety.

Most of the global SMR technologies are still in the research and development stage and most of the activities are led by state-owned or well-established companies. Two of the most notable technologies currently in the demonstration phase are the Akademik Lomonosov (KLT-40S) developed by Rosatom and the HTR-PM developed by a consortium of China Huaneng Group, CNEC, and Tsinghua University. Several start-ups from other countries have now also joined the SMR market.

The development of small reactors dates back to the 1950s, when the United States and the Soviet Union both developed small reactors for military purposes. Under the U.S. Army Nuclear Power Program (1954–77), the United States developed eight units of small reactors ranging from 0.1–40 MWe. In particular, ML-1 was a 0.3 MWe mobile power plant with a water-moderated HTR fueled by high-enriched uranium. The reactor was about the size of a standard shipping container, which could be transported easily by truck or airplane and set up in twelve hours. The PM-2A reactor, running as a combined heat and power source for a remote arctic location, was designed to demonstrate the capability to assemble a nuclear power plant from prefabricated components. The 10 MWe MH-1A, fueled with low-enriched uranium (4%–7%), was the first FNPP and operated in the Panama Canal Zone from 1968 to 1977 on a converted Liberty ship.

Around the same time, the Soviet Union was also developing smaller reactors. The Joint Institute for Power and Nuclear Research (Sosny) in Belarus developed the 0.6 MWe Pamir-630D air-cooled nuclear reactor, which ran on 45% enriched uranium fuel and zirconium hydride moderator and drove a Brayton cycle gas turbine with dinitrogen tetroxide.[22] Prior to the Pamir-630D, a modularly designed PWR prototype, TES-3 (1.5 MWe), was developed with modules mounted on four heavy tank chassis. Each tank chassis was self-propelled so that the different modules could be mobilized for assembly onsite.

Land-Based SMR Technologies

Most SMR technologies currently in operation or in advanced stages of development are meant for land-based deployment (see **Table 1**). PWRs (including iPWRs) remain the preferred design for land-based SMRs. Both PWRs and boiling water reactors (BWRs) belong to the LWR family, arguably the most mature and proven nuclear power technologies. In the pursuit of Generation IV, SFRs and MSRs have become increasingly popular among start-ups.

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[21] IAEA, "Advanced Reactor Information System," https://aris.iaea.org.

[22] V.M. Paliukhovich, "Safe Decommissioning of Mobile Nuclear Power Plant," IAEA, October 2002, https://inis.iaea.org/collection/NCLCollectionStore/_Public/33/052/33052291.pdf.

TABLE 1 Selected land-based SMR technologies

Name	Capacity (MWe)	Type	Developer
VBER-300	300	PWR	OKBM Afrikantov, Russia
OPEN100	100	PWR	Energy Impact Center, United States
SMR-160	160	PWR	Holtec, United States; SNC-Lavalin, Canada
BANDI-60S	60	PWR	Korea Electric Power Corporation, South Korea
Rolls-Royce SMR	220–440	PWR	Rolls-Royce, UK
NuScale	77	iPWR	NuScale Power and Fluor, United States
SMART	100	iPWR	Korea Atomic Energy Research Institute, South Korea
RITM-200M	50	iPWR	OKBM Afrikantov, Russia
RITM-200N	55	iPWR	OKBM Afrikantov, Russia
ACP100	125	iPWR	China National Nuclear Corporation, China
CAREM25	27	iPWR	China Nuclear Energy Association, China; INVAP, Argentina
BWRX-300	300	BWR	GE Hitachi, United States
PRISM	311	SFR	GE Hitachi, United States
Natrium	345	SFR	TerraPower and GE Hitachi, United States
ARC-100	100	SFR	ARC with GE Hitachi, United States
Hermes prototype	<50	MSR-Triso	Kairos, United States
Integral MSR	192	MSR	Terrestrial Energy, Canada
Moltex SSR-W	300	MSR	Moltex, UK
HTR-PM	210	HTR	Institute of Nuclear and New Energy Technology, CNEC, and Huaneng, China
Xe-100	80	HTR	X-energy, United States
BREST	300	LFR	Research and Development Institute of Power Engineering, Russia

SOURCE: Victor Nian, "Progress in Nuclear Power Technology," in *Encyclopedia of Sustainable Technologies*, ed. Martin A. Abraham (Cambridge: Elsevier, 2017).

Floating Nuclear Power Plants

FNPPs or marine SMRs refer to SMRs designed to operate on a floating platform, such as a ship or barge located offshore or nearshore. Today, there are only four companies working on FNPPs (see **Table 2**). Russian and Chinese companies have adopted the proven PWR designs, and UK and Danish companies have embraced the innovative Generation IV MSR designs.

The KLT-40S was derived from the proven KLT-40 reactor used in icebreakers. Being an FNPP means that the KLT-40S can be mobilized to power remote communities, such as those in the Arctic, supplying 35 MW of electricity and up to 35 MW of heat for desalination or district heating.[23] The KLT-40S is designed with a uranium fuel burn-up of 45 gigawatt-day per tonne over a refueling

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[23] Victor Nian, "Nuclear Power Becomes Critical to Arctic Dominance," Oil Price, December 11, 2018, https://oilprice.com/Alternative-Energy/Nuclear-Power/Nuclear-Power-Becomes-Critical-To-Arctic-Dominance.html.

TABLE 2 Selected marine SMR technologies

Name	Capacity (MWe)	Type	Developer(s)	Main application
RITM-200M	50	iPWR	OKBM Afrikantov, Russia	Marine propulsion (icebreakers)
KLT-40S	35	PWR	OKBM Afrikantov, Russia	Energy production
ACPR50S	60	PWR	CGN, China	Energy production
m-MSR	200	MSR	Core Power, UK	Energy production and marine propulsion
CMSR	100	MSR	Seaborg Technologies, Denmark	Energy production
The Can	250	MSR	ThorCon, United States	Energy production
Unknown	Unknown	MSR	China State Shipbuilding Corporation, China	Marine propulsion (container ship)

SOURCE: Nian, "Progress in Nuclear Power Technology."

cycle of 3–4 years with onboard refueling capability and spent fuel storage. The operating lifetime is 40 years, with a 12-year operating cycle for major overhaul and spent-fuel offloading. The current design of the Akademik Lomonosov, a 21,500-ton barge, mounted with two KLT-40S reactor units, could become an economical option for cogeneration of power, heat, or hydrogen.[24]

The RITM series is considered the "flagship" SMR design in Russia.[25] Although the KLT-40S is currently in the demonstration stage, it will be replaced by the RITM-200M, which will become the commercial offering in FNPPs, or optimized floating power units (OFPUs).[26] The RITM-200M is a 50 MWe iPWR derived from the RITM-200 used in icebreakers with inherent safety features. OFPUs are designed with a servicing cycle of 10–12 years to avoid onboard storage of spent fuel with an operating lifetime of 60 years. RITM-200M units are much smaller than KLT-40S units and only require a 12,000-ton barge for a twin-mounted OFPU.

Announced in 2016, the ACPR50S produced by the China General Nuclear Power Group (CGN) is a 60 MWe marine PWR-based FNPP for powering isolated electrical grids such as offshore oil production fields and islands.[27] The ACPR50S is designed to be a conventionally constructed, flat-bottom, double-hull, and double-bottom barge. CGN's FNPP can be self-propelled to allow siting flexibility and to better reach remote locations. The reactor is designed for a refueling cycle of 2.5 years and a lifetime of 40 years. In December 2023 the state-owned China State Shipbuilding Corporation announced that its Jiangnan Shipbuilding division has developed a 24,000 TEU (twenty-foot equivalent unit) container ship using MSR as the source of energy for propulsion.[28]

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[24] Victor Nian and Sheng Zhong, "Economic Feasibility of Flexible Energy Productions by Small Modular Reactors from the Perspective of Integrated Planning," *Progress in Nuclear Energy* 118 (2020): 103106.

[25] "Small Nuclear Power Reactors," World Nuclear Association, February 16, 2024, https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.

[26] "Russia Develops Optimized Floating Power Unit for Hot Climate," Sea News, September 22, 2020, https://seanews.ru/en/2020/09/22/en-russia-develops-optimized-floating-power-unit-for-hot-climate.

[27] "ACPR Small Modular Reactor (SMR) of CGNPC," China General Nuclear Power Corporation, October 2016, https://nucleus.iaea.org/sites/INPRO/df13/Presentations/026_ACPR%20Small_Modular_Reactor_(SMR)_of_CGNPC_20161020-wanl.pdf.

[28] "CSSC Designs Containership Using Molten Salt Nuclear Reactor," *Maritime Executive*, December 5, 2023, https://maritime-executive.com/article/china-present-design-for-containership-using-molten-salt-nuclear-reactor.

By design, all FNPPs can be considered a floating offshore energy source for producing carbon-free electricity. All FNPPs can also deliver combined heat and power (CHP) supply for remote locations, such as offshore oil drilling platforms, offshore mining facilities, and coastal and isolated island communities. To achieve net-zero carbon emissions, FNPPs can work in synergy with offshore and onshore renewable energy to power future sustainable economic and industrial development. If maritime electrification gains strong momentum, FNPPs can also be transformed into offshore floating charging stations for fully electric oceangoing vessels and potentially other marine vessels and apparatus for scientific and strategic applications.[29]

The Advantages of SMRs and FNPPs

SMR technologies have several key advantages in comparison with conventional large nuclear reactors. First, design simplification incorporates passive mechanism improvements and greater design integration to reduce the number of components and hence interdependencies among systems. Next, standardization of the dominant or preferred design allows for the deployment of multiple units of the same design at multiple sites with minimal or no adaptation for different conditions at the sites. Furthermore, modularization and smaller size make the transport of modules and the reactor much easier than it is for large reactors. With aggressive modularization techniques tailored to local logistical constraints and transport standards, factory fabrication levels of 60%–80% could be achieved for SMRs with electrical power outputs below 300 MWe.[30] Modularization allows for standardization of major components, such as the reactor vessel, nuclear-critical valves and pipes, and other mechanical instruments to be built in a factory environment through batch production. This would also facilitate the implementation of advanced manufacturing techniques such as electron beam welding and diode laser cladding, powder-metallurgy hot isostatic pressing, and additive manufacturing.[31]

The priority is always to avoid explosions and meltdowns. Given that explosions occur because of pressurized reactor cores, cores operating at low atmospheric pressure such as the MSRs might be preferred. In the event of containment failure, radioactive materials (in heavy liquid form) would be deposited only locally rather than being carried across countries and continents by wind. Now with "portable" design associated with the FNPP concept, SMRs can add safety and efficiency assurance with autonomous operation without onsite refueling.[32]

Following the Fukushima nuclear disaster, the development of Generation IV reactors has gained momentum, especially the HTR, HTR-PM, and MSR technologies. The typical enrichment of U-235 in an LWR is 3%–5% with a refueling cycle of 18–24 months. In some of the Generation IV designs, such as MSRs, U-235 enrichment is increased to around 20% with a much longer

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[29] Jun Yuan and Victor Nian, "A Preliminary Evaluation of Marinized Offshore Charging Stations for Future Electric Ships," Asian Development Bank Institute, ADBI Working Paper, November 2020, https://www.adb.org/sites/default/files/publication/655471/adbi-wp1199.pdf.

[30] Clara Anne Lloyd, "Modular Manufacture and Construction of Small Nuclear Power Generation Systems" (PhD diss., Department of Engineering, University of Cambridge, 2019).

[31] Chris Lewis et al., "Small Modular Reactors: Can Building Nuclear Power become More Cost-Effective?" Ernst & Young, March 2016; and "Advanced Nuclear Technology: Demonstration of Powder Metallurgy-Hot Isostatic Pressing," Electric Power Research Institute, June 2018.

[32] Victor Nian and John Bauly, "Nuclear Power Developments: Could Small Modular Reactor Power Plants Be a "Game Changer"? The ASEAN Perspective," *Energy Procedia* 61 (2014): 17–20.

refueling cycle.[33] The goal of a long refueling cycle, especially in FNPPs, is to eliminate the need for onsite refueling, thereby offering additional assurance of safety and security.

Another notable design in the early R&D stage is the fast-neutron reactor (FNR) technology. Running on a fast-neutron spectrum with higher uranium enrichment, FNRs can use depleted plutonium (as a result of the uranium fission process) as additional fuel for the reactor, while addressing concerns over safeguards. Some FNR concepts feature a reactor core in liquid state or the use of liquid metal as an alternative primary coolant, such as liquid sodium, lead, or lead-bismuth.

Applications

The goal of SMR and FNPP technologies is to be user-centric and provide improved safety, efficiency, and economical operation. With a smaller footprint, SMRs offer more flexibility in siting the reactors. Given their transportability, inherent safety designs, and a potentially longer refueling cycle, SMRs can be deployed closer to the user in a decentralized manner, such as a micro grid or distributed grid concept for heat and electricity distribution.

Because they are small, SMRs and FNPPs offer flexibility to expand capacity. When planning for large reactor deployment, there needs to be significant upfront investments poured into the infrastructure development to accommodate the sudden increase in power-generating capacity in the range of a gigawatt to tens of gigawatts. The SMR concept allows capacity planning to start with the deployment of a small-scale MW range suitable for most remote or island communities. As the demand increases, more “power modules” or reactors can be deployed at the same site, possibly within the same containment. This ability to follow the increase in demand also allows flexibility and sufficient lead time for more economical infrastructure planning and expansion. When paired with energy storage systems or the more advanced power-to-gas concept, SMRs can be further transformed into “load-following” power supplies to manage the fluctuating demand.[8]

The development of FNPPs is beginning to alter the competitive landscape of the clean energy technology market. An FNPP is a MW-class mobile power bank that can be transported to the user location to provide around-the-clock carbon-free energy. In addition to the ability to supply offshore facilities, FNPPs can be connected to an onshore utility grid. The concept is to schedule the rotations of multiple ships at the point of energy consumption. Maintenance and refueling would be carried out in a shipyard, possibly away from the user location or country.

FNPPs can be operated in place of a physical onshore power plant without the need for heavy capital commitment upfront by the user. A proper scheduling of FNPPs can be arranged to ensure higher availability and allow for a flexible power purchase agreement between the vendor and the user in terms of the contractual period and quantity. At the same time, FNPPs relieve the user country from the responsibilities of operating a nuclear power plant, refueling, handling spent fuel, managing radioactive waste, and fulfilling other nonproliferation-related obligations.

As carbon-free CHP technology, SMRs and FNPPs could enable the much-anticipated hydrogen or ammonia economy. Revisiting the proposed SMR designs, while iPWRs are constrained by pressure limitations and thus operate in the range of 300–400 °C, other reactors can operate at much higher temperature levels. Liquid metal–cooled fast reactors are in the range of 400–600 °C, MSRs in the range of 600–700 °C, and HTRs in the range of 600–900 °C.[34] Since both ammonia

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[33] Nian, “The Prospects of Small Modular Reactors in Southeast Asia.”

[34] Nian, “Progress in Nuclear Power Technology.”

and hydrogen production require industrial-grade heat, MSRs and HTRs are plausible candidates to supply carbon-free process heat. More importantly, the small footprint and user-centric design approach allow these SMRs to be deployed close to industrial users, thereby reducing cost and improving the efficiency of the overall industrial system.

With SMRs operating as a multi-energy utility, the Indo-Pacific could rely on such advanced technologies to enable a sustainable hydrogen or ammonia economy. Especially in the case of hydrogen, where long-distance transport technology and large-scale storage infrastructure are still under development, SMRs and particularly FNPPs could offer a timely solution to produce hydrogen and ammonia either in existing facilities by providing heat and power or in offshore locations away from heavily populated areas to alleviate negative public perception. Depending on the distance from shore, FNPPs could still function as an offshore clean electricity supply to power onshore economic activities.

With the numerous safety and reliability considerations, SMRs and FNPPs can be designed for deployment at locations with extreme climate conditions, such as the polar regions. The advantages of a long refueling cycle—and possibly even no refueling over the power plant's lifetime—can eliminate the need for the user to handle radioactive fuel materials. More importantly, there will be no release of harmful pollutants or greenhouse gas emissions from SMRs or FNPPs, unlike with diesel generators. All these characteristics are important to ensure sustainability and energy access in less developed regions and off-grid communities in the Indo-Pacific, especially in areas where renewables are not the ideal option due to climatic conditions.

With technological innovation, compact SMRs could also emerge as a competitive CHP technology for extraterrestrial applications in the longer-term future. The enormous fuel and oxygen requirements for power-generation technologies relying on fossil fuel and the low energy density of hydrogen render them impractical for long-term applications beyond the surface of the Earth. The fuel and air requirements of SMRs are negligible compared with a fossil-fuel power plant. Extraterrestrial facilities and devices, such as the International Space Station and Mars rover, currently rely on photovoltaic systems for producing electricity, notwithstanding the use of isotope batteries. A combination of intermittency and limited electricity-generating capacity has been a technical barrier to carrying out energy-intensive research activities. The portability, onsite assembly, and self-contained feature of SMRs could appeal to leading economies in the Indo-Pacific, especially China, to explore the option of powering future space missions to Tiangong Space Station or Mars missions with SMR or vSMR (very small modular reactor) technologies. On that note, NASA has developed and demonstrated the Kilopower Reactor Using Stirling Technology (KRUSTY) with 10-kilowatt power output capacity for powering future space missions.[35]

Economics

The main reason for supporting nuclear energy development lies with its cost competitiveness in decarbonization from a whole-system perspective.[36] The economics of SMRs include four main considerations. First, SMRs have much smaller capacity, so the total upfront capital commitment

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[35] "Demonstration Proves Nuclear Fission System Can Provide Space Exploration Power," NASA, May 2, 2018, https://www.nasa.gov/press-release/demonstration-proves-nuclear-fission-system-can-provide-space-exploration-power.

[36] Organisation for Economic Co-operation and Development (OECD), Nuclear Energy Agency, "The Costs of Decarbonization: System Costs with High Shares of Nuclear and Renewables," 2019, available at https://inis.iaea.org/collection/NCLCollectionStore/_Public/50/015/50015393.pdf.

is significantly less than it is for a large nuclear reactor. Next, even though economies of scale might be less favorable to SMRs because their cost per unit of capacity is expected to be higher, this problem can be addressed through standardization, batch production in a factory environment, and repeat project implementation. Third, SMRs, especially advanced models, offer user-centric CHP or multi-energy-output applications that can further improve the economics of energy production. Fourth and finally, while the levelized cost of electricity generation from SMRs is likely to be higher than that from large reactors, SMRs can allow flexibility in financing and contractual arrangements.[37]

Beyond the economics of energy production, the early development of advanced Generation IV SMR technologies, such as HTRs and MSRs, offers industrialization opportunities. For newcomers with an established nuclear research program, there are opportunities to cooperate with promising start-ups to codevelop intellectual property relevant to the advanced Generation IV technologies or in nuclear power technology in general. Countries interested in developing indigenous reactor technologies can make long-term strategic plans to establish industrial supply chains and to test critical technologies that would sufficiently support the placement of future nuclear power plant projects onshore or offshore. All can be achieved through partnering with a state and an established nuclear power industry without being constrained by a type of nuclear reactor technology.

From the perspective of national energy planning, integrating SMRs and FNPPs into long-term energy plans offers additional options to develop a low-carbon or net-zero carbon economy. The advantages of SMRs would be particularly appealing in Southeast Asia or for countries with small or less developed grid infrastructures. Opting for SMRs and FNPPs could help alleviate concerns over stranded assets to keep up with the incremental demand, while also gradually replacing those older or obsolete assets to minimize the economic impact on the energy sector. If the ultimate market size and consistency in national nuclear policy are of concern, FNPPs could enable newcomers to benefit from an operating expenditure–driven approach to enjoy carbon-free electricity without worrying about upfront capital commitments, spent fuel and radioactive waste management, and other long-term obligations.

Conclusions

The nuclear power industry has made significant progress in terms of both technology and its business model. With their small size and scalability, SMRs and FNPPs could be an attractive option for the developing ASEAN economies, addressing concerns over a reliable and sustainable electricity supply. Their small generating capacity and the user-centric design enable significantly greater flexibility in energy system planning, especially in the context of a distributed multi-energy grid, combining electricity, heat, hydrogen, and other sources. The passive and inherent safety features, such as the HTR and MSR technologies, will also make future nuclear power plants "Fukushima-proof."

Given the heavy upfront financial commitment and the negative public perception of traditional large nuclear reactors, SMRs offer better project risk management and financial viability. Today, the nuclear reactor market has moved beyond the dominance of the traditional state-owned

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[37] Nian, "The Prospects of Small Modular Reactors in Southeast Asia."

or established technology vendors like Rosatom, CGN, Westinghouse, and Framatome. Entrepreneurial start-ups and joint ventures developing innovative SMR systems enable a broader choice of technologies for newcomers to consider, potentially in a vendor-neutral approach.[38]

The emergence of FNPPs in this decade likewise represents significant progress in the nuclear power industry by creating a mobile energy bank that potentially disrupts the traditional approach focused on land-based nuclear power projects. FNPPs are particularly important for economies and communities with small grid sizes or that are located in off-grid or remote areas because they can bring clean energy to the consumer without the need to pull thousands of kilometers of power cable or build mega-infrastructure to accommodate gigawatt-level grid capacity expansion. The FNPP as a mobile nuclear power plant enables a new business model, such as asset leasing, without the need for user involvement in refueling, spent fuel management, and radioactive waste disposal.

The realization of a sustainable energy future powered by SMRs and FNPPs in the near term is dependent on four critical factors. First, innovative SMR or FNPP technologies and solutions should be advanced as early as possible with cooperation throughout the industrial supply chain. Next, industry standards should be established among SMR technologies to ensure some degree of compatibility and interoperability for energy production. Doing so will help with the regulatory process. Third, user countries should be committed to adopting and scaling up SMR or FNPP technologies to enjoy the benefits of economies of scale. Finally, and most importantly, "green passage" for transportable SMRs and FNPPs is needed to facilitate safe and efficient mobility of these technologies for nearshore, offshore, and maritime applications.

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[38] Victor Nian et al., "Accelerating Safe Small Modular Reactor Development in Southeast Asia," *Utilities Policy* 74 (2022): 101330.

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The Emergence of Carbon Capture, Utilization, and Storage: Policy Implications for the Indo-Pacific

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EXECUTIVE SUMMARY

This essay explores the critical role of carbon capture, utilization, and storage (CCUS) in addressing energy security and achieving net-zero emissions within the Indo-Pacific region.

MAIN ARGUMENT

As Indo-Pacific nations industrialize, energy demand will rise, creating an urgent need to reduce carbon emissions without compromising economic growth. CCUS can serve as a transitional solution, reducing emissions from existing fossil fuel infrastructure while renewable energy capacity is developed. It thus offers a viable path to balance the clean energy transition with economic stability, especially in fossil fuel–dependent economies. However, the deployment of CCUS faces multiple challenges, including high costs, long development timelines, technological limitations, and a lack of regulatory frameworks in many Indo-Pacific nations. Additionally, political instability and regional geopolitical tensions further hinder the international collaboration needed to establish cross-border CO_2 transport and storage infrastructure.

POLICY IMPLICATIONS

- *Strengthen regulatory frameworks for CCUS*. Indo-Pacific countries should integrate CCUS into their climate commitments and energy transition policies. Developing clear regulations and standards for CCUS operations would provide a foundation for sustainable project development.
- *Encourage regional cooperation*. To overcome geographic and resource limitations, countries in the Indo-Pacific should work toward geopolitical stability and cooperative agreements, similar to the European Union's "networks and hubs" model, to facilitate shared CO_2 transport and storage solutions.
- *Increase financial incentives for CCUS*. Governments should introduce financial mechanisms such as subsidies, tax credits, and grants to lower the high costs associated with CCUS deployment. This would attract private investment and enable larger-scale adoption of these technologies.
- *Promote technological innovation and capacity building*. International partnerships involving the U.S., EU, and Asian countries could drive research and development to lower costs, improve technology, and develop an international certification system for CCUS carbon removal, facilitating a more robust CCUS infrastructure in the Indo-Pacific.

Carbon capture, utilization, and storage (CCUS) is a process that captures carbon dioxide (CO_2) emissions from sources like fossil-based power-generation plants or industrial facilities so that they will not enter the atmosphere. The CO_2 will either be used as feedstock in various applications to create products or services or be injected into deep geological formations for geological time periods (i.e., thousands of years). According to a report from the Intergovernmental Panel on Climate Change released in 2022, CCUS technologies, especially direct air carbon capture and storage and bioenergy with carbon capture and storage, are critical decarbonization strategies in most mitigation pathways. In a majority of global energy consumption scenarios with low greenhouse gas emissions, a considerable amount of CCUS is applied.[1]

Besides being an important strategy for decarbonization, CCUS can also help address energy security concerns. As much of the world industrializes and urbanizes, global energy demand will increase for the foreseeable future.[2] In addition, energy security is now a growing priority for governments around the world. Therefore, even though fossil fuel consumption is projected to peak by 2030,[3] it will be almost impossible to abandon fossil fuels in the next few decades because they are a reliable and stable source of energy for countries, and renewable energy capacity is insufficient in the near term. In this case, CCUS could play a key role in striking a balance between the clean energy transition and energy security. This is because retrofitting existing fossil fuel facilities with CCUS will significantly reduce carbon emissions, allow the facility operation to last longer, and ensure a reliable energy supply. Moreover, transitioning to a clean energy pathway that limits global warming to 2 °C or below will result in a substantial amount of unburned fossil fuel and stranded fossil fuel infrastructure, which is costly, especially for developing countries with limited financial resources.[4] CCUS retrofit offers an infrastructure asset protection strategy that could alleviate concerns about stranded investment and reduce the controversy around transitioning from fossil fuels to renewable energy.

The Current State of CCUS

CCUS development has gained significant momentum in recent years, driven by strengthened climate targets and policy support around the world. As of 2023, there are approximately 45 commercial CCUS facilities in operation globally, with a total annual capture capacity of more than 50 million tonnes (Mt) of CO_2. Nine large-scale CCUS facilities (with capture capacity of more than 100,000 tonnes of CO_2 per year, or more than 1,000 tonnes of CO_2 per year for direct air carbon capture and storage facilities) started operating in 2023, with five in the United States and four in China. There are currently over seven hundred CCUS projects in different stages of development across the value chain. In addition, according to estimates by the International Energy Agency (IEA), in 2023 the announced CO_2 capture capacity for 2030 increased by 35%,

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[1] Intergovernmental Panel on Climate Change (IPCC), *Climate Change 2022: Mitigation of Climate Change* (Geneva, 2022), https://www.ipcc.ch/report/ar6/wg3.

[2] "International Energy Outlook 2023—Table: World Total Primary Energy Consumption by Region—Energy Use: World," U.S. Energy Information Administration, https://www.eia.gov/outlooks/aeo/data/browser/#/?id=1-IEO2023&region=0-0&cases=Reference&start=2020&end=2050&f=A&linechart=Reference-d230822.21-1-IEO2023&ctype=linechart&sid=&sourcekey=0.

[3] International Energy Agency (IEA), *World Energy Outlook 2023* (Paris: IEA, 2021), https://www.iea.org/reports/world-energy-outlook-2023.

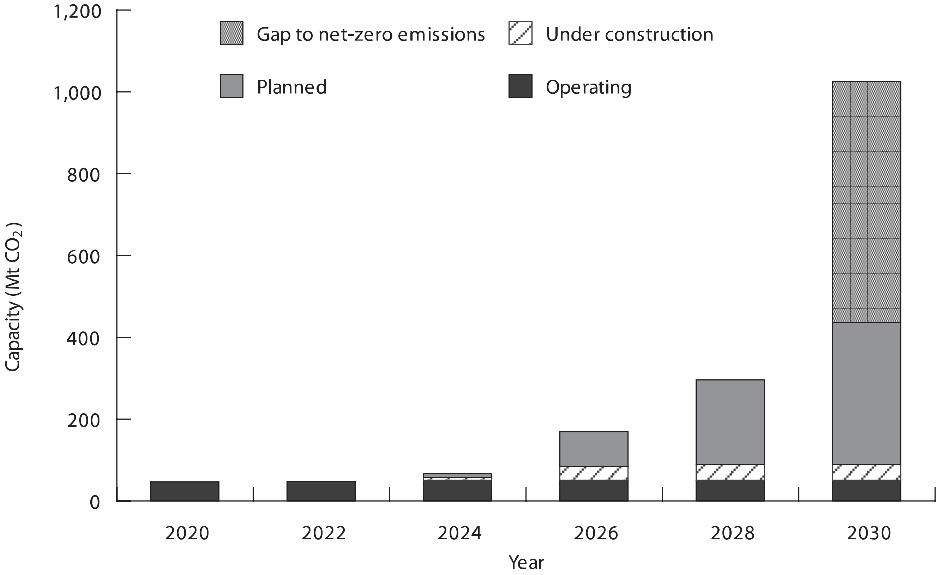
[4] Konstaintin Löffler et al., "Modeling the Low-Carbon Transition of the European Energy System—a Quantitative Assessment of the Stranded Assets Problem," *Energy Strategy Reviews* 26 (2019): 100422.

and the announced capacity for storage increased by 70%. This means that the total amount of CO_2 capture and storage capacity in 2030 is now projected to be around 435 Mt and 615 Mt, respectively.[5]

However, even though the momentum of CCUS development was strong and positive in 2023, it is still not enough. To achieve net-zero carbon emissions for the global energy sector, the CO_2 capture and storage capacity in 2030 will likely need to be around one gigatonne (Gt). The currently planned capture and storage capacity in 2030 is only around 40% and 60% of that number, respectively, assuming that all announced projects can be implemented (**Figure 1**).[6]

Multiple issues result from this gap. First, there are technology limitations. Although "CO_2 capture and subsurface injection is a mature technology for [natural] gas processing and enhanced oil recovery," CO_2 capture and utilization technology is less mature in power generation and industrial processes, such as cement and chemical production.[7] Cost is another problem. The cost of implementing CCUS projects is high, as CO_2 capture equipment consumes energy, while CO_2 transportation, injection, and monitoring require the building of new infrastructure such as pipelines.[8] In addition, despite the planned increases in storage capacity, CO_2 storage sites can take significant time to come online because assessing and developing potential sites is time-consuming

FIGURE 1 Scenario for current and planned global large-scale CO_2 storage capacity vs. net-zero emissions in the energy sector



SOURCE: IEA, CCUS Projects Database.

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[5] IEA, "Tracking Clean Energy Progress 2023," July 2023, https://www.iea.org/reports/tracking-clean-energy-progress-2023.

[6] IEA, "Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach," September 2023, https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach.

[7] IPCC, *Climate Change 2022*, 28.

[8] Edward S. Rubin, John E. Davison, and Howard J. Herzong, "The Cost of CO_2 Capture and Storage," *International Journal of Greenhouse Gas Control* 40 (2015): 380, 386.

and expensive. Even if the current targets are achieved, they will fall far short of the significant expansion of CO_2 storage capacity that is needed—from less than 50 Mt today to around 1 Gt by 2030, which is a more than twenty-fold increase. Without storage sites, developing other parts of the CCUS value chain, including CO_2 pipelines, is very difficult. Last but not least, CCUS faces many socioeconomic challenges, including potential negative environmental impacts, volatile international energy prices, low profits, and the lack of public support.[9]

Nonetheless, efforts are being made to increase CCUS capacity and promote technological innovation to lower the cost. Government funding for the development of CCUS facilities continues to increase.[10] According to a 2023 report from the IEA, "ongoing subsidy programs in the United States and Europe made over USD 20 billion available to CCUS projects."[11] New international and national initiatives have also been announced to provide policy support for CCUS development. For example, the Carbon Management Challenge program was launched at the April 2023 Major Economies Forum to accelerate the deployment of CCUS, and 22 countries have joined the program to date.[12] The European Parliament and the Council of the European Union reached a political agreement in early 2024 on the Net-Zero Industry Act, which outlines a comprehensive pathway for Europe to scale up CO_2 storage capacity to at least 50 Mt per year.[13] In addition, several technological innovations to reduce the cost of CCUS are being tested. For example, NET Power's 50-megawatt clean energy plant was equipped with a CCUS facility based on Allam cycle technology, which could significantly reduce capture costs.[14] Other areas of innovation include modular carbon capture systems, roadside CO_2 recovery devices, and direct air capture, according to a recent analysis of patent data.[15]

Countries Leading the Development of CCUS

Realizing the importance of CCUS in achieving carbon neutrality, many countries in the world are actively developing CCUS facilities. This section highlights the progress and summarizes the best practices of some countries.

The United States

To date, the United States has remained the world leader in CCUS development. There are fifteen CCUS facilities currently in operation in the United States, with the capacity to capture

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[9] Zoe Kapetaki, Jelena Simjanović, and Jens Hetland, "European Carbon Capture and Storage Project Network: Overview of the Status and Developments," *Energy Procedia* 86 (2016): 17.

[10] Global CCS Institute, "Global Status of CCS 2023: Scaling Up through 2030," November 9, 2023, https://www.globalccsinstitute.com/wp-content/uploads/2024/01/Global-Status-of-CCS-Report-1.pdf.

[11] IEA, "Tracking Clean Energy Progress 2023."

[12] "Frequently Asked Questions," Carbon Management Challenge, https://www.carbonmanagementchallenge.org/cmc/frequently-asked-questions; and "Participants," Carbon Management Challenge, https://www.carbonmanagementchallenge.org/cmc/participants.

[13] "Net-Zero Industry Act," European Commission, https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/green-deal-industrial-plan/net-zero-industry-act_en; and "Commission Staff Working Document for a Regulation of the European Parliament and of the Council on Establishing a Framework of Measures for Strengthening Europe's Net-Zero Technology Products Manufacturing Ecosystem (Net Zero Industry Act)," European Commission, June 19, 2023, 56, https://single-market-economy.ec.europa.eu/document/download/9193f40c-5799-4b1d-8dfc-207300e9610d_en?filename=SWD_2023_219_F1_STAFF_WORKING_PAPER_EN_V9_P1_2785109.PDF.

[14] IEA, "Tracking Clean Energy Progress 2023."

[15] Xiang Yu et al., "Trends in Research and Development for CO_2 Capture and Sequestration," *ACS Omega* 8, no. 13 (2023): 11643–64.

about 22 Mt of CO_2 per year, or 0.4% of the country's total annual CO_2 emissions.[16] Although CCUS is used only to a small extent today, the United States is actively growing its capacity. In 2023 alone, the total number of CCUS facilities operating, in construction, and in development increased by 73 compared with 2022.[17] If all projects are completed, they would increase the country's CCUS capacity significantly.

Strong policy intervention is providing the most important momentum behind the growth of CCUS in the United States. The U.S. government has been driving investment and leveraging incentives to support the development of CCUS. In 2021 the Infrastructure Investment and Jobs Act was enacted, providing over $12 billion for CCUS, including $2.5 billion for carbon storage, $8 billion for hydrogen hubs, and more than $200 million for CCUS technology development.[18] In addition, the United States enacted the Inflation Reduction Act in 2022, which enhanced the 45Q tax credit (a tax credit for carbon sequestration) to encourage investment in CCUS. The tax credit for every tonne of CO_2 captured and permanently stored in geological formations increased to $85 ($180 for direct air capture) "for qualified facilities or carbon capture equipment that meet certain prevailing wage and apprenticeship requirements," which could benefit industries such as chemicals, petrochemicals, steel, refineries, cement, and hydrogen.[19] Stimulated by these financial incentives, CCUS is growing in U.S. clean hydrogen and ammonia production, where it has become more economically attractive. In addition, guided by the Environmental Protection Agency's new rule released in April 2024, development of CCUS at fossil fuel power plants continued at 23 facilities, more than half of which are planned to start operation in the late 2020s.[20] Many CCUS projects in cement and steel, as well as one project involving direct air carbon capture and storage, are also in development.

Despite the rapid growth in investment, some problems remain to be addressed. In the United States, CCUS is still not economically competitive enough. Most of the current CCUS projects use captured CO_2 for enhanced oil recovery, where CO_2 is injected into geological formations to extract hard-to-recover oil. This practice can provide revenue, making a project profitable, but volatile international oil prices resulting from geopolitical realities could undermine the commercial viability of these CCUS projects.[21] In addition, permitting has become a major bottleneck for CCUS development amid a surge in the number of CCUS permit applications. For example, the rapid increase in Class VI wells (used for permanent CO_2 storage) and pipeline infrastructure permit applications requires a significant ramp up of federal capacity in terms of regulatory and technical expertise, and questions remain surrounding the timing of these permits. In this case, state primacy—an authority to administer injection wells delegated by the Environmental Protection Agency to certain states—could be an important tool to expand CCUS

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[16] Congressional Budget Office, "Carbon Capture and Storage in the United States," December 2023, 1, https://www.cbo.gov/system/files/2023-12/59345-carbon-capture-storage.pdf.

[17] Global CCS Institute, "Global Status of CCS 2023," 29.

[18] Infrastructure Investment and Jobs Act, Pub. L. No. 117–58 (2021), https://www.congress.gov/bill/117th-congress/house-bill/3684.

[19] Angela C. Jones and Donald J. Marples, "The Section 45Q Tax Credit for Carbon Sequestration," Congressional Research Service, CRS Report for Congress, IF11455, August 25, 2023, https://crsreports.congress.gov/product/pdf/IF/IF11455.

[20] "Greenhouse Gas Standards and Guidelines for Fossil Fuel–Fired Power Plants," U.S. Environmental Protection Agency, August 7, 2024, https://www.epa.gov/stationary-sources-air-pollution/greenhouse-gas-standards-and-guidelines-fossil-fuel-fired-power.

[21] Jonathan M. Moch, William Xue, and John P. Holdren, "Carbon Capture, Utilization, and Storage: Technologies and Costs in the U.S. Context," Belfer Center for Science and International Affairs, Harvard Kennedy School, January 2022, https://www.belfercenter.org/publication/carbon-capture-utilization-and-storage-technologies-and-costs-us-context.

regulatory capacity.[22] Finally, community engagement is critical for the deployment of CCUS projects. Unsuccessful outreach could lead to a lack of public acceptance and local opposition, thus resulting in the cancellation of CCUS projects, as has happened in the past.[23]

The European Union

Momentum for CCUS development continues in Europe. There are 119 CCUS projects in various stages of development in Europe, representing a 63% increase from 2022.[24] Many countries, such as Germany, France, Denmark, and the Netherlands, are committed to developing carbon management strategies.

As in the United States, government funding is critical for CCUS projects in Europe. Under the latest Innovation Fund round, the EU has issued over 3.86 billion euros to 41 clean technology projects, and 5 of these projects include a CCUS component.[25] In addition, the EU's Connecting Europe Facility program awarded almost 480 million euros to CO_2 transportation and storage projects.[26] Other significant CCUS project funding occurred in Denmark, Norway, the United Kingdom, and the Netherlands.[27] These funds enable the development of CO_2 transport pipelines in the EU, including the Aramis CCUS project in the Netherlands, the Porthos project to transport CO_2 from Rotterdam to the North Sea, and a 1,000-kilometer German onshore pipeline project by OGE that connects industries to the port of Wilhelmshaven.[28] Moreover, many declarations, agreements, and memoranda of understanding have been developed to facilitate international collaboration and deploy CCUS transport and storage projects. In particular, Norway has the largest number of bilateral agreements with other countries as it is looking to become the CO_2 storage hub for the EU.[29]

Besides leveraging funding, the EU has also enacted many policies to boost CCUS development. Some of the latest policies related to CCUS development are summarized in **Table 1**.

Lessons can be learned from the EU's experiences in developing CCUS capacity. First, a favorable policy framework and environment are essential for CCUS development. The emphasis on promoting CCUS in EU manufacturing, which can be seen in the policies summarized in Table 1, serves as a great example. There is, however, still a lack of regulation, but it is clear that the policy framework is growing. In addition, a successful business model tailored to local conditions is critical to boost CCUS development. The EU is a great example of the "networks and hubs" model, in which the traditional full value chain of CCUS (i.e., capture, transport, and storage) is broken up and different entities operate segments of the full value chain. This business model provides several benefits, such as spreading infrastructure costs and reducing commercial risk by

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[22] Patrice Lahlum, "EPA's Class VI Well Program Key to Deploying CO_2 Geologic Storage," Great Plains Institute, February 17, 2022, https://betterenergy.org/blog/epas-class-vi-well-program-key-to-deploying-co2-geologic-storage.

[23] Kapetaki et al., "European Carbon Capture and Storage Project Network: Overview of the Status and Developments."

[24] Global CCS Institute, "Global Status of CCS 2023," 43.

[25] "Innovation Fund: EU Invests €3.6 Billion of Emissions Trading Revenues in Innovative Clean Tech Projects," European Commission, Press Release, July 13, 2023, https://ec.europa.eu/commission/presscorner/detail/en/ip_23_3787; and "Projects Selected for Grant Preparation," European Commission, https://climate.ec.europa.eu/eu-action/eu-funding-climate-action/innovation-fund/calls-proposals/large-scale-calls/projects-selected-grant-preparation_en.

[26] "Connecting Europe Facility: Nearly €600 Million for Energy Infrastructure Contributing to Decarbonisation and Security of Supply," European Commission, Press Release, December 8, 2023, https://energy.ec.europa.eu/news/connecting-europe-facility-nearly-eu600-million-energy-infrastructure-contributing-decarbonisation-2023-12-08_en.

[27] Global CCS Institute, "Global Status of CCS 2023, 41.

[28] Ibid.

[29] Ibid., 48.

TABLE 1 Summary of the EU's latest CCUS policies

Policy	Time adopted/proposed	Policy summary
Carbon Removals and Carbon Farming Regulation	April 2024	This regulation creates the world's first voluntary certification framework for permanent carbon removal from CCUS projects. By mandating third-party verification, promoting data transparency, and streamlining certification processes, it facilitates investment in innovative CCUS technologies.
Industrial Carbon Management Strategy	February 2024	This strategy outlines a comprehensive approach for the EU to scale up industrial carbon management capacity through CCUS and the deployment of CO_2 transport and storage infrastructure. This strategy also covers the role that CCUS can play in decarbonizing the EU economy by 2030, 2040, and 2050.
Net-Zero Industry Act	March 2023	Stemming from the Green Deal Industrial Plan, this initiative "aims to scale up the manufacturing of clean technologies in the EU," including CCUS. Specifically, it outlines a comprehensive pathway for Europe to scale up CO_2 storage capacity to at least 50 Mt per year by 2030.
Green Deal Industrial Plan	February 2023	The purpose of this plan is to create a supportive environment to scale up the EU's manufacturing capacity of green technologies, which include CCUS.

SOURCE: "Carbon Removals and Carbon Farming," European Commission, https://climate.ec.europa.eu/eu-action/carbon-removals-and-carbon-farming_en; "European Parliament Adopts the EU Carbon Removals Certification Framework," Global CCS Institute, April 12, 2024, https://www.globalccsinstitute.com/news-media/latest-news/european-parliament-adopts-the-eu-carbon-removals-certification-framework/#:~:text=On%2010%20April%2C%20the%20European,certification%20framework%20for%20carbon%20removals; "Industrial Carbon Management," European Commission, https://energy.ec.europa.eu/topics/carbon-management-and-fossil-fuels/industrial-carbon-management_en; "Net-Zero Industry Act," European Commission, https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/ green-deal-industrial-plan/net-zero-industry-act_en; "Commission Staff Working Document for a Regulation of the European Parliament and of the Council on Establishing a Framework of Measures for Strengthening Europe's Net-Zero Technology Products Manufacturing Ecosystem (Net Zero Industry Act)," European Commission, June 19, 2023, 56; and "Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions: A Green Deal Industrial Plan for the Net-Zero Age," European Commission, February 1, 2023, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023DC0062.

allowing companies to focus on certain parts of the value chain, as well as generating economies of scale. Following this model, cross-border pipeline networks for the transport of captured CO_2 have grown. Finally, more R&D for improving CCUS is needed. Such efforts should seek to decrease CO_2 capture costs, improve operational safety, minimize negative environmental and health impacts, and identify the best available technologies for pollution prevention and CO_2 measurement.[30]

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[30] Adriana Reyes-Lúa and Kristin Jordal, "Industrial CO_2 Capture Projects: Lessons Learned and Needs for Progressing towards Full-Scale Implementation," CCUS Projects Network, December 17, 2020, 5, https://www.ccusnetwork.eu/files/sites/default/files/tg2_briefing-industrial-co2-capture-projects-lessons-learned.pdf.

China

Since the announcement of carbon peaking and carbon neutrality targets in 2020, the momentum of CCUS development has been growing in China. The country's primary form of CO_2 utilization is geological, such as enhanced oil and gas recovery. Yet biological utilization (such as using CO_2 for fertilizer) and chemical utilization (such as using CO_2 for building materials) have been increasing.[31] By the end of 2022, the number of CCUS pilot projects in various development stages had increased to roughly one hundred. Around half of these projects are currently in operation, with a total CO_2 capture capacity of over 4 Mt per year and a CO_2 injection capacity of more than 2 Mt per year, representing a 33% and 65% increase, respectively, from 2021.[32] In addition, CCUS facilities were installed in various industries, including power generation, steel, cement, chemical, oil and gas, and hydrogen. In particular, the number of projects in hard-to-abate industries, such as cement and steel, has significantly increased since 2022.[33]

China's government has leveraged various instruments to support CCUS development, including policies targeting R&D, investment, tax incentives, subsidies, and capacity building.[34] The number of CCUS-related policies from the central government has been increasing in the last decade, and targets for applying CCUS technologies to hard-to-abate industries such as steel and cement have been proposed in the Carbon Peaking Implementation Plan for Industry.[35] Many provinces have also released directives and guidelines to develop CCUS. There is a lack of concrete policy tools, though, as most of China's CCUS policies provide guidance without outlining specific regulations for different aspects of the CCUS value chain, such as technical standards for CCUS operation, commercial models, and operation monitoring. Meanwhile, financial support for CCUS is gradually increasing in China. Shenzhen and Beijing are providing grants or awards to encourage CCUS development.[36]

Despite rapid CCUS development in recent years, CCUS capacity in China is far from adequate to meet the need for achieving carbon neutrality targets. To meet China's 2060 target, CO_2 capture capacity should reach 1–2.5 billion tonnes per year. China's current capture capacity, however, accounts for only 0.16%–0.40% of the projected demand under the target.[37] Key issues for China to develop CCUS include the following.

A lack of clarity in policies. In China's CCUS policy spectrum, technical standards and guidelines for certain sections of the CCUS value chain remain scarce. In addition, CCUS development

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[31] "CCUS Progress in China—A Status Report," Global CCS Institute, March 17, 2023, 14, https://www.globalccsinstitute.com/wp-content/uploads/2023/03/CCUS-Progress-in-China.pdf.

[32] Ibid., 12.

[33] Ibid., 14.

[34] Wenjuan Dong et al., "The Second Year of the Tsinghua University–Harvard University Project on Technological Systems and Innovation Policy for Climate Neutrality: Synthesis Report," Institute of Climate Change and Sustainable Development, Tsinghua University, May 2024, 32, https://ncstatic.clewm.net/rsrc/2024/0611/19/0131d61cb3daac468daaac8807b5abc0.pdf.

[35] Ministry of Industry and Information Technology of the People's Republic of China, "Gongye he Xinxihua Bu, Guojia Fazhan Gaige Wei, Shengtai Huanjing Bu guanyu yinfa Gongye Lingyu Tan Da Feng Shishi Fangan de tongzhi" [Notice of the Ministry of Industry and Information Technology, the National Development and Reform Commission, and the Ministry of Ecology and Environment on Issuing the Implementation Plan for Carbon Peaking in the Industrial Sector], July 7, 2022, 12, 15, https://www.gov.cn/zhengce/zhengceku/2022-08/01/content_5703910.htm.

[36] Shenzhen Municipal Development and Reform Commission, "Shenzhen shi Fazhan he Gaige Weiyuanhui guanyu fabu 2024 nian Zhanlüexing Xinxing Chanye Zhuanxiang Jijin Xiangmu Shenbao Zhinan (Diyipi) de tongzhi" [Notice on the Release of the First Batch of 2024 Strategic Emerging Industry Special Fund Project Application Guidelines], April 9, 2024, https://fgw.sz.gov.cn/gkmlpt/content/11/11235/post_11235374.html#2659; and Beijing Municipal Bureau of Economy and Information Technology and Beijing Municipal Bureau of Finance, "Beijing shi Jingji he Xinxi Hua Ju Beijing shi Caizheng Ju guanyu yinfa 2024 nian Beijing Shi Gaojingjian Chanye Fazhan Zijin Shishi Zhinan de tongzhi" [Notice on Issuing the Implementation Guidelines for the 2024 Beijing High-Tech Industry Development Fund], January 19, 2024, https://www.beijing.gov.cn/zhengce/zhengcefagui/202401/t20240122_3542234.html.

[37] "CCUS Progress in China—A Status Report."

involves thirteen different governmental agencies. This results in communication inefficiency and a lack of clarity about regulatory responsibilities.[38] Therefore, it is necessary to craft long-term development plans for CCUS, promote research in technical standards, and establish a cross-departmental collaboration mechanism.

Spatial mismatch. In China the distance between CO_2 sources and storage sites is long. The major sources of emissions are located in eastern and southern China, but the majority of CO_2 storage sites are located in northeast and northwest China.[39] Addressing this issue requires the construction of a nationwide pipeline system, the progress of which has been slow. National-level planning and pilot pipeline projects in major CO_2-emitting areas could be a solution.

High cost and urgent need for more capacity. Although CCUS cost in China is lower than the average cost in other countries, it is still not low enough to make CCUS competitive with other carbon-reduction options, let alone enable large-scale deployment. However, there is an urgent need for increased CCUS capacity in China to avoid large amounts of stranded infrastructure in coal, cement, steel, and other industries.[40] Under these circumstances, China needs to promote cost-saving technology innovation and establish large-scale CCUS pilot projects to achieve economies of scale.

Slow progress to commercialization. Compared with the United States and Europe, China lacks successful commercial CCUS models. Existing CCUS business models in China are mostly decentralized and designed for single projects, which causes high operation costs and increases financial risk. Learning from other countries' experience, China could leverage governmental subsidies, tax credits, carbon removal certification, voluntary carbon trading, green electricity certificates, and other instruments to develop business models, such as regional CCUS hubs, and encourage the adoption of CCUS among companies.[41]

Policy Implications

As the world industrializes and urbanizes, global energy demand will grow rapidly for the foreseeable future, and energy security is becoming an increasingly important topic in every country's political agenda. CCUS can help provide energy security by facilitating a smoother and steadier transition from fossil fuels to renewable energy while avoiding large amounts of stranded fossil fuel infrastructure.

CCUS is particularly important for the clean energy transition of countries in the Indo-Pacific. In tandem with the region's rapid economic growth, energy demand has risen significantly. Many states are heavily reliant on fossil fuels to meet energy demand, including China and India, and fossil fuels will still account for a significant portion of their energy mix in the next decade. In order to achieve the net-zero emission targets, many countries in the region thus share an urgent need to quickly increase their CCUS capacity.

However, CCUS development in the Indo-Pacific is facing headwinds. First, economic considerations often take top priority in the political agenda over the clean energy transition and

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[38] Zhang Jiutian et al., "Several Key Issues for CCUS Development in China Targeting Carbon Neutrality," *Carbon Neutrality* 1, no. 17 (2022): 12.

[39] "CCUS Progress in China—A Status Report," 8.

[40] "Ibid.

[41] Xiping Wang et al., "Research on CCUS Business Model and Policy Incentives for Coal-Fired Power Plants in China," *International Journal of Greenhouse Gas Control* 125 (2023): 103871.

climate commitments,[42] and given the high cost of CCUS to date, countries might not have the willingness to significantly expand capacity. Another challenge is that many governments in this region, such as Indonesia, Cambodia, Malaysia, and Thailand, are operating in unstable political environments that make the expansion of CCUS capacity difficult. The time between project conception and commissioning of a CCUS facility is usually long, averaging about six years globally, and requires long-term planning.[43] Last but not least, geopolitical tension in the region hinders international cooperation on CCUS expansion. Many countries have limited domestic CO_2 storage capacity but are located close to suitable storage sites in neighboring countries' territorial waters. Although the EU's "networks and hubs" model could be applied to create a regional CO_2 transport and storage industry, geopolitical tension makes it difficult to construct cross-border infrastructure.

To leverage CCUS in the Indo-Pacific to facilitate the clean energy transition and address energy security concerns, it is important to fill the current gap in policy and regulation. A starting point could be integrating CCUS into countries' climate commitments and clean energy transition pathways, and then gradually developing related policies and regulations. Countries in the region must also promote geopolitical stability and seek peaceful solutions to potential conflicts that could be barriers to establishing a regional CO_2 transport and storage system. In addition, international collaboration among Asian countries, the EU, and the United States could promote technology innovation and policy dialogue, which would help lower CCUS costs, devise technical standards, and even facilitate an international CCUS carbon removal certification system.

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[42] Meredith Miller, "Realizing LNG's Potential to Meet Southeast Asia's Energy and Climate Goals," in "The Revenge of Energy Security: Reconciling Asia's Economic Security with Climate Ambitions," National Bureau of Asian Research, NBR Special Report, no. 105, November 2023, 50, https://www.nbr.org/wp-content/uploads/woocommerce_uploads/sr105_revengeofenergysecurity_nov2023.pdf.

[43] IEA, "Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach," 133.

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The Re-emergence of Energy Security and the Role of the Hydrogen Economy: A South Korean Perspective

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EXECUTIVE SUMMARY

This essay explores the role of the hydrogen economy in response to the recent re-emergence of energy security in the global and the South Korean context and considers the hydrogen economy as one of the most feasible options to build a sustainable energy system.

MAIN ARGUMENT

The re-emergence of energy security as a central concern has necessitated the exploration of alternative and sustainable energy sources. Hydrogen, as an energy carrier, has drawn significant attention due to its potential to decarbonize various sectors and ensure long-term energy security. South Korea's strategic investments and policies demonstrate a strong commitment to fostering a sustainable hydrogen economy. However, significant challenges remain, including high production costs, technological immaturity, and infrastructure development. Addressing these challenges requires continued government support, international collaboration, and advancements in hydrogen technologies. By leveraging the potential of the hydrogen economy, South Korea could enhance its energy security and contribute to global efforts to achieve a low-carbon, sustainable energy future.

POLICY IMPLICATIONS

- Hydrogen, as an energy carrier, offers a promising solution to decarbonize various sectors and ensure long-term energy security. South Korea's strategic investment supported by ambitious policies demonstrates a strong commitment to fostering a sustainable hydrogen economy.
- There is a need for a market for the excess electricity generated by renewable energy to be converted into hydrogen.
- A life-cycle hydrogen ecosystem based on hydrogen supply chains in South Korea is required for a full-fledged hydrogen economy to materialize, which would help address long-term energy security concerns while achieving carbon neutrality by 2050.
- International cooperation with countries that have advanced hydrogen technologies is another critical component of South Korea's strategy to accelerate the transition to a hydrogen economy.

Russia's invasion of Ukraine in 2022, coupled with fluctuating fossil fuel prices, geopolitical tensions, and the pressing need to address climate change, has rekindled global concerns about energy security. South Korea has been significantly affected by these challenges. Because the country imports nearly all of its energy resources, ensuring a stable and secure energy supply is paramount. In this context, the hydrogen economy presents a promising solution to achieve long-term energy security while promoting sustainability and reducing greenhouse gas emissions. In particular, the environment surrounding energy is changing rapidly both internally and externally. Major countries have declared ambitious targets for achieving carbon neutrality, and significant geoeconomic changes such as instability in global supply chains due to the Covid-19 pandemic and surges in resource prices are occurring simultaneously. Accordingly, every nation, including South Korea, is at a crossroads to choose the most optimal energy policy.

In this context, this essay investigates the recent developments in energy security as a result of changes in the global energy market supply and demand structure and the implementation of energy transition policies and seeks ways to respond to possible energy crises in the future. First, it examines the types and levels of crisis factors that need to be prepared for by analyzing changes in the trade structure and the impact of the oil and gas market from the implementation of global energy conversion policies. It then considers the case of South Korea and explores options for a system that can enhance the effectiveness of energy security policies in response to these crisis situations.

Comprehensive economic, ecological, technological, and political approaches are required to address the scope of energy security. Short-term, medium-term, long-term, and ultra-long-term step-by-step measures are needed. Furthermore, because achieving a stable power supply only with renewable energy is practically impossible, it is necessary to utilize various energy sources such as nuclear power and thermal power generation. In addition, it is necessary to support the energy security system by expanding the transmission and distribution network and improving the power market system to revitalize distributed energy.

In the long term, the hydrogen economy is expected to play an essential role in addressing both issues of energy security and climate change. Hydrogen can be utilized as a store of energy through hydrogen fuel cell (HFC) technology. Once captured and stored in a HFC, hydrogen gas bonds are broken, and the reaction creates transferable electricity with only the byproducts of heat and water. HFCs will secure energy storage means while expanding and preempting the blue hydrogen market to promote virtual power plants through sector coupling, decentralization, and the expansion of energy data networks. The South Korean government could pursue energy security by investing in emerging energy industries and markets. Energy security entails diversity: rationally adjusting the energy mix to ensure a balance between nuclear power, renewable energy, and traditional energy sources, while bolstering the grid's net dependable capacity, which is the reliable output of its power sources. Additionally, the private sector could revitalize the overseas resource acquisition industry, advance solar and wind energy, and promote the development of new energy sources aligned with the modern, data-centric world.

Energy Transition, Energy Security, and the Hydrogen Economy

Navigating an accelerated clean energy transition while prioritizing energy security will not be easy. The global crisis arising from Russia's invasion of Ukraine and the ongoing conflict in the Middle East demonstrate the complexity, severity, and unpredictability of energy crises. Unforeseen geopolitical and climate-driven challenges will continue to threaten domestic and international energy security. Amid this uncertainty, global players are recognizing green hydrogen's energy security advantages.[1] By replacing natural gas and other fossil fuels in difficult-to-decarbonize sectors, countries minimize their exposure to volatile export markets. Increasingly threatened by climate risks, governments are now designing transition strategies that rely on green hydrogen to promote energy resilience.[2]

Hydrogen is regarded as a next-generation energy source, is an eco-friendly energy source with no greenhouse gas emissions, can store large amounts of energy over long periods of time, and is a burgeoning energy source without regional bias. In this context, hydrogen is regarded as an important option for the energy transition in terms of both sustainable energy and energy security. Thus, it is expected to play a key role in achieving carbon neutrality by 2050.

Discussion on the close relationship between environmental issues and energy security is ongoing.[3] Currently, there is international consensus on the positive impact of hydrogen on energy security. The International Renewable Energy Agency confirmed in 2019 that hydrogen has the potential to enhance energy security by increasing the availability of domestic energy supplies and storage. While renewable energy sources are abundant around the world, they have some issues such as intermittency and storage, which can be solved by hydrogen. Hydrogen production and fuel-cell technology promises to introduce more flexibility into energy systems and can transfer energy produced from renewables to all sectors. This includes industry (refining plants, chemical production), heat or electricity production (heat demand in buildings, electricity sector gas turbines), and transportation (especially in long-distance transport, where HFC vehicles offer the same operational performance as conventional vehicles). Furthermore, green hydrogen facilitates the integration of renewable energy sources into energy systems. This can help manage intermittent and power storage challenges.[4] Green hydrogen, which is produced with renewable energy sources, will thus be key to driving the future hydrogen economy because it can be used in many industries in the future as a sustainable energy source that boasts zero-carbon emissions.

The International Energy Agency (IEA) has concluded that the global hydrogen production market will grow steadily by an average of 9.2% annually from $129.6 billion in 2020, reaching $201.4 billion by 2025. It also estimates that the cost of producing green hydrogen will decrease by around 50% by 2030, and that the cost of producing gray hydrogen will be much higher than

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[1] There are several different colors of hydrogen, with varying degrees of carbon emissions. Gray hydrogen is produced through a process of steam methane reforming or gasification where only the hydrogen is captured and stored, while the carbon dioxides are released into the atmosphere. Blue hydrogen also uses steam methane reforming or gasification, but the production process is coupled with industrial carbon capture, utilization, and storage processes, resulting in no emissions. Green hydrogen employs electrolysis using electricity from renewables to split water into hydrogen and oxygen. For further information, see Natalie Marchant, "Grey, Blue, Green—Why Are There so Many Colours of Hydrogen?" World Economic Forum, July 27, 2021, https://www.weforum.org/agenda/2021/07/clean-energy-green-hydrogen.

[2] Oleksiy Tatarenko et al., "Case Study: Storing Green Hydrogen to Safeguard Energy Security," RMI, Brief, 2023.

[3] Ewa Lazarczyk Carlson, Kit Pickford, and Honorata Nyga-Łukaszewska, "Green Hydrogen and an Evolving Concept of Energy Security: Challenges and Comparisons," *Renewable Energy* 219 (2023): 119410.

[4] Ibid.

that of producing green hydrogen by 2050.[5] This is welcome news, given that the biggest reason that hydrogen energy is not currently making a meaningful contribution to decarbonization is the relatively high cost of investment. Of course, for this scenario to become a reality, additional investment in hydrogen production, distribution, storage, and fueling facilities will be required.

Several steps must be taken to effectively expand the market for hydrogen. Above all, it is necessary to establish an environment that can create economic ripple effects by linking the value chain of hydrogen production, storage, transportation, and utilization with various existing industries. Special attention should be paid to diversifying energy sources and securing a stable energy supply chain. Hydrogen should be used as a key energy source in various sectors such as basic industrial materials, transportation, steel, oil refining, and chemicals, as well as for power generation, completing the hydrogen economy ecosystem.

The Case of South Korea

South Korea's annual energy consumption is ranked within the world's top ten. Due to the low availability of domestic energy sources and the country's high dependence on energy imports, it is an important national policy to strengthen energy security capabilities. Energy security refers to the ability to supply energy without interruption at an affordable price. Analysis of energy security–related indicators shows that, since 2000, energy sources used in South Korea have become more diverse, dependence on crude oil has decreased, and oil suppliers have been diversified.

Since the Paris Agreement, the government has been working toward the global goal of achieving carbon neutrality. However, following the economic recession caused by the Covid-19 pandemic, the energy market crisis caused by Russia's invasion of Ukraine, and several climate-induced weather events, the world is facing numerous complex challenges that are hindering the transition from fossil fuels to clean energy. Given South Korea's high level of dependence on energy imports, any instability in supply chains has a significant impact. Efforts to reach carbon neutrality will be an essential component of both achieving energy security and transitioning to clean energy.

Hydrogen has the potential to facilitate South Korea's response to both its energy security and sustainability challenges. The country currently has plans to further develop solar and offshore wind power. By using these resources to produce green hydrogen, it can reduce its dependence on imported fossil fuels and enhance its energy security. In this fashion, green hydrogen can help Sough Korea achieve its climate change commitments. The government has pledged to reduce the intensity of its greenhouse gas emissions by 40% by 2030 compared with 2018 levels. Green hydrogen can play a key role in achieving this target by replacing fossil fuels in sectors such as transportation, industry, and power generation.[6]

South Korea's pursuit of energy security has resulted in a rich knowledge base of development, expenditure, and resource diversification, yielding dynamic yet rapid economic progress. Leveraging its strengths, the country aims to lead the transition to a hydrogen economy and contribute to global carbon neutrality by enhancing energy security and

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[5] International Energy Agency, "The Future of Hydrogen: Seizing Today's Opportunities," Report, June 2019, https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf. The report was prepared by the IEA for the G-20 in Japan.

[6] Shalin Sheth, "The Impact of Green Hydrogen on India's Energy Security and Sustainability," *Times of India*, March 2, 2023.

coordinating efforts between nuclear power plants, offshore wind power, and carbon capture, utilization, and storage technology.

The Evolution of South Korea's Hydrogen Economy Policy

Recognizing the value of hydrogen as both an energy source and a means of responding to climate change, the South Korean government has been promoting hydrogen policies since the early 2000s (see **Table 1** for a list of policies since 2019).[7] But the hydrogen economy was not highlighted as a policy priority until it appeared as one of three major strategic investment areas in the Innovative Growth Strategy Investment Direction in August 2018. After that, the government announced the Hydrogen Economy Revitalization Roadmap in January 2019, and in February 2020 the National Assembly enacted the Hydrogen Economy Promotion and Hydrogen Safety Management Act to institutionalize the hydrogen economy. Based on this law, the Hydrogen Economy Committee was launched in July 2020.

The Hydrogen Economy Revitalization Roadmap envisioned South Korea becoming a leader of the global hydrogen economy by supplying hydrogen fuel cells and hydrogen-powered vehicles (see **Table 2**). The legal foundation was also established in 2020 by enacting the Hydrogen Economy Act, which contains regulations and safety standards for the hydrogen industry. The First Basic Plan for Implementing the Hydrogen Economy was launched during the 5th Hydrogen Economy Committee in November 2022 and included three roadmaps: the Creation of Clean Hydrogen Ecosystem, the Strategy to Promote the World's No. 1 Hydrogen Industry, and the Strategy for the Future of Hydrogen Technology.[8]

As the government works to reach carbon neutrality by 2050, the strategy to develop the hydrogen economy is being revised and supplemented accordingly. Through the First Basic Plan for Implementing the Hydrogen Economy, hydrogen supply and demand targets for 2030 and 2050 have been set, and numerous strategies and tasks have been proposed. With various demonstration projects and research currently underway, the hydrogen industry is steadily expanding.[9] However, progress is still in its early stages, and further legal and policy measures to promote private investment are essential.

The government has also emphasized R&D to realize carbon neutrality and transition to a hydrogen economy by establishing a basic carbon-neutral national plan at the Carbon Neutrality Green Growth Committee in 2023.[10] The level of domestic hydrogen production technology remains at 75% of that of most advanced countries. This could be improved to better address energy security concerns as well as improve industrial competitiveness, which is essential to survive in the global hydrogen market.

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[7] In 2005 the South Korean government established the Comprehensive Master Plan for Hydrogen Economy as a foundation for the country's hydrogen economy.

[8] Office for Government Policy Coordination (South Korea), press release, November 9, 2022.

[9] The First Basic Plan for Implementing the Hydrogen Economy announced a detailed implementation strategy for the life-cycle ecosystem of clean hydrogen. The plan set domestic clean hydrogen supply and demand targets of 3.9 and 27.9 million tons of hydrogen by 2030 and 2050, respectively, and prepared four strategies and fifteen tasks to achieve them.

[10] Presidential Commission on Carbon Neutrality and Green Growth, "National Basic Plan for Carbon Neutrality and Green Growth," April 12, 2023.

TABLE 1 Policies of the hydrogen economy in South Korea

Year	Policy and legislation	Key points
January 2019	Hydrogen Economy Revitalization Roadmap	• Called for South Korea to become a global leader in the hydrogen economy, with hydrogen cars and fuel cells as two major axes. • Proposed the hydrogen economy as a growth engine of innovative technology and a driving force of eco-friendly energy. • Included policy directions, goals, and implementation strategies of hydrogen production, storage, transportation, and utilization to revitalize the hydrogen economy by 2040.
April 2019	Hydrogen Standardization Strategy Roadmap	• Proposed international standards focusing on areas where South Korea can lead technology (20% acquisition of international standards). • Established national standards that conform with international standards. • Called for the deployment of products and services with guaranteed performance and safety through Korean Standards certification for core components.
October 2019	Implementation Strategy of Hydrogen Demonstration City	• Called for the development of a healthy and clean city where citizens experience urban innovation while using hydrogen as the main energy source by establishing a hydrogen ecosystem (hydrogen production-storage-mobility-utilization).
	Future Auto Industry Development Strategy: 2030 National Roadmap	• Focused on hydrogen vehicles and electric vehicles. • Put forth a strategy for South Korea to become a global automotive leader by 2030. • Called for South Korea to accelerate domestic distribution and provide the global market with eco-friendly vehicles. • Established a strategy to transform the ecosystem for HFC vehicles based on private investment worth 60 trillion won.
	Hydrogen Technology Development Roadmap	• Set goals for hydrogen production, including raising demand to 5.26 million tons per year (2040) to secure price competitiveness at the level of fossil fuels (3,000 won per kilogram by 2040). • Proposed the completion of a hydrogen life-cycle technology development base by 2030, including refueling infrastructure and domestic production of refueling equipment and materials with high overseas dependence.
December 2019	Comprehensive Measures for Hydrogen Safety Management	• Established a safety system on par with global leaders. • Established intensive management of hydrogen charging stations, production bases, and fuel cells. • Created a sustainable safety ecosystem and spread safety culture through communication and cooperation.

Table 1 continued

Year	Policy and legislation	Key points
February 2020	Enactment of Hydrogen Law	• Provided a legal basis for securing the safety of low-pressure hydrogen products such as water electrolysis facilities (using renewable energy) and hydrogen fuel facilities.
July 2020	Strengthening Competitiveness of Hydrogen Industry Ecosystem	• Fostered global leading companies in each field of production, transportation, and utilization and prepared related policies so that various companies can participate in the hydrogen economy. • Proposed a stable hydrogen supply plan for each region and created a regional ecosystem by strengthening cooperation between the central government, local governments, and local innovation organizations. • Took the domestic hydrogen industry ecosystem to the next level by promoting specific overseas projects and to lead the hydrogen economy.
	Launching of Hydrogen Economy Committee	• Tasked with establishment, implementation, inspection, and evaluation of the Hydrogen Economy Basic Plan as a hydrogen economy control tower and establishment and promotion of major hydrogen economy policies. • Designated the Hydrogen Convergence Alliance as an agency dedicated to promoting the hydrogen industry, Korea Gas Corporation as an agency dedicated to hydrogen distribution, and Korea Gas Safety Corporation as an agency dedicated to hydrogen safety.
February 2021	Enforcement of the World's First Hydrogen Act	• Included a system for promoting the implementation of the hydrogen economy, fostering and supporting hydrogen-specialized companies, promoting the installation of hydrogen charging stations and fuel cells, creating software and hardware infrastructure, dedicated institutions, safety management, and supplementary regulations. • Composed of two pillars: fostering policy to realize the hydrogen economy and regulatory policy for hydrogen safety management.
November 2021	Basic Plan for Implementing the Hydrogen Economy	• Set goal of 27.9 million tons of hydrogen demand in 2050 to be met by clean hydrogen. • Set goal of replacing the fossil fuel–based power generation with hydrogen.
	5th Hydrogen Economy Committee	• Introduced the Clean Hydrogen Ecosystem, the Strategy to Promote the World's No. 1 Hydrogen Industry, and the Strategy for the Future of Hydrogen Technology.
December 2022	Revision of Hydrogen Law	• Included mandatory sale and use of clean hydrogen, the introduction of clean hydrogen portfolio standards, and definitions of hydrogen power generation and hydrogen power generator.
December 2023	6th Hydrogen Economy Committee	• Introduced the Operation Plan for Clean Hydrogen Certification Scheme; the Promotion Strategy of Hydrogen Industry for Materials, Parts, Equipment; the Operation Plan of National Hydrogen-Focused Laboratory; and Measures to Expand Deployment of Hydrogen Fuel Cell Vehicles

SOURCE: Korea Institute for Industrial Economics and Trade, "Strategy for Hydrogen Industry Promotion to Implement Carbon Neutral," Research Report, July 2022; and author's own research.

TABLE 2 Targets of the Hydrogen Economy Roadmap

			2018	2022	2040
Targets	**Hydrogen vehicles** ***(export)*** ***(domestic)***		1,800 *(900)* *(900)*	81,000 *(14,000)* *(67,000)*	6,200,000 *(3,300,000)* *(2,900,000)*
	Hydrogen refueling stations		14	310	1,200
	Fuel cells	**Power generation** ***(domestic)***	307 MW (total)	1.5 GW *(1 GW)*	15 GW *(8 GW)*
		Homes/buildings	7 MW	50 MW	2.1 GW
	Hydrogen supply		130,000 tons/year	470,000 tons/year	5,260,000 tons/year
	Hydrogen price		–	6,000 won/kg	3,000 won/kg

SOURCE: Ministry of Trade, Industry and Energy.

NOTE: MW=megawatts; GW=gigawatts.

Nuclear Hydrogen

Nuclear power is another important source of hydrogen. Because it can reliably produce large-scale electricity and heat without emitting greenhouse gases, many countries, including the United States, France, and Japan, are actively developing nuclear technology that can be used to produce hydrogen. According to the Legislative Research Service, nuclear hydrogen has recently emerged as an important avenue for South Korea to achieve carbon neutrality and strengthen its energy security.[11]

South Korea already possesses world-class nuclear technology. Based on the capabilities developed so far, the country will strongly promote the powering-up strategy through nuclear power. While promoting the construction and export of new nuclear power plants, industrial growth engines and synergies are created through nuclear-linked industrial clustering. Nuclear energy is thus essential not just for the clean energy transition and energy security but for national economic development.

The Hydrogen Economy: Ecosystem Governance

The South Korean government has started to cultivate a "hydrogen economy ecosystem" in earnest by creating large-scale hydrogen demand in the power-generation and transportation sectors and establishing the world's largest hydrogen supply chain.[12] The realization of the hydrogen economy is becoming more important than ever as the instability of the energy supply chain has intensified due to the prolonged war in Ukraine. It is necessary to create large-scale hydrogen demand to drive the development of the hydrogen economy. In line with the expansion

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[11] National Assembly Research Service, "Emerging Nuclear Hydrogen in the Perspectives of Carbon Neutrality and Energy Security," June 13, 2024. The National Assembly Research Service mentioned in an analysis of the 2022 parliamentary audit issue that in South Korea "hydrogen production using nuclear is emerging as an important issue in terms of achieving carbon neutrality and strengthening energy security."

[12] Under the Hydrogen Economy Promotion and Hydrogen Safety Management Act, the Hydrogen Economy Committee is a hydrogen economy control tower composed of private experts, including ministers from eight related ministries, industry, academia, and organizations. According to the 5th Hydrogen Economy Committee, by "pushing for the creation of a 'hydrogen economy ecosystem' in earnest…. [h]ydrogen technology will be fully localized in 2030."

of hydrogen, the foundation for mass supply will be expanded by establishing a clean hydrogen production system that uses nuclear power. In addition, the committee announced the direction of the hydrogen economy policy in line with the new government's national task of "establishing a clean hydrogen supply chain and fostering the world's no. 1 hydrogen industry." The policy direction suggested three growth strategies: (1) expanding scale and scope, (2) developing infrastructure and institutions, and (3) advancing industry and technology in order to establish South Korea as the world's eminent hydrogen power.

Conclusion

The re-emergence of energy security concerns underscores the importance of transitioning to sustainable and secure energy sources. The hydrogen economy offers a viable means to address these concerns, providing flexibility, decarbonization, and enhanced energy resilience. South Korea's strategic investments and policies demonstrate a strong commitment to fostering a sustainable hydrogen economy. However, significant challenges remain, including high production costs, technological immaturity, and infrastructure development. Addressing these challenges requires continued government support, international collaboration, and advancements in hydrogen technologies. By leveraging the potential of the hydrogen economy, South Korea can enhance its energy security and contribute to global efforts to achieve a low-carbon, sustainable energy future.

Hydrogen is an essential factor in South Korea's clean energy future and is expected to make significant contributions to decrease carbon emissions from industrial development and improve the quality of life. First, South Korea can leverage its existing hydrogen-oriented factor endowments—like HFC vehicles and broader storage and production technology—to lead the global market. Second, it can rely on hydrogen to decarbonize various sectors, including power generation, transportation, industry, and buildings. Third, South Korea can improve national energy security by diversifying energy sources through the introduction of hydrogen. Hydrogen is a flexible and multipurpose energy carrier. In particular, green hydrogen produced by renewables and nuclear power can be stored, transported, and used in large quantities.

The South Korean government should promote its hydrogen policy by stabilizing electricity supply and demand, increasing efficiency, accumulating domestic technologies, fostering related industries, and stabilizing supply chains. Considering the global trend of countries focusing on hydrogen policy to respond to climate change, the South Korean government should emphasize the production and use of clean hydrogen, along with the development of related technologies. While aggressive supply targets that do not reflect technical uncertainty should be avoided, the government should continue its prioritization of developing the hydrogen economy.

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