ERIA Research Project Report FY2025, No. 12

Viet Nam's Transition Pathways: Technology and Innovation for Carbon Neutrality by 2050

Edited by

Soichi Morimoto

Seiya Endo

Rino Hirose

Hideaki Obane

Kei Shimogori

Atsutaka Yamada

Yu Nagatomi

Ichiro Kutani

Toshiyuki Sakamoto

Nobuo Tanaka

Fengjun Duan

Kentaro Noma

Daisuke Kiuchi

Han Phoumin

Economic Research Institute for ASEAN and East Asia

Viet Nam's Transition Pathways: Technology and Innovation for Carbon Neutrality by 2050

Economic Research Institute for ASEAN and East Asia (ERIA)
Sentral Senayan II 6th Floor
Jalan Asia Afrika No. 8, Gelora Bung Karno
Senayan, Jakarta Pusat 12710
Indonesia

ERIA Research Project Report FY2025. No. 12
Published in July 2025

Acknowledgements

This study is the result of collaborative efforts amongst institutions and experts supporting Asia's energy transition toward sustainable future. We would like to express our sincere gratitude to the Institute of Energy Economics, Japan (IEEJ), for their technical leadership and modelling expertise on carbon neutral scenario analysis. Special thanks go to Mr Nobuo Tanaka, CEO of Tanaka Global Inc. and Executive Director Emeritus of the International Energy Agency (IEA), and Dr Fengjun Duan, Senior Research Fellow at the Canon Institute for Global Studies (CIGS), for their strategic insights and continued guidance on in-depth nuclear energy analysis.

We also acknowledge the valuable input from Vietnamese stakeholders including the Central Policy and Strategy Commission (CPSC) and the Ho Chi Minh National Academy of Politics (HCMA) whose policy perspectives were essential in shaping this study. The support from the Economic Research Institute for ASEAN and East Asia (ERIA) provided the institutional foundation and regional policy relevance necessary to address Viet Nam's complex energy challenges.

Lastly, we thank all contributors who participated in the review process and provided feedback to improve the rigour and relevance of this report. Their collaboration and dedication have been instrumental in advancing the shared vision of a low-carbon, secure, and economically vibrant energy future for Viet Nam.

List of Project Members

Part 1: Carbon Neutral Scenario Analysis

Institute of Energy Economics, Japan

Soichi Morimoto, Senior Researcher, Climate Change and Energy Efficiency Unit

Seiya Endo, Senior Economist, Energy Data and Modelling Center

Rino Hirose, Economist, Energy Data and Modelling Center

Hideaki Obane, Senior Economist, Energy Data and Modelling Center

Kei Shimogori, Senior Researcher, Energy Security Unit

Atsutaka Yamada, Researcher, Climate Change and Energy Efficiency Unit

Yu Nagatomi, Manager, Energy Data and Modelling Center

Ichiro Kutani, Director, Energy Security Unit

Toshiyuki Sakamoto, Director, Climate Change and Energy Efficiency Unit

Economic Research Institute for ASEAN and East Asia

Kentaro Noma, Programme Manager on Energy

Daisuke Kiuchi, Chief Programme Manager on Energy

Han Phoumin, Senior Energy Economist

Part 2: Potential Utilisation of Nuclear Power in Viet Nam

Nobuo Tanaka, CEO, Tanaka Global, Inc. / Executive Director Emeritus, The International Energy Agency

Fengjun Duan, Senior Research Fellow, The Canon Institute for Global Studies

Economic Research Institute for ASEAN and East Asia

Kentaro Noma, Programme Manager on Energy

Daisuke Kiuchi, Chief Programme Manager on Energy

Han Phoumin, Senior Energy Economist

Contents

List of Figures

List of Tables

Introduction

Energy Landscape in Viet Nam

Viet Nam has experienced strong economic growth, with gross domestic product (GDP) increasing at an average annual rate of 6%–7% over the past decade. This growth has been driven by industrialisation, urbanisation, and demographic expansion. As a result, final energy consumption has increased in tandem, growing at an average rate of about 5% per year since 2000. This substantial increase in energy demand not only reflects the nation's economic progress but also highlights a structural shift in consumption patterns. Due to changes in industrial structure and rising income levels, Viet Nam has been transitioning from traditional biomass to modern energy sources such as fossil fuels and electricity. The share of traditional biomass in total final energy consumption declined from more than 50% in 2000 to just 10% in 2022. Notably, electricity demand has expanded rapidly in recent years, accounting for almost 30% of total final energy consumption in 2022.

Correspondingly, Viet Nam has achieved impressive growth in electricity generation, with a compound annual growth rate of about 10% from 2000 to 2022. Total electricity generation increased from about 30 terawatt-hours (TWh) in 2000 to about 250 TWh by 2022. Coal-fired power plants have dominated the sector, accounting for 40%–50% of the total electricity supply. However, the expansion of coal capacity has had significant environmental consequences, substantially increasing Viet Nam's carbon footprint.

At the same time, Viet Nam has emerged as a regional leader in renewable energy, particularly in solar and wind power. Solar photovoltaic (PV) generation has expanded from negligible levels in 2017 to nearly 28 TWh by 2022, recently providing around 10% of the country's electricity. Wind power has also grown steadily. However, integrating these variable renewable sources into the national grid remains a challenge. Addressing the intermittency and fluctuation of solar and wind energy requires modernised grid infrastructure and robust energy storage systems to ensure reliable and efficient energy dispatch.

The rise in final energy consumption and electricity generation has driven a corresponding rise in primary energy supply, which has grown at an average annual rate of about 6% since 2000. Although the country possesses significant indigenous energy resources in coal, oil, and natural gas, domestic production has not kept pace with surging demand. As a result, Viet Nam has been a net energy importer since 2015. Coal imports have surged, largely due to the energy-intensive manufacturing sector, and reliance on imported refined petroleum products and liquefied natural gas (LNG) is growing. Natural gas is expected to play a transitional role in the energy mix, supporting the shift from coal to cleaner sources. Recent investments in LNG infrastructure, including new import terminals and gas-fired power plants, reflect this strategic direction. Nevertheless, increasing dependence on energy imports raises concerns about energy security and vulnerability to global price volatility.

These energy trends have led to a sharp rise in carbon dioxide (CO_2) emissions, primarily due to the heavy reliance on coal for industrial processes and electricity generation. CO_2 emissions from fuel combustion have increased from about 50 million tonnes in the early 2000s to nearly 300 million tonnes in the early 2020s, making the country one of the region's highest carbon emitters.

Viet Nam now stands at a pivotal juncture in its energy development. As one of Southeast Asia's fastest-growing economies, the country faces the complex challenge of sustaining economic growth whilst ensuring energy security and addressing the urgent imperative of environmental sustainability.

Key Policy Developments in Viet Nam

The government has committed to achieving carbon neutrality by 2050, as outlined in its nationally determined contribution (NDC) reported in 2022 under the Paris Agreement. This ambitious goal is central to Viet Nam's Vision 2045, which aims to transform the country into a high-income nation whilst fostering a sustainable energy ecosystem. The vision prioritises reducing dependence on fossil fuels, enhancing energy efficiency, and expanding renewable energy capacity to mitigate the impacts of climate change. To support these objectives, Viet Nam has introduced several key policies:

National Climate Change Strategy to 2050

The strategy, established under Decision No. 896/QD-TTg, provides a long-term vision for enhancing climate resilience and transitioning towards a low-carbon economy. The strategy sets specific emission reduction targets whilst ensuring sustainable economic growth. By 2030, Viet Nam aims to reduce total greenhouse gas emissions by 43.5% compared with the business-as-usual (BAU) scenario, limiting energy emissions to 457 million metric tonnes of CO_2 equivalent. By 2050, energy emissions are expected to decrease further to 101 million metric tonnes, aligning with the national commitment to achieving net-zero emissions. The strategy integrates cross-sector policies covering energy, industry, agriculture, and transport, serving as a foundation for mobilising both domestic and international resources to support Viet Nam's climate goals.

Power Development Plan 8

The Power Development Plan 8 (PDP8) provides a strategic direction for the energy transition in response to rising energy demand and decarbonisation objectives. The plan aims to gradually reduce coal dependency, capping coal-fired power capacity at about 30 gigawatts (GW) by 2030, in line with commitments under the Just Energy Transition Partnership. Simultaneously, PDP8 supports the large-scale expansion of renewable energy, particularly solar and wind power, whilst advancing grid modernisation and energy efficiency initiatives.

In April 2024, the government approved the PDP8 Implementation Plan, which outlines specific projects, investment frameworks, and regulatory measures to ensure timely achievement of PDP8 targets. The plan includes mechanisms to streamline investment approvals, prioritise grid expansion for renewable integration, and enhance energy storage capabilities. It also aims to attract private sector participation by providing clearer guidelines for direct power purchase agreements and offering incentives to renewable energy developers. These efforts seek to establish a reliable, resilient, and sustainable energy system aligned with Viet Nam's long-term climate commitments and economic growth aspirations.

Hydrogen Energy Development Strategy

Under Decision No. 165/QD-TTg, Viet Nam has set forth a strategic plan to integrate hydrogen (H_2) as a key energy source of its future energy mix. The strategy targets annual H_2 production of 100,000 to 500,000 tonnes by 2030, scaling up to 10 million–20 million tonnes per year by 2050. It focuses on developing infrastructure for both green and blue hydrogen, facilitating their adoption in power generation, transport, and industry. The strategy aims to reduce emissions, reinforce energy security, drive technological advancements, and attract significant domestic and international investment, positioning Viet Nam as a regional leader in H_2 energy.

Economic Growth Targets and Potential Use of Nuclear Power

Viet Nam has set an economic growth target of at least 8% in 2025, with plans to achieve double-digit growth in the coming years to support its ambition of becoming a high-income nation by 2045. This ambitious economic trajectory is expected to further amplify energy demand. Nuclear power is once again being considered as a viable option to ensure a stable baseload supply, reduce emissions, and enhance grid stability. Although Viet Nam suspended its nuclear power development plans in 2016, recent discussions indicate renewed interest in nuclear energy, particularly in adopting small modular reactors (SMRs) and next-generation nuclear technologies.

Purpose and Structure of the Report

This report aims to address the critical research question: **How can Viet Nam achieve carbon neutrality by 2050 whilst meeting its growing energy demand and realising its potential for double-digit economic growth?**

To answer this question, the study is structured as follows:

Part 1: Carbon-neutral Scenario Analysis

This section employs a comprehensive energy system modelling approach to evaluate Viet Nam's pathways towards carbon neutrality. It uses a cost-optimal technology selection framework that assesses more than 350 energy technologies across the entire energy system, examined under three distinct scenarios: baseline (BL), carbon neutral

(CN), and carbon neutral with high economic growth (CN_HighGDP). These scenarios examine the economic efficiency of key decarbonisation technologies and strategies, including renewable energy integration; nuclear power; H_2 adoption; electrification; and carbon capture, utilisation, and storage (CCUS). The analysis quantifies the economic implications of the energy transition by estimating total system costs, marginal abatement costs, and marginal electricity prices required to support low-carbon development.

Part 2: Potential Use of Nuclear Power

This section provides an in-depth examination of nuclear energy's role in Viet Nam's energy transition. It evaluates various nuclear technologies, including conventional large-scale reactors and emerging SMRs, considering their feasibility within the energy landscape. The analysis addresses regulatory frameworks, infrastructure readiness, public acceptance, and economic viability. It explores strategic implementation pathways, such as policy incentives and international cooperation, to determine how nuclear energy could complement Viet Nam's decarbonisation strategy whilst ensuring a stable baseload power supply.

By integrating energy system modelling, technology assessments, and policy recommendations, this report provides structured guidance to support Viet Nam's transition to a carbon-neutral economy whilst sustaining economic growth and ensuring long-term energy security.

Part 1
Carbon-neutral Scenario Analysis

Soichi Morimoto

Seiya Endo

Rino Hirose

Hideaki Obane

Kei Shimogori

Atsutaka Yamada

Yu Nagatomi

Ichiro Kutani

Toshiyuki Sakamoto

Kentaro Noma

Daisuke Kiuchi

Han Phoumin

Chapter 1
Analytical Framework

1.1. Institute of Energy Economics, Japan–New Earth Model

The analysis presented in this study was conducted using the Institute of Energy Economics, Japan (IEEJ)–New Earth (NE) model, an optimal technology model developed by Otsuki et al. (2022, 2019), which encompasses the entire energy system. The model covers all 10 Association of Southeast Asian Nations (ASEAN) countries[1] from 2017 to 2070, using 2017, 2030, 2040, 2050, 2060, and 2070 as representative years. The study focuses on energy-related CO_2 emissions.

The IEEJ-NE model is formulated as a linear programming model. Like the market allocation model developed under the Energy Technology Systems Analysis Program of the International Energy Agency (IEA), it incorporates the cost and performance of individual energy technologies as input values. The model identifies a single, cost-minimising combination of technology scale and operational patterns across ASEAN, subject to constraints such as CO_2 emissions and supply–demand balance. It covers both energy conversion and end-use sectors (industry, transport, residential, and commercial), and incorporates more than 350 technologies. Evaluation criteria include capital costs, fuel costs, and CO_2 emissions.

The model encompasses a wide range of technologies, including low-carbon options such as solar PV, onshore and offshore wind power, H_2, and ammonia (NH_3)–fired power generation, and negative-emission technologies such as direct air capture with carbon storage (DACCS), and bioenergy with carbon capture and storage (BECCS) (Table 1.1). The model comprehensively represents the energy system, from primary energy production and imports to secondary energy conversion, intraregional energy trade, CO_2 capture and storage (CCS), and final energy consumption. It also accounts for sector-specific consumption of various energy types (Figure 1.1).

Modelling of the end-use sectors draws on data from the Economic Research Institute for ASEAN and East Asia (ERIA) outlook, the IEA energy balance tables, and the IEEJ outlook. However, some sectors could not be fully simulated due to data limitations in the public domain (Figure 1.2).

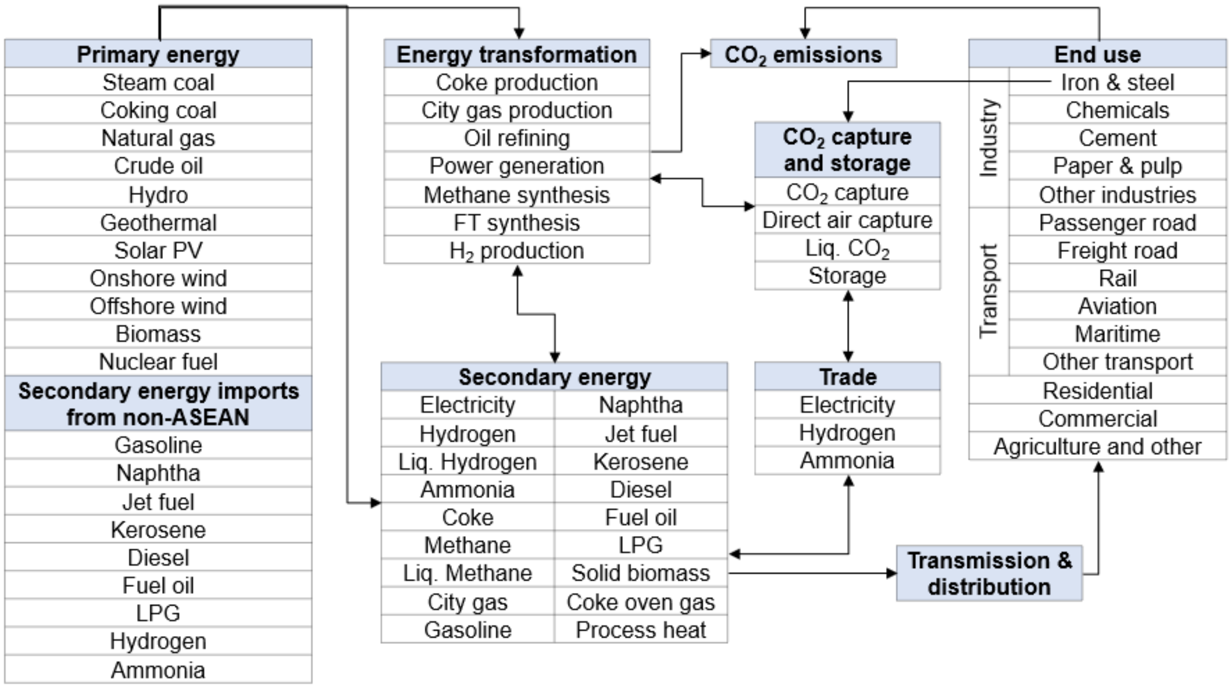
[1] Brunei Darussalam, Cambodia, Indonesia, the Lao People's Democratic Republic, Malaysia, Myanmar, the Philippines, Singapore, Thailand, and Viet Nam.

Table 1.1. Selected Clean Technologies in the Model

Category	Technologies
Renewables	Ground-mounted solar PV, rooftop solar PV, onshore wind, bottom-fixed offshore wind, floating offshore wind, hydropower, geothermal, biomass
Nuclear	Large-scale reactor, small modular reactor
CO_2 capture, utilisation, and storage	Capture: Chemical absorption, physical absorption, direct air capture Utilisation: Methane synthesis, FT liquid fuel synthesis Storage: Geological storage
H_2	Supply: Electrolysis, coal gasification, methane reforming, H_2 separation from NH_3, H_2 trade amongst ASEAN countries, imports from non-ASEAN countries Consumption: H_2 turbine, natural gas–H_2 co-firing, fuel cell electric vehicle, H_2-based direct reduced iron–electric arc furnace, fuel cell ship, H_2 aviation, H_2 heat for industries, fuel synthesis (methane, FT liquid fuel, NH_3)
NH_3	Supply: NH_3 synthesis, NH_3 trade amongst ASEAN countries, NH_3 imports from non-ASEAN countries Consumption: NH_3 turbine (new builds and retrofit), coal–NH_3 co-firing, H_2 separation
Negative-emission technologies	Direct air capture with CCS (direct air CCS), biomass-fired power generation with CCS

ASEAN = Association of Southeast Asian Nations, CCS = carbon capture and storage, CO_2 = carbon dioxide, FT = Fischer-Tropsch, H_2 = hydrogen, NH_3 = ammonia, PV = photovoltaic.
Source: Author.

Figure 1.1. Modelled Energy System



CO_2 = carbon dioxide, FT = Fischer-Tropsch, H_2 = hydrogen, liq. = liquid, LPG = liquefied petroleum gas, PV = photovoltaic.
Source: Author.

Figure 1.2. Data Availability for Modelled End-use Sectors

		BRN	KHM	IDN	LAO	MYS	MMR	PHL	SGP	THA	VNM
Industry	Iron & Steel			✓		✓	✓	✓		✓	✓
	Cement			✓				✓		✓	✓
	Chemicals	✓		✓		✓	✓	✓	✓	✓	✓
	Paper & Pulp			✓			✓	✓		✓	✓
	Other industries	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Transport	Passenger LDV	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Bus & Truck	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Rail			✓		✓	✓	✓	✓	✓	✓
	Aviation			✓		✓	✓	✓		✓	✓
	Navigation			✓		✓	✓	✓	✓	✓	✓
	Other transport	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Residential & Commercial		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Agriculture and other		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

BRN = Brunei Darussalam, IDN = Indonesia, KHM = Cambodia, LAO = Lao People's Democratic Republic, LDV = light-duty vehicle, MMR = Myanmar, MYS = Malaysia, PHL = Philippines, SGP = Singapore, THA = Thailand, VNM = Viet Nam.
Note: Assumptions regarding iron and steel manufacturing are based on World Steel Association (2023) data. Cement sector assumptions, including country-specific efficiency factors, are based on Global Cement and Concrete Association (2023) data.
Source: Author.

Within the model, the total cost – expressed as the sum of fixed costs, fuel costs, and variable costs, such as operation and maintenance (O&M) – is minimised using the objective function indicated in equation (1):

$$\boldsymbol{min\ TotalCost} = \sum_{\boldsymbol{y}} \sum_{\boldsymbol{r}} \sum_{\boldsymbol{i}} \left(\boldsymbol{Fix_{y,r,i}} + \boldsymbol{Fuel_{y,r,i}} + \boldsymbol{Variable_{y,r,i}}\right) \cdot \boldsymbol{R_y} \qquad \textbf{(1)}$$

Where:

Fix: fixed cost (annualised capital cost + fixed O&M cost)

Fuel: fuel cost

Variable: variable O&M cost

R: discount coefficient (discount rate: 8%)

Subscripts: y = year, r = region, i = technology

The model operates under typical constraints, including CO_2 emission limits for the representative years, hourly power supply–demand balance, maximum capacity of each power source, and load curve requirements (see Otsuki et al. [2022, 2019]). To ensure reliability during periods of low solar and wind generation, the model requires support from storage discharge (e.g. lithium-ion batteries), H_2-/NH_3-fired power generation, or thermal power with CCS.

Power supply and demand are represented in 4-hour intervals to capture fluctuations in renewable output and the required balancing mechanisms. One year is divided into 2,190 time slices (4-hour resolution).

The model explicitly simulates co-firing technologies in both existing and new thermal power plants. These include coal co-firing with biomass (20%, 40%, 60%, 80%, and 100%), and NH_3 (20%, 40%, 60%, 80%, and 100%), and gas co-firing with H_2 (20%, 40%, 60%, 80%, and 100%). Technologies modelled include coal-fired power, integrated coal gasification combined cycle, gas-fired and gas-combined cycle generation, oil-fired power, solar PV (ground-mounted and rooftop-mounted), onshore and offshore wind power (bottom-fixed and floating), biomass-fired power, hydropower, geothermal power, nuclear (large-scale and SMRs), new H_2- and NH_3-fired power generation, pumped hydro and lithium-ion battery storage, and H_2 storage tanks.

The model simulates both domestic production and international imports of H_2 and NH_3. H_2 is assumed to be used for power generation, fuel synthesis, industry, and transport, whilst NH_3 is used only for power generation.

Negative-emission technologies are incorporated, specifically DACCS and BECCS. Direct air capture (DAC) extracts CO_2 directly from the atmosphere. The captured CO_2 can either be stored in deep geological formations, achieving negative emissions, or combined with H_2 to produce synthetic fuels through carbon recycling. As of 2023, 17 DAC plants operate worldwide, capturing less than 10,000 tonnes of CO_2 per year (IEA, 2023a). Although DAC is energy intensive and currently costly, it is expected to become more competitive as carbon prices rise in pursuit of carbon neutrality.

1.2. Scenario Settings

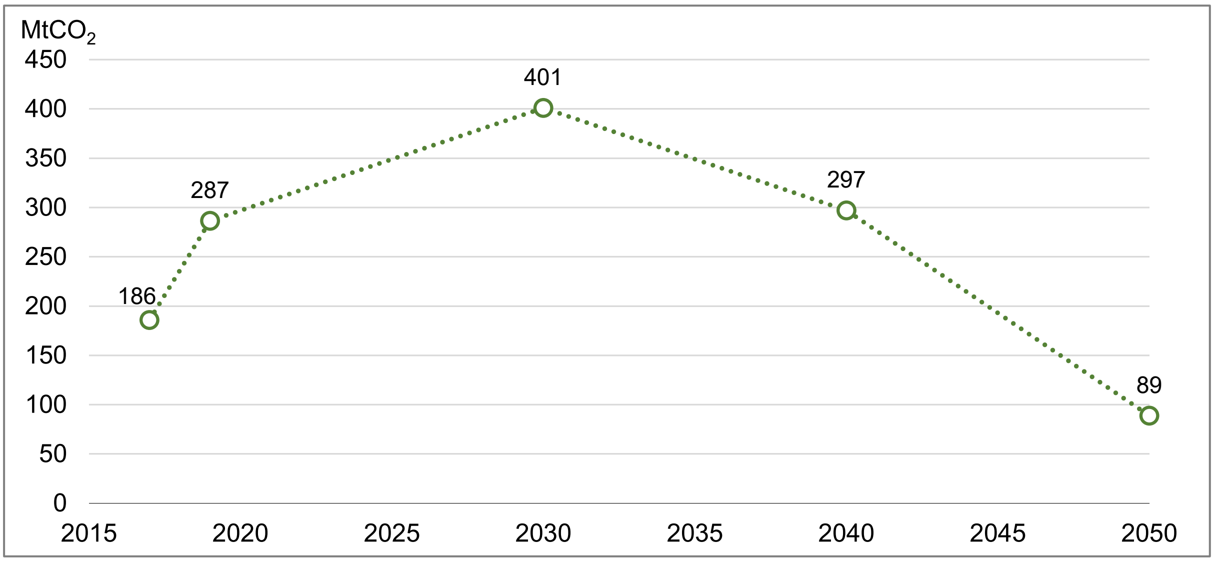
Three scenarios were set for this study (Table 1.2). For all scenarios except the BL, emission reduction constraints were applied based on the National Strategy on Climate Change by 2050 (Government of Viet Nam, 2022) and are shown in Figure 1.3. For both the BL and CN scenarios, the average annual GDP growth rate is assumed to be 5.2% from 2019 to 2050. This assumption aligns with the ERIA Energy Outlook (forthcoming), which projects GDP growth as an extrapolation of historical trends. In the CN_HighGDP scenario, the GDP growth rate is assumed to achieve double-digit (10%) around 2030 before gradually converging to the same rate as projected in the ERIA Energy Outlook in the long term. This results in an average annual GDP growth rate of 7.1% from 2019 to 2050. The CN_HighGDP scenario considers advancements in nuclear technology to explore the potential role of nuclear power in meeting surging energy demand driven by massive economic growth. It should be noted that, in both the CN and CN_HighGDP scenarios, other ASEAN countries are also assumed to achieve carbon neutrality by 2050 or 2060, accounting for land use, land-use change, and forestry emissions.

Table 1.2. Overview of Scenario Settings

Scenario	Emission Reduction Constraints	Average GDP Growth Rate (2019–2050)	Nuclear Technology Advancement
Baseline	None	5.2%	None
Carbon Neutral	Yes	5.2%	None
Carbon Neutral with High Economic Growth	Yes	7.1%	Yes

Source: Author.

Figure 1.3. Energy-related Carbon Dioxide Emissions Constraints in the Carbon-neutral and Carbon-neutral with High Economic Growth Scenarios



$MtCO_2$ = metric tonne of carbon dioxide.
Note: The greenhouse gas (GHG) emissions pathway for the energy sector, as shown in the National Strategy on Climate Change by 2050, was adjusted to reflect energy-related carbon dioxide (CO_2) emissions. This was achieved by applying a factor of 88%, which represents the share of energy-related CO_2 in total energy GHG emissions, based on the national emission inventory for 2016.
Source: Author, based on Government of Viet Nam (2022) and Ministry of Natural Resources and Environment (2020).

1.3. Key Assumptions

(a) Regional division and transmission network

The main transmission lines (500 kilovolts) run from north to south, connecting major power plants across the country. In the model, Viet Nam is divided into six nodes – north, north central, central central, central highlands, south central, and south – to account for the uneven distribution of renewable energy resources, energy service demands, and existing facilities. The expansion of transmission lines between regions is determined endogenously within the model. This study imposes upper limits on the capacity of international interconnections with the Lao People's Democratic Republic and Cambodia, based on planned infrastructure developments (Table 1.3). Conversely, no upper limit is assumed for the capacity of domestic transmission lines within Viet Nam.

Table 1.3. Assumed Distance and Capacity of Transmission Lines

		Distance (km)	Capacity (MW)	
			Existing	Upper limit
Domestic	N – NC	250	2,200	-
	NC – CC	350	1400	-
	CC – CH	350	2,000	-
	CC – SC	350	400	-
	CH – S	400	4,000	-
	SC – S	650	2,500	-
Intl.	Cambodia – S	100	200	200
	Lao PDR – NC	100	860	5,000

CC = central central, CH = central highlands, intl. = international, km = kilometre, MW = megawatts, N = north, NC = north central, S = south, SC = south central.
Note: Existing capacity of domestic lines is based on Vietnam Electricity (2020).
Source: Author.

(b) Energy service demand

The energy model in this study assumes energy service demand as an exogenous variable (Table 1.1 and Table 1.5). The estimation process for energy service demand is outlined as follows:

(i) Assumptions for GDP and population are set exogenously. The population projection, which is common across all scenarios, is based on the medium variants from the United Nations (2024). For the BL and CN scenarios, GDP projections follow the latest ERIA Energy Outlook (forthcoming). In the CN_HighGDP scenario, GDP is assumed to achieve double-digit growth (10%) around 2030 and gradually converge to the long-term rate projected by the ERIA Energy Outlook, as described in the previous section.

(ii) Subsequently, several socio-economic parameters closely related to energy demand are estimated using econometric methods and classified by sector. For the industrial sector, parameters include production volumes of energy-intensive materials such as steel, cement, pulp and paper, and chemical products. In the transport sector, the number of vehicles is used as a key energy demand indicator. In the residential and commercial sector, GDP or GDP per capita serves as a direct determinant of energy demand. These parameters are estimated through econometric regression using population and GDP data.

(iii) Energy consumption is subsequently derived from energy intensity, sector activity indicators, and actual consumption data. The results of this estimation serve as input data for the IEEJ-NE model and constitute key assumptions for optimisation calculations.

The average GDP growth rate in the BL and CN scenarios is projected to be 5.6% per year in 2019–2030, which is moderate compared with the historical growth rate of 6.5% per year in 2009–2019. This difference is mainly due to the slower projected pace of population growth over the same period. As population growth is not expected to continue at its previous rate, GDP growth is projected to adjust accordingly. By contrast, the CN_HighGDP scenario reflects the government's aspiration for further economic acceleration. Although it also assumes slower population growth, it projects higher productivity per capita and sustained economic growth, with GDP growth rates of 6.9% per year in 2019–2030 and 9.2% per year in 2030–2040. This includes a peak period of double-digit growth (10%) in 2030–2035.

Based on these GDP assumptions, various service demands, such as steel production and transport, were estimated using econometric methods and used as inputs for the model analysis.

Table 1.4. Energy Service Demand for the Baseline and Carbon Neutral Scenarios

Item	Unit	2019	2030	2040	2050
Population	Million	96	103	106	107
GDP	Billion US$ (2015)	315	572	977	1,517
	Annual growth rate, %	-	5.6% (2019–2030)	5.5% (2030–2040)	4.5% (2040–2050)
Crude steel production	Million tonnes	19	34	49	61
Cement production	Million tonnes	97	157	220	258
Passenger cars	Billion vehicle-km	15	66	94	106
Buses and trucks	Billion vehicle-km	22	56	97	144
Data centres	TWh	-	1.4	5.8	19.7

GDP = gross domestic product, km = kilometre, TWh = terawatt-hours.
Note: Electricity demand from data centres is estimated by dividing the global demand forecast (JST, 2022) by the number of data centres currently operating in the country (Data Center Map).
Source: Author.

Table 1.2. Energy Service Demand for the Carbon-neutral with High Economic Growth Scenario

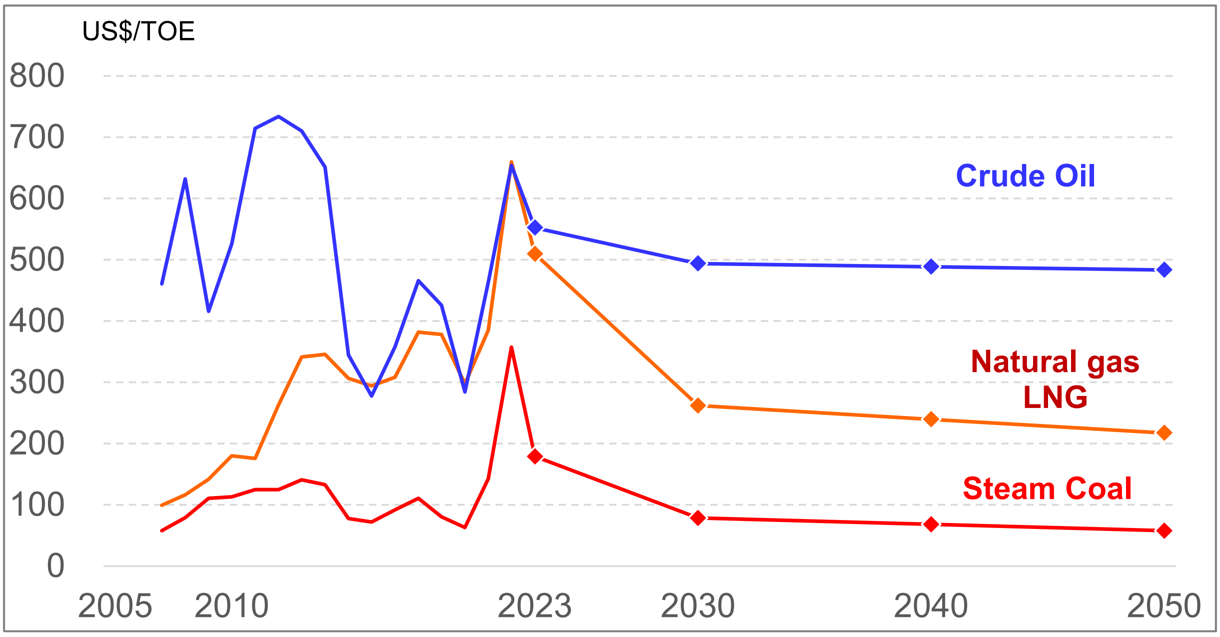
Item	Unit	2019	2030	2040	2050
Population	Million	96	103	106	107
GDP	Billion US$ (2015)	315	659	1,596	2,662
	Annual growth rate (%)	-	6.9% (2019–2030)	9.2% (2030–2040)	5.2% (2040–2050)
Crude steel production	Million tonnes	19	39	79	105
Cement production	Million tonnes	97	178	337	421
Passenger cars	Billion vehicle-km	15	74	142	170
Buses & Trucks	Billion vehicle-km	22	63	146	230
Data centres	TWh	-	1.4	7.5	26.1

GDP = gross domestic product, km = kilometre, TWh = terawatt-hours.
Note: Electricity demand from data centres is estimated by dividing the global demand forecast (JST, 2022) by the number of data centres in operating in the country (Data Center Map).
Source: Author.

(c) Fossil fuel prices

A common pricing structure is assumed for both domestic and imported fossil fuels. Future prices for coal and natural gas are estimated using historical data from ASEAN and projected figures for Japan, based on the Stated Policies Scenario (STEPS) in the *IEA World Energy Outlook 2023* (IEA, 2023b). Crude oil prices are estimated in the same way, using international market prices.

Figure 1.4. Fossil Fuel Prices



LNG = liquefied natural gas, TOE = tonne of oil equivalent.
Note: 2017 real prices. Historical coal and natural gas prices are based on Indonesian data.
Source: Author, based on the Stated Policies Scenario of the International Energy Agency (2023b).

(d) Hydrogen and ammonia imports from outside ASEAN

In this model, H_2 and NH_3 may be produced domestically or be imported from outside ASEAN. The maximum permissible imports of H_2 and NH_3 from non-ASEAN countries are assumed to account for up to 15% of the total BL primary energy supply in 2040, rising to 30% after 2050. The assumed import prices of H_2 and NH_3, inclusive of international transport costs, are presented in Table 1.6. These prices are based on Japan's long-term targets (Ministerial Council on Renewable Energy, Hydrogen and Related Issues, 2023).

The study does not specify the production method for imported H_2, whether green H_2 produced via electrolysis powered by renewable electricity or blue H_2 derived from fossil fuels combined with CCS. Nor does it identify specific H_2-exporting countries. However, given their geographic proximity and potential for clean H_2 production, Australia, India, and Middle Eastern countries are considered likely suppliers.

Table 1.6. Maximum Volume and Prices for Imported Hydrogen and Ammonia

	2030	2040	2050
Maximum volume of H_2 and NH_3 imports (% of total primary energy in the baseline)	-	15%	30%
Import H_2 prices (US cents per Nm^3-H_2)	30.0	25.0	20.0
Import NH_3 prices (US cents per Nm^3-H_2)	17.5	16.9	16.3

H_2 = hydrogen, NH_3 = ammonia, Nm^3 = normal cubic metre.
Note: 2017 real prices.
Source: Author, based on the Ministerial Council on Renewable Energy, Hydrogen and Related Issues (2023) for prices.

(e) Solar and wind resources

The upper limit of solar and wind energy capacity is estimated using geographic information systems (GIS) data originally developed by IEEJ, incorporating information on building, land use (500-metre [m] grid meshes), and marine use (1-kilometre grid meshes) data. Figure 1.5 shows the schematic design of the GIS data. Building-mounted PV is assumed to be installed on all rooftops, whilst ground-mounted PV is considered for deployment on weed-covered and bare land, excluding protected areas. To avoid land-use conflicts with onshore wind turbines, ground-mounted PV is allocated only to areas where the average annual wind speed at a height of 100 m is less than 5.0 m per second. Conversely, onshore wind installations are limited to areas with average wind speeds of 5.0 m per second or above.

Offshore wind power is assumed to be installed in areas with an average annual wind speed at a height of 200 m of 7.0 m per second or more, excluding protected areas and locations where vessel traffic equipped with automatic identification system averages fewer than 100 vessels per day. Bottom-fixed wind turbines are installed in waters shallower than 60 m, whilst floating wind turbines are installed in deeper waters. Capital expenditure is assumed to increase with water depth (See Section 3.13 [j]).

Figure 1.6 summarises the estimated upper limit of solar and wind energy resources. In Viet Nam, areas suitable for solar and wind power energy are mostly concentrated in the northern and south-central regions.

For both PV and wind power, the grid cell (mesh) with the closest average global horizontal irradiance or average annual wind speed was selected from the available areas. Corresponding 4-hourly irradiance and wind data for 2023 were obtained from Renewables.ninja at the latitude and longitude of the selected mesh.

Table 1.7 summarises the annual capacity factors for PV and onshore wind, estimated using the hourly data from Renewables.ninja. The onshore wind capacity factor is highest in the central-central and south-central regions, remains around 10% in the north, and falls below 10% in the central highlands. In contrast, capacity factors for PV exhibit less regional variation. The highest PV capacity factor is assumed in the north, and the lowest in the central-central region.

Figure 1.7 shows the annual capacity factors of offshore wind. Capacity factors are not shown for grades with no suitable offshore wind turbine installation locations, such as those with insufficient wind resources. Overall, offshore wind capacity factors are higher in south-central and southern regions than in other areas.

Figure 1.5. Schematic Design of Geographic Information Systems Data

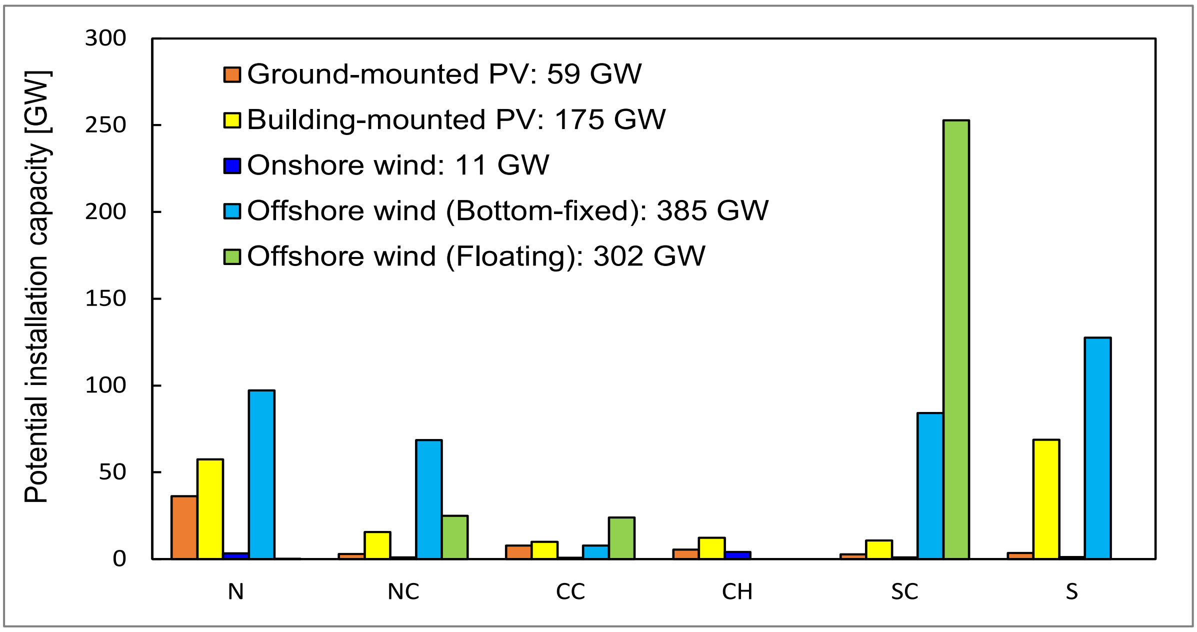
(A) Building

(B) Land-use data (500-metre grid mesh)

(C) Marine-use data (1-kilometre grid mesh)

Source: Author.

Figure 1.6. Estimated Upper Limit of Solar and Wind Energy Capacity



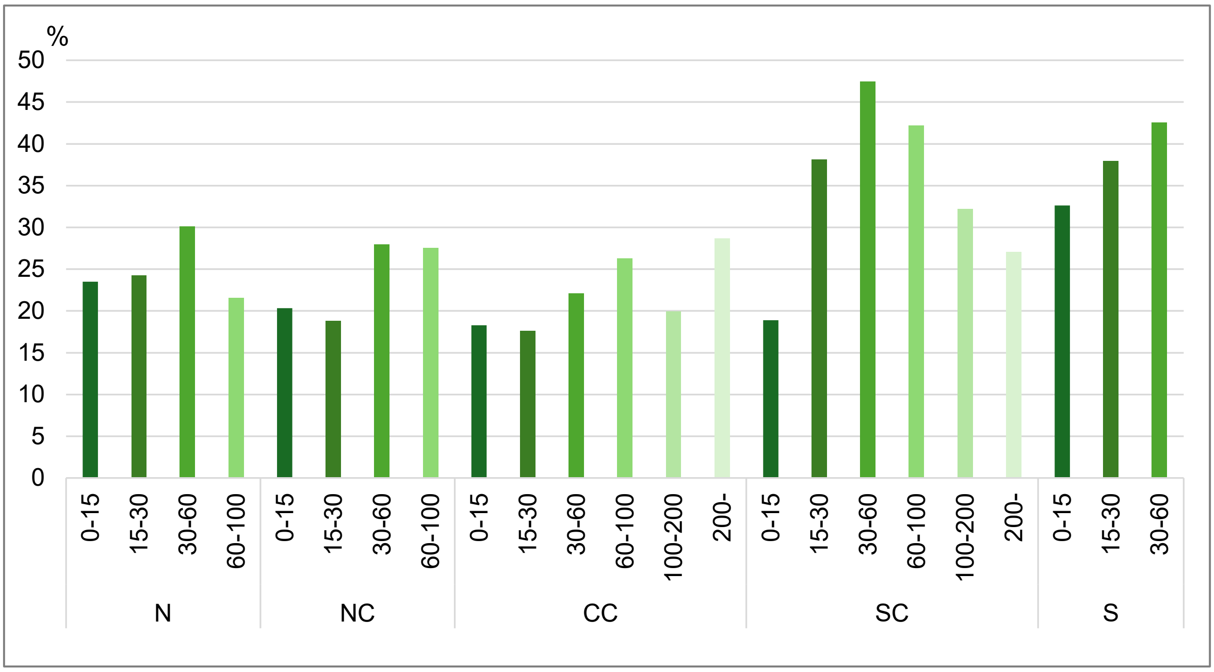
CC = central central, CH = central highlands, GW = gigawatt, N = north, NC = north central, PV =photovoltaic, S = south, SC = south central.
Source: Author.

Table 1.7. Capacity Factors of Solar Photovoltaic and Onshore Wind

Region		Solar PV	Onshore Wind
N	%	17.7	10.1
NC	%	15.5	13.6
CC	%	15.1	18.1
CH	%	16.8	8.1
SC	%	16.3	16.0
S	%	16.0	14.5

CC = central central, CH = central highlands, N = north, NC = north central, PV = photovoltaic, S = south, SC = south central.
Note: Capacity factors are based on data from Renewables.ninja.

Figure 1.7. Capacity Factors of Offshore Wind



CC = central central, N = north, NC = north central, S = south, SC = south central.
Note: Capacity factors are based on data from Renewables.ninja. The numbers on the horizontal axis represent water depth. Categories without bars indicate areas where no offshore wind resources are assumed.
Source: Author.

(f) Hydro, geothermal, and biomass resources

The upper limits of hydro, geothermal, and biomass power generation capacity are based on various literatures (Table 1.8). In this study, biomass energy use in end-use sectors is assumed to remain fixed at the 2017 level.

Table 1.8. Upper Limits of Hydro, Geothermal, and Biomass for Power

		N	NC	CC	CH	SC	S	Total
Hydro power	GW	17.5	1.9	3.3	8.0	2.8	1.5	35.0
Geothermal power	GW	0.5	0.2	0.1	0.2	0.1	0.3	1.4
Biomass for power	Mtoe	3.3	1.2	0.7	1.5	0.8	1.8	9.3

CC = central central, CH = central highlands, GW = gigawatt, Mtoe = million tonnes of oil equivalent, N = north, NC = north central, S = south, SC = south central.
Note: The total hydro potential is assumed based on Vietnam Electricity (2019), geothermal on Asian Development Bank (ADB) (2017), and biomass on ADB (2015) and *Vietnam Briefing* (2018). Regional potentials are estimated by downscaling national totals using existing capacity (for hydro) or land area (for geothermal and biomass). Biomass potential for power includes input for co-firing.
Source: Author.

(g) Carbon dioxide storage resources

The assumed annual CO_2 storage capacities are shown in Table 1.9. The annual storage capacity is set at 0.3% of the cumulative CO_2 storage potential in 2040, increasing to 0.6% by 2050. This assumption ensures the sustainability of CO_2 storage capacity beyond 2050. Whilst accurately estimating CO_2 storage potential remains challenging, the IEA (2021) reports that ASEAN countries possess abundant potential, with a combined cumulative capacity of 133.4 gigatonnes of CO_2 across six countries: Brunei Darussalam, Indonesia, Malaysia, the Philippines, Thailand, and Viet Nam. This study also considers the possibility of cross-border CO_2 imports and exports amongst ASEAN countries.

Table 1.9. Upper Limit of Annual CO_2 Storage

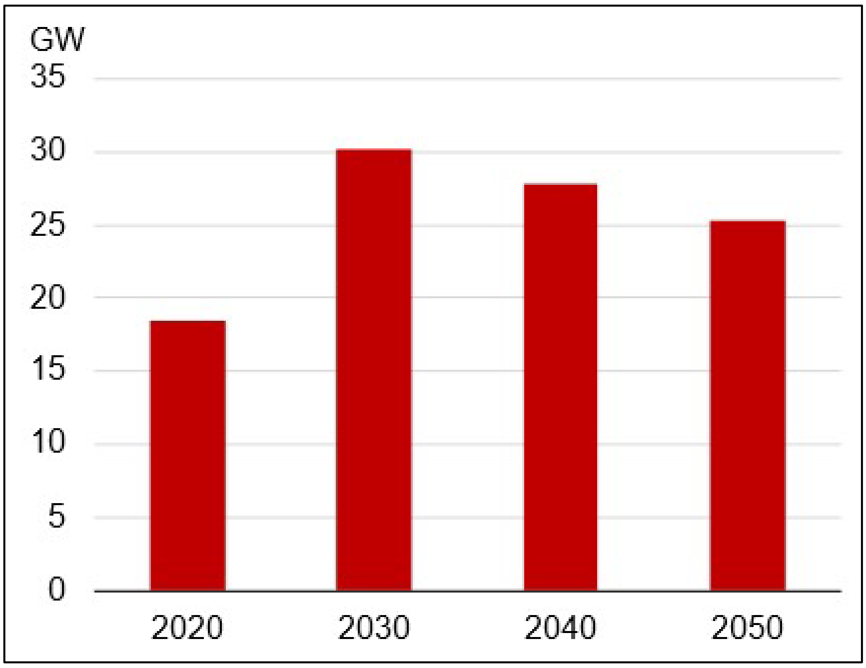
	2030	2040	2050
% of cumulative potential	0.03%	0.3%	0.6%
Annual capacity, $MtCO_2$	3.1	35	71

$MtCO_2$ = metric tonnes of carbon dioxide.
Note: Cumulative storage potential in Viet Nam is assumed to be 11.8 gigatonnes of CO_2, based on International Energy Agency (2021).
Source: Author.

(h) Existing coal-fired power capacity and operation

In the CN and CN_HighGDP scenarios, existing coal-fired power generation is treated as exogenous in both capacity and operation. The coal-fired power capacity is fixed based on the outlook provided in the PDP8 (Government of Viet Nam, 2023) (Figure 1.8). These plants are assumed to operate until 2050 to avoid becoming stranded assets. Emissions from coal-fired power generation can be reduced by capturing CO_2 or through co-firing with biomass or ammonia. Co-firing options are prepared at various ratios: 20%, 40%, 60%, 80%, and 100%.

Figure 1.8. Assumed Coal-fired Power Capacity

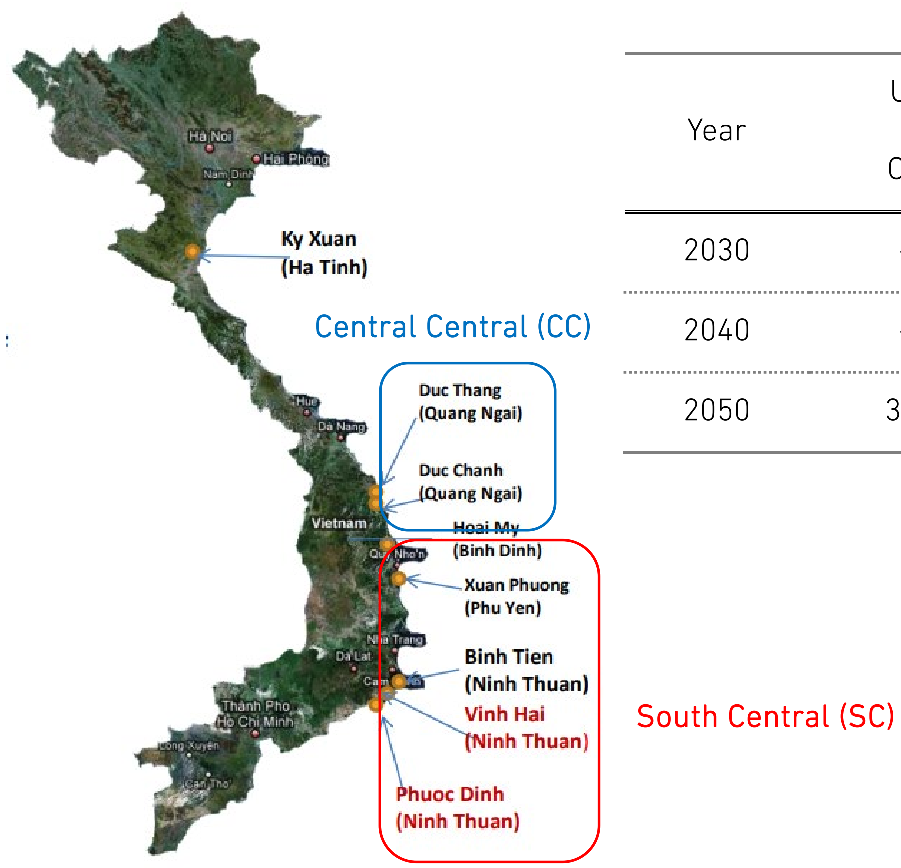


GW = gigawatt.
Note: For 2050, the lower projection value from the Government of Viet Nam (2023) is used.
Source: Author.

(i) Nuclear power capacity

The upper limit of nuclear power plant capacity is determined based on the previous government's plan (Figure 1.9). This plan identified eight potential sites for the construction of new nuclear power plants, including Ninh Thuan province in the south and several sites in the central region. This study assumes the deployment of nuclear power capacity in both the southern and the central regions, in line with the potential sites identified. Specifically, it is assumed that eight units – equivalent to the previous Ninh Thuan 1 and 2 projects – will become operational in Ninh Thuan Province by 2050, along with two additional reactors in the central region. In November 2024, the National Assembly approved plans to resume the Ninh Thuan nuclear power project, and the Prime Minister has expressed expectations for its accelerated completion. Accordingly, the first unit is assumed to become operational around 2030.

Figure 1.9. Potential Site and Assumed Upper Limit of Nuclear Power Capacity



Year	Upper limit (GW)	
	CC	SC
2030	-	1.2
2040	-	5.0
2050	3.0	10.0

CC = central central, GW = gigawatt, SC = south central.
Source: Author's additions based on LE, Doan Phac (2011) (left), and author (right).

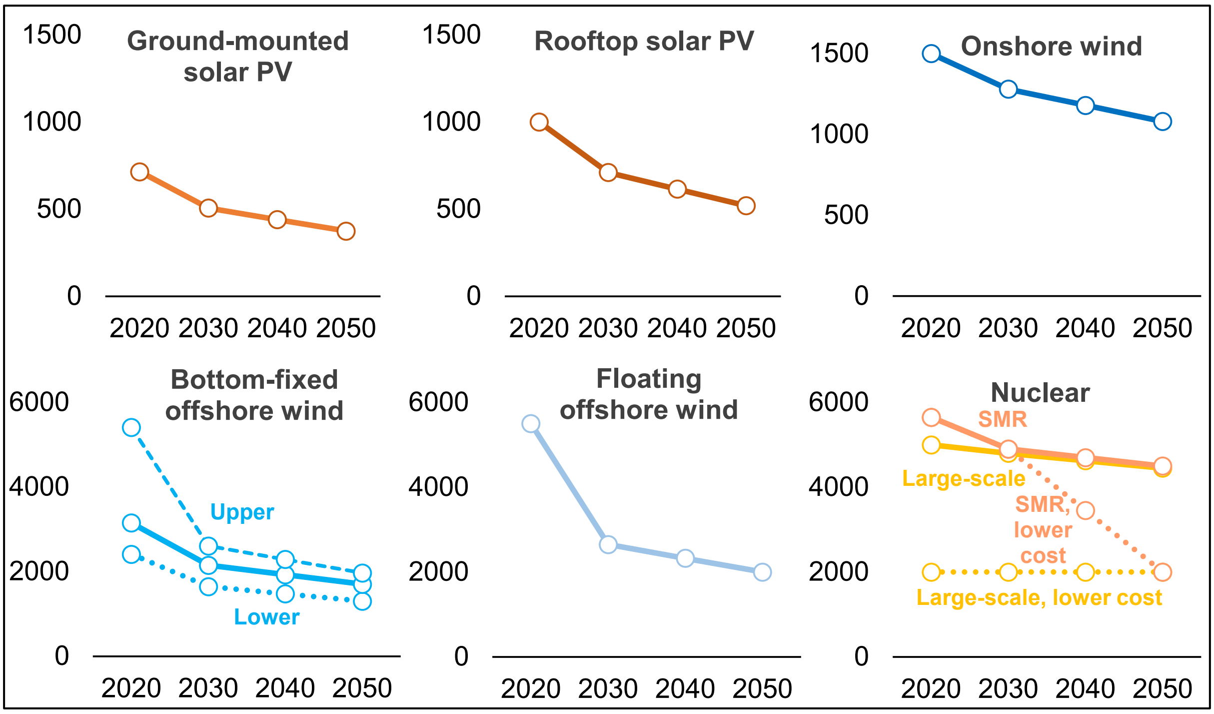
(j) Power generation technology cost

Capital costs for power generation technologies are based on the Viet Nam technology catalogue for power generation (ERIA and Danish Energy Agency [DEA], 2023). To reflect the range of actual costs, the capital costs of bottom-fixed offshore wind turbines are divided into three grades, according to bathymetry (0–15 m, 15–30 m, and 30–60 m). Current costs are determined based on project surveys (Japan Ship Technology Research Association [JSTRA], 2024).

In the CN_HighGDP scenario, the lower bound of the cost range for large-scale nuclear reactors is adopted. SMR costs are also assumed to decrease over time, converging with large-scale reactor costs by 2050. A 60-year operational lifetime is assumed for all nuclear power plants in every scenario.

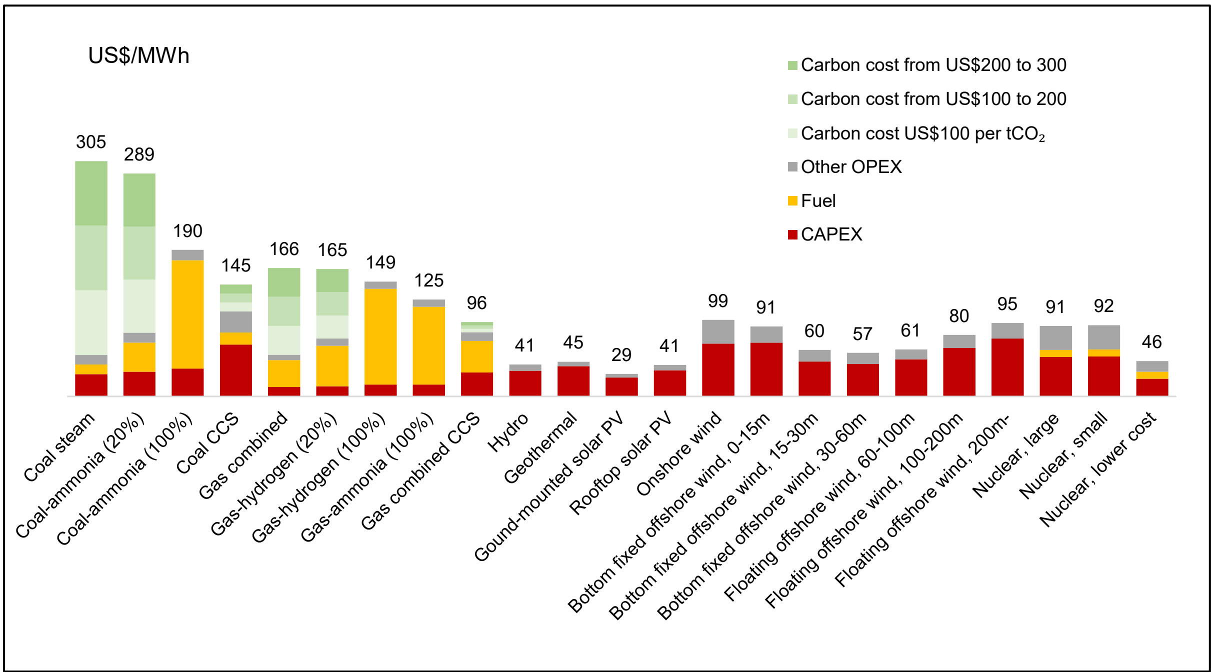
The levelised cost of electricity (LCOE) for the various technologies in the SC region in 2050 is shown in Figure 1.11. Estimates are based on assumptions about fuel prices, technical specifications, and capacity factors. Coal- and gas-fired power plants equipped with CCS are shown to have lower LCOE than those using H_2 or NH_3 co-firing or single-firing. Offshore wind generally shows lower LCOE than nuclear; however, nuclear remains cost competitive under lower capital cost assumptions.

Figure 1.10. Capital Costs of Solar Photovoltaic, Wind Power, and Nuclear Power (US$/kW)



kw = kilowatt, PV = photovoltaic, SMR = small modular reactor.
Note: 2017 real price.
Source: Author, based on Economic Research Institute for ASEAN and East Asia and Danish Energy Agency (2023) and Japan Ship Technology Research Association (2024).

Figure 1.11. Estimated Levelised Cost of Electricity (South Central, 2050)



CAPEX = capital expenditure, CCS = carbon capture and storage, m = metre, mm = millimetre, MWh = megawatt-hour, OPEX = operational expenditure, PV = photovoltaic.

Note: 2017 real prices. A discount rate of 8% is applied. All levelised cost of electricity (LOCE) values represent new-build construction. 'Gas-ammonia' refers to 100% ammonia-firing in retrofitted natural gas turbines. Capacity factors assumed: 60% for thermal, 42% for hydro, 80% for geothermal, 16% for solar PV, 16% for onshore wind, 19%–47% for bottom-fixed offshore wind, 27%–42% for floating offshore wind, and 80% for nuclear. See 1.3 (c) and (d) for fuel prices, and (e) for variable renewable energy capacity factors.

Source: Author.

(k) Capital cost and energy consumption of direct air capture

DAC requires enormous energy, both electrical power for the fans that extract CO_2 from the atmosphere and heat for desorbing CO_2 from the sorbent material. As a result, the cost of energy is a key factor in DAC's overall cost.

Given the uncertainty surrounding DAC technological progress, three cases have been prepared (Table 1.10). In the low case, capital expenditure and energy consumption are based on Fasihi et al. (2019), showing significant anticipated reductions in capture costs. The high case assumes no further improvements beyond 2020. The mid case takes the average values of the low case and high scenarios. This study adopts the mid case in its modelling.

Table 1.10. Assumed Technological Specifications of Direct Air Capture

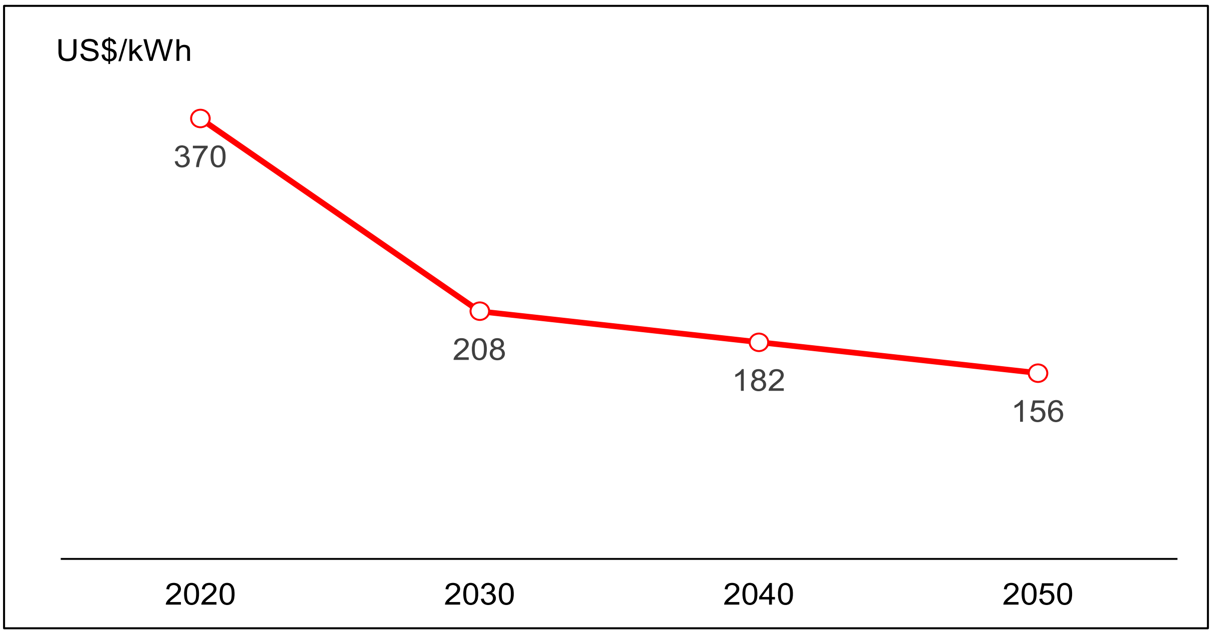
	Case	2020	2030	2040	2050
Capital cost (US$/[t$CO_2$/year])	Low	906	420	294	247
	Mid	906	663	600	576
	High	906	906	906	906
Electricity input (kWh/tCO_2)	Low	1,535	1,458	1,385	1,316
	Mid	1,535	1,497	1,460	1,426
	High	1,535	1,535	1,535	1,535
Capturing cost (US$/t$CO_2$)	Low	276	203	178	165
	Mid	276	240	227	221
	High	276	276	276	276

kWh = kilowatt-hour, tCO_2 = tonne of carbon dioxide.
Note: 2017 real prices. The low case is based on Fasihi et al. (2019). Electricity cost is assumed to be US$0.1 per kWh for capture cost estimation.
Source: Author.

(l) Battery storage cost

The model includes pumped hydro storage, batteries, and compressed H_2 tanks as energy storage technologies. The required capacities for batteries and compressed H_2 tanks are determined endogenously within the simulation. The manufacturing cost of lithium-ion batteries is expected to decline substantially. Future cost reductions are based on projections by the National Renewable Energy Laboratory of the United States (US) (Figure 1.13). For Viet Nam, this study assumes no capacity for pumped hydro storage.

Figure 1.13. Assumed Lithium-ion Battery Cost



kWh = kilowatt-hour.
Note: 2017 real prices.
Source: Author, based on Cole and Frazier (2020).

Chapter 2

Results

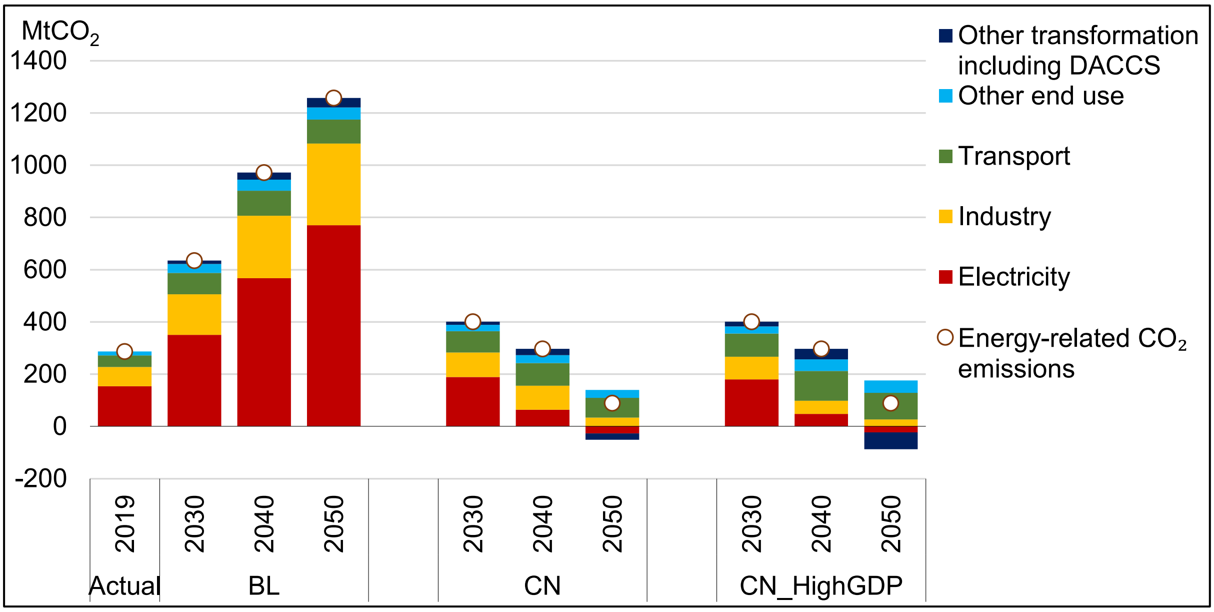
2.1. Key Energy-related Indicators

The main results of the model analysis for energy and emissions are shown in Figure 2.1 through Figure 2.13. The following section outlines these results, proceeding from downstream to upstream across the energy system. The analysis focuses primarily on the CN and BL scenarios for comparison, with attention later given to the CN_HighGDP scenario.

Energy-related Carbon Dioxide Emissions

Under the BL scenario, which imposes no emission constraints and allows the expanded use of coal, energy-related CO_2 emissions increase significantly through to 2050 (Figure 2.1). By contrast, the CN scenario limits total emissions to meet reduction targets, particularly achieving substantial early reductions in the electricity sector ahead of end-use sectors. By 2050, negative emissions technologies such as BECCS and DACCS will become cost competitive, offsetting residual emissions from hard-to-abate sectors such as high-temperature industrial processes and heavy-duty transport. The industrial sector also sees notable emission reductions compared with the BL scenario.

Figure 2.1. Sector Energy-related Carbon Dioxide Emissions



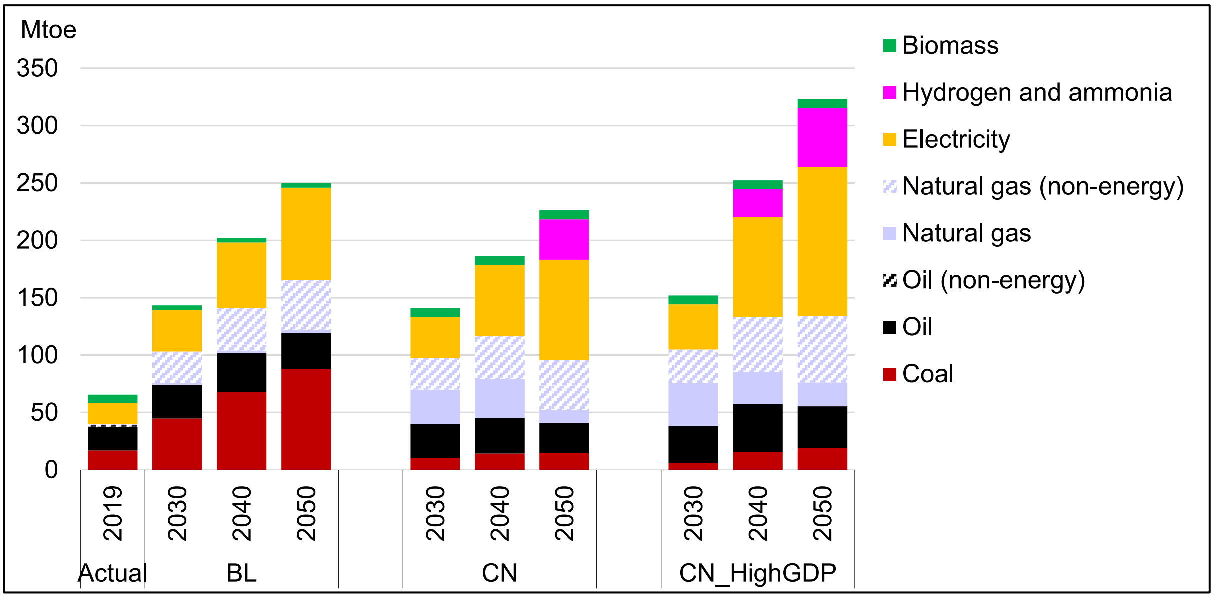
BL = baseline, CN = carbon neutral, CN_HighGDP = carbon-neutral with high economic growth, DACCS = direct air capture with carbon storage, $MtCO_2$ = metric tonne of carbon dioxide.
Source: Author.

Final Energy Consumption

In the BL scenario, final energy consumption is estimated to be 3.8 times higher in 2050 than in 2019, driven by robust economic growth. Conversely, under the CN scenario, final energy consumption in 2050 is 9.4% lower than in the BL scenario, owing to advancements in energy efficiency and increased electrification (Figure 2.2). However, the extent of additional energy savings in the CN scenario appears minimal in this cost-minimisation model, as energy-efficient technologies are also adopted in the BL scenario when deemed cost-effective, even in the absence of emission constraints. Concerning the energy mix, electricity consumption increases whilst coal consumption decreases in the CN scenario. Oil consumption remains relatively stable, as the road transport sector exhibits minor differences between the CN and BL scenarios (Figure 2.3). Passenger vehicles will largely shift to battery electric vehicles (BEVs) by 2050, even under the BL scenario. In contrast, buses and trucks begin partially shifting to BEVs after 2040 in the CN scenario.

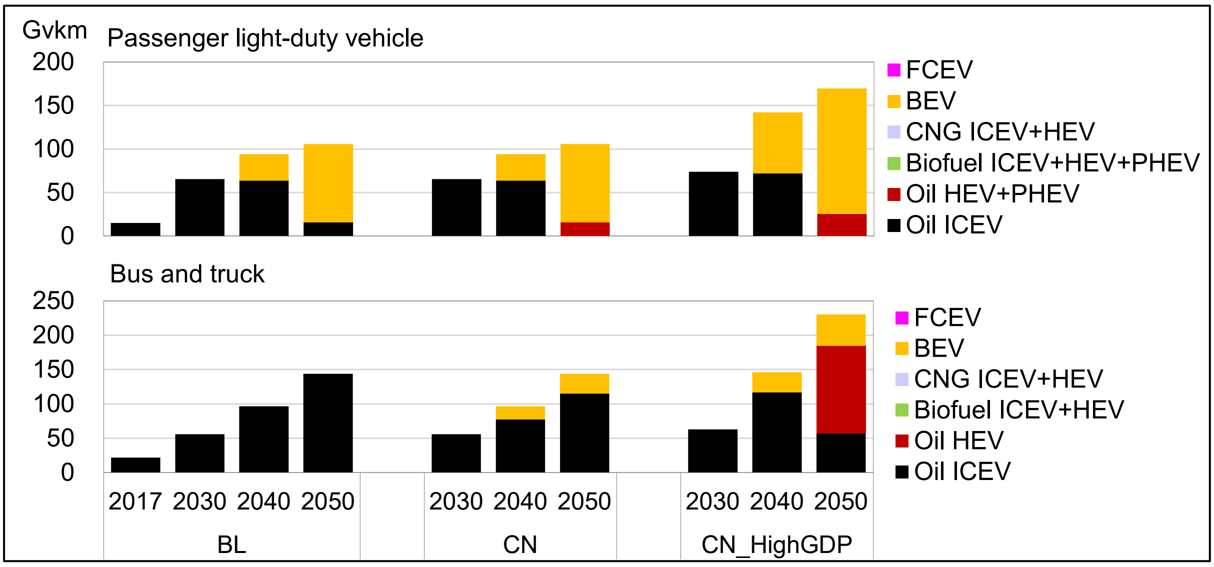
Electricity demand also increases to accommodate electrolysis and DAC by 2050, alongside rising industrial usage (Figure 2.4). The share of electricity losses increases after 2040, partly due to periods of low demand during which offshore wind-generated electricity is not fully utilised. Gaseous fuels are primarily consumed by industrial boilers and furnaces. Natural gas, excluding non-energy uses, increases significantly from 2030 to 2040 before transitioning to H_2 in 2050. In the CN scenario, the remaining coal consumption – mainly for blast furnaces and cement kilns – declines significantly following CCS deployment after 2040.

Figure 2.1. Final Energy Consumption



BL = baseline, CN = carbon neutral, CN_HighGDP = carbon-neutral with high economic growth, Mtoe = metric tonne of oil equivalent.
Source: Author.

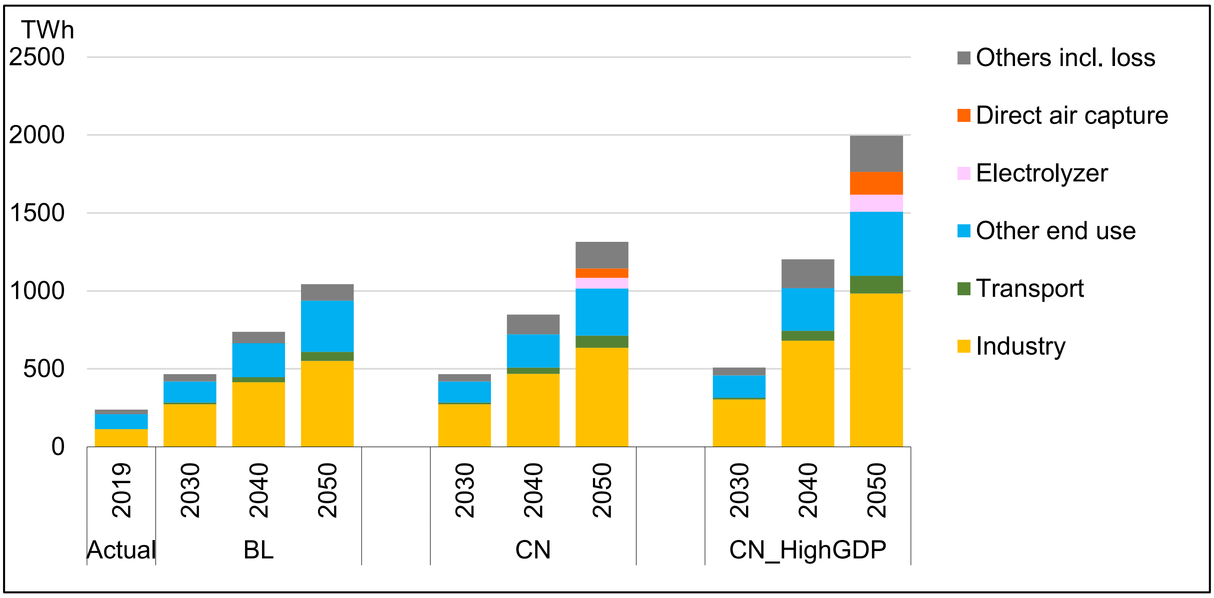
Figure 2.2. Travel Distance by Vehicle Technology



BEV = battery electric vehicle, BL = baseline, CN = carbon neutral, CN_HighGDP = carbon-neutral with high economic growth, CNG ICEV = compressed natural gas internal combustion engine vehicle, FCEV = fuel cell electric vehicle, Gvkm = gigavehicle kilometre, HEV = hybrid electric vehicle, PHEV = plug-in electric vehicle.

Source: Author.

Figure 2.4. Electricity Demand



BL = baseline, CN = carbon neutral, GDP = gross domestic product, incl. = including, TWh = terawatt-hour.

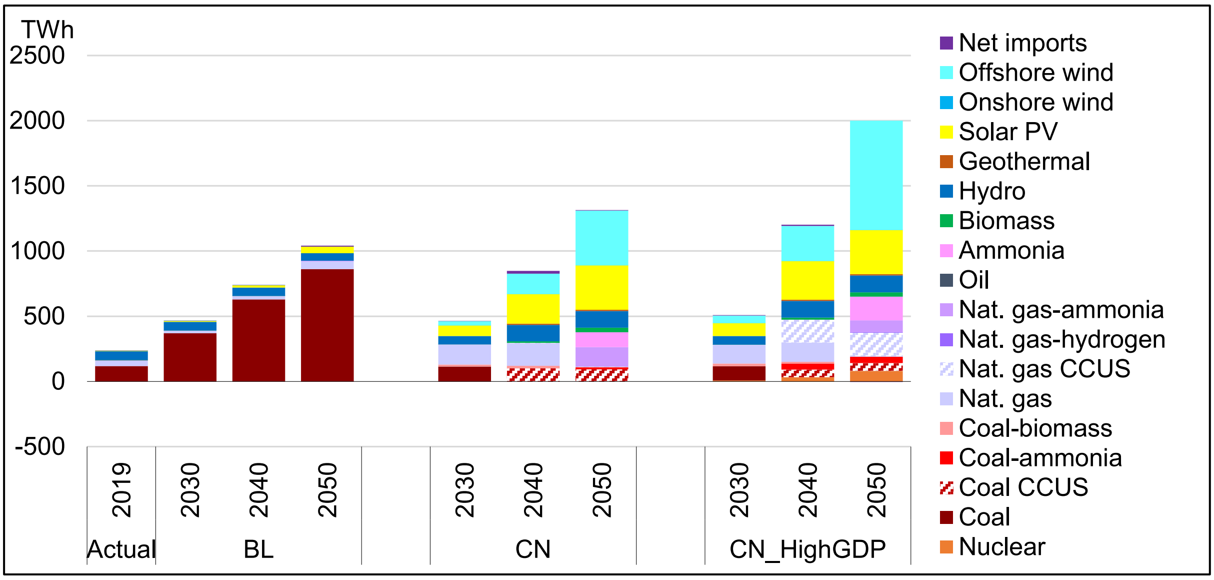
Note: 'Others incl. loss' is calculated by subtracting the electricity demands of industry, transport, other end-use sectors, electrolysers, and direct air capture from total power generation (Figure 2.5).

Source: Author.

Power Generation

Power generation increases at a much faster pace than total final energy consumption, reaching 5.5 times its 2019 level by 2050 under the CN scenario (Figure 2.5). After 2040, renewables – especially offshore wind and solar PV – dominate the power mix. Gas-fired generation increases from 2030 to 2040, shifting completely to clean thermal power by 2050 (Figure 2.6), with retrofitting of gas plants to NH_3 firing or newly installed NH_3 firing. Coal-fired power, the capacity and operation of which are assumed exogenously, is decarbonised by equipping all plants with CCS after 2040. Biomass power also adopts CCS (BECCS) after 2040. In the CN scenario, nuclear power is not selected due to the greater cost competitiveness of wind power (Figure 1.11).

Figure 2.5. Power Generation by Technology

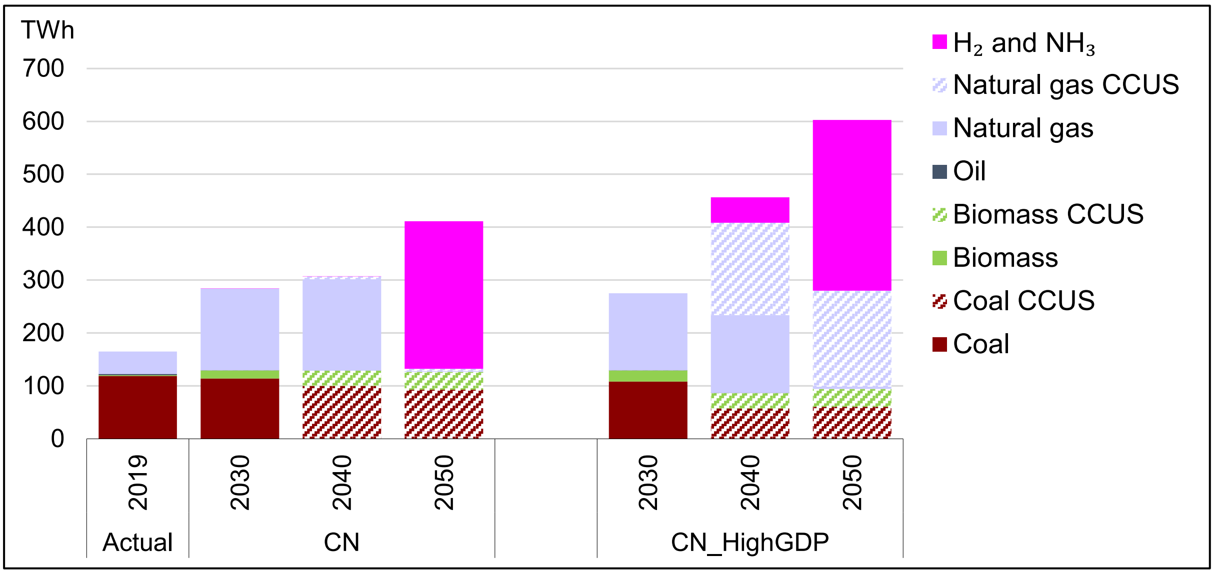


BL = baseline; CCUS = carbon capture, utilisation, and storage; CN = carbon neutral; GDP = gross domestic product; PV = photovoltaic; TWh = terawatt-hour.

Note: Includes curtailed electricity from variable renewable energy sources. 'Nat. gas-ammonia' refers to 100% ammonia firing in retrofitted natural gas turbines.

Source: Author.

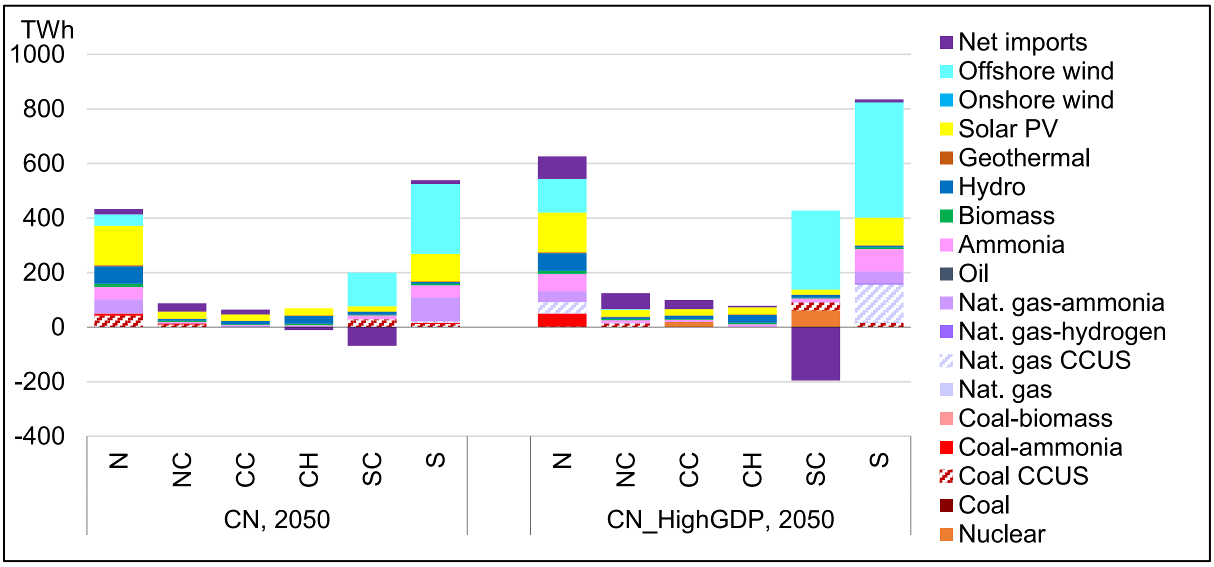
Figure 2.6. Thermal Power Generation by Energy Source



CCUS = carbon capture, utilisation, and storage; CN = carbon neutral; CN_HighGDP = carbon-neutral with high economic growth; H_2 = hydrogen; NH_3 = ammonia; TWh = terawatt-hour.
Source: Author.

Substantial infrastructure investment is required to manage the mass deployment of solar PV and offshore wind. Due to the geographical mismatch between electricity demand and variable renewable energy (VRE) resources, the SC region is projected to become a net electricity exporter by 2050 (Figure 2.7, Figure 2.8). To achieve this electricity flow, interregional transmission capacity must expand significantly, reaching 5.0 times the 2020 level by 2050 (Figure 2.9). In addition to thermal generation, battery storage is introduced to enhance grid flexibility in response to increasing VRE penetration. Battery storage capacity is projected to reach 188 gigawatt-hours by 2050 (Figure 2.10).

Figure 2.7. Regional Power Generation by Technology in 2050

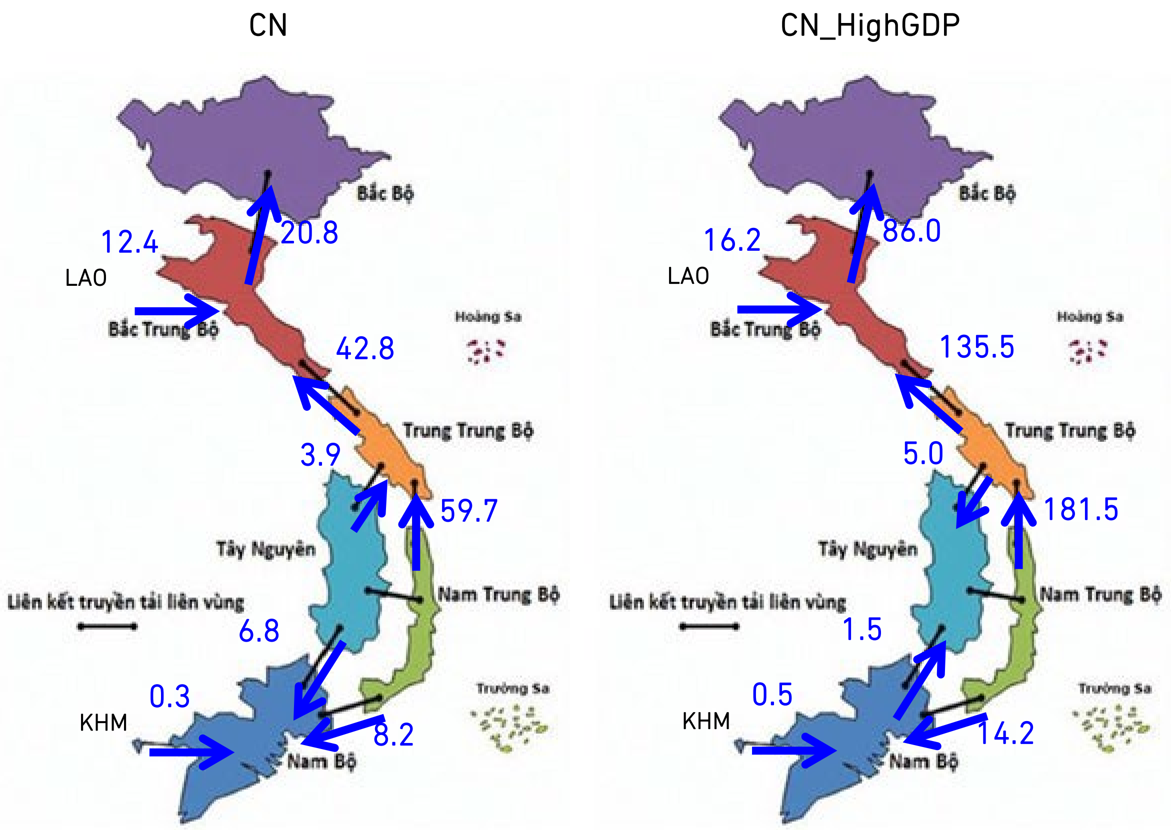


CCUS = carbon capture, utilisation, and storage; CN = carbon neutral; CN_HighGDP = carbon-neutral with high economic growth; nat. = natural; PV = photovoltaic; TWh = terawatt-hour.

Note: Includes curtailed electricity from variable renewable energy sources. 'Nat. gas-ammonia' refers to 100% ammonia firing in retrofitted natural gas turbines.

Source: Author.

Figure 2.8. Annual Net Electricity Flow in 2050 (TWh)

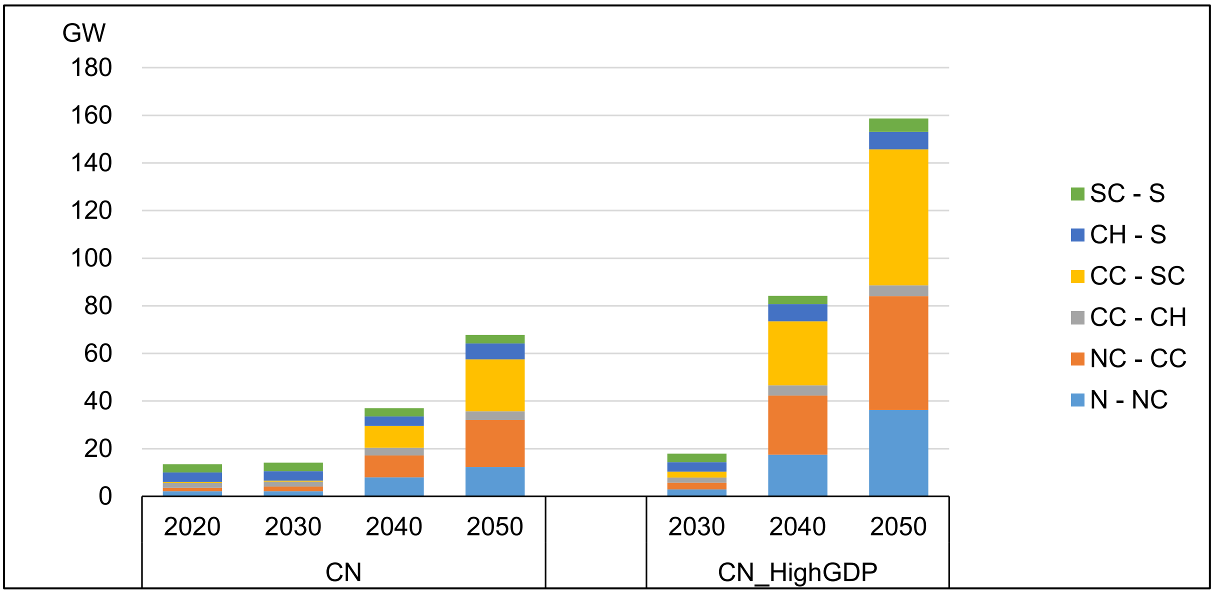


CN = carbon neutral, CN_HighGDP = carbon-neutral with high economic growth, TWh = terawatt-hour.

Note: Includes electricity losses during transport.

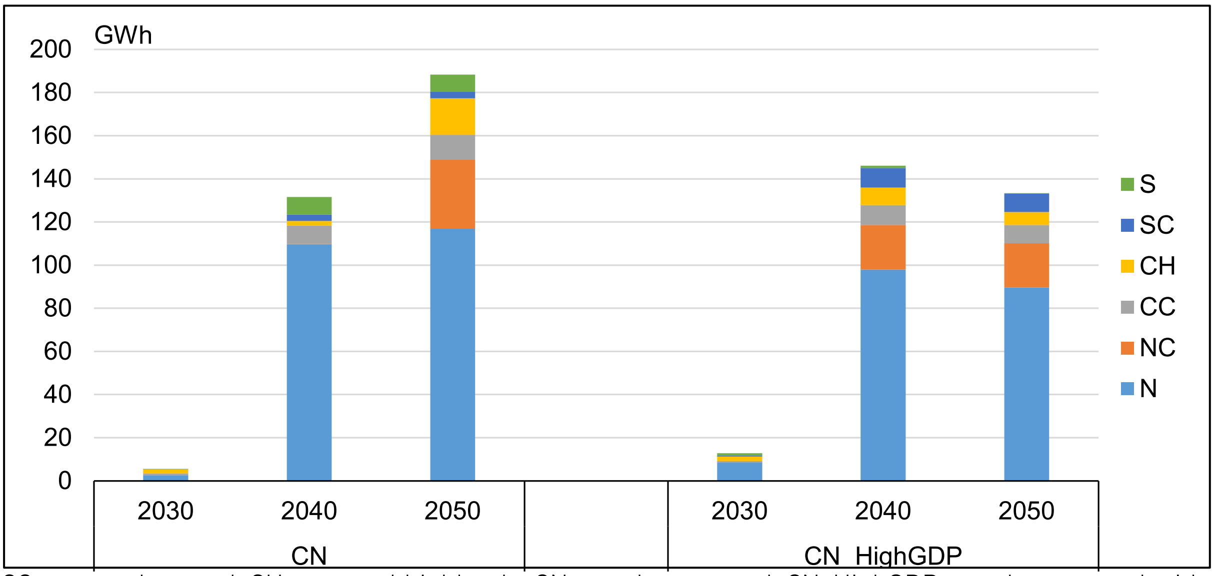
Source: Author, based on Vietnam Electricity (2020).

Figure 2.9. Transmission Line Capacity



CC = centra central, CH = central highlands, CN = carbon neutral, CN_HighGDP = carbon-neutral with high economic growth, GW = gigawatt, N = north, NC = north central, S = south, SC = south central.
Source: Author.

Figure 2.3. Installed Battery Storage Capacity

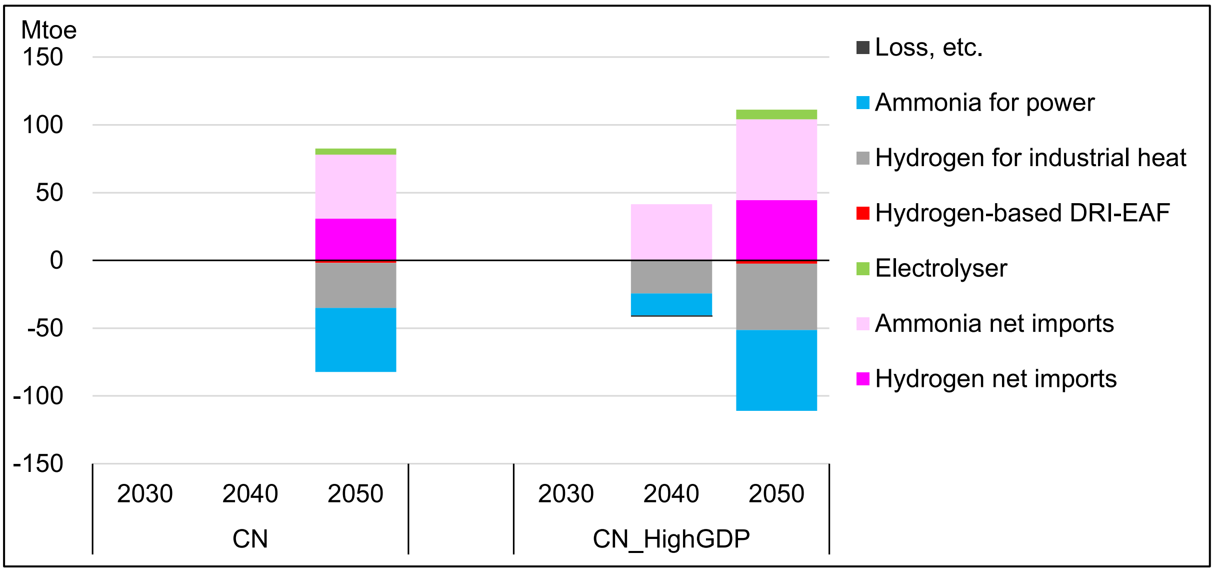


CC = central central, CH = central highlands, CN = carbon neutral, CN_HighGDP = carbon-neutral with high economic growth, GWh = gigawatt-hour, N = north, NC = north central, S = south, SC = south central.
Source: Author.

Hydrogen; Ammonia; and Carbon Capture, Utilisation, and Storage

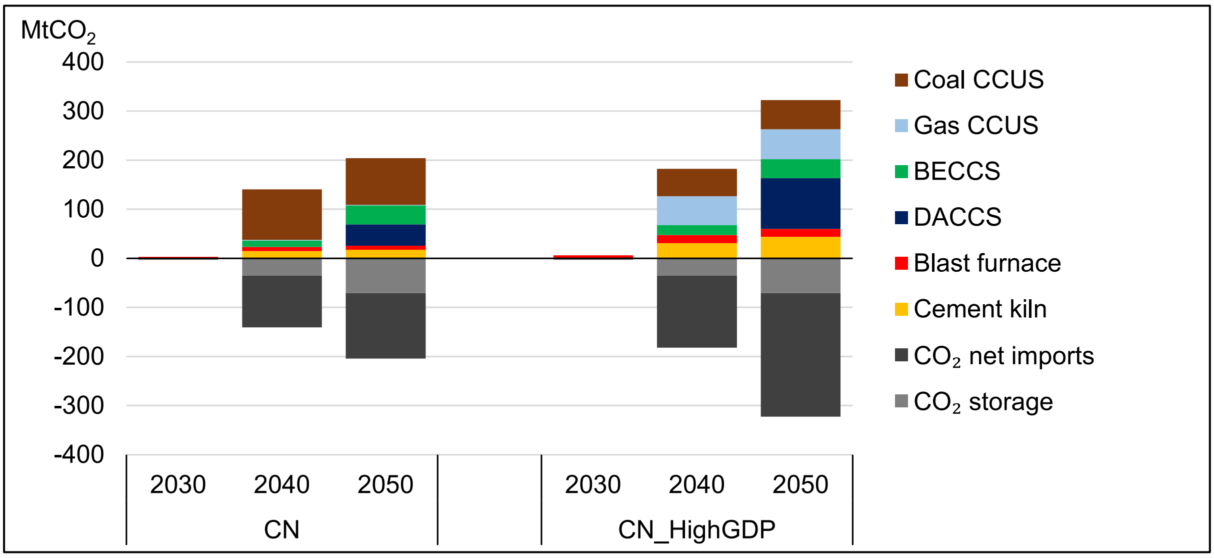
H_2 and NH_3 are mainly supplied through inexpensive imports, with H_2 used in industry and NH_3 in power generation (Figure 2.11). CO_2 is captured from coal-fired power plants, blast furnaces, cement kilns, biomass-fired power plants, and DAC systems (Figure 2.12). Due to limited domestic storage, captured CO_2 is exported to neighbouring ASEAN countries. CCU was not selected for this study due to its high cost.

Figure 2.11. Supply and Demand of Hydrogen and Ammonia



CN = carbon neutral, CN_HighGDP = carbon-neutral with high economic growth, DRI-EAF = direct reduced iron-electric arc furnace, Mtoe = metric tonne of oil equivalent.
Source: Author.

Figure 2.4. Supply and Demand of Captured Carbon Dioxide

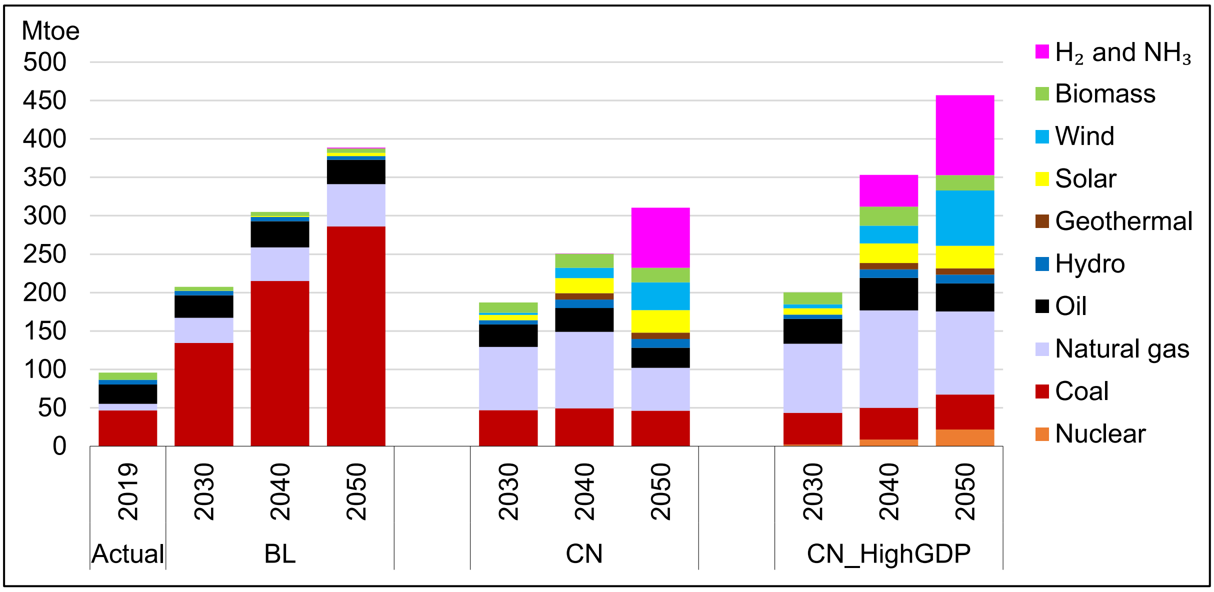


BECCS = bioenergy with carbon capture and storage; CCUS = carbon capture, utilisation, and storage; CN = carbon neutral; CN_HighGDP = carbon-neutral with high economic growth; DACCS = direct air capture with carbon storage; GDP = gross domestic product; $MtCO_2$ = metric tonne of carbon dioxide.
Source: Author.

Primary Energy Supply

Primary energy supply patterns reflect the changes in final energy consumption and power generation (Figure 2.13). In the CN scenario, the total primary energy supply is much smaller than in the BL scenario due to energy savings and the assumption that solar, wind, and hydro have a conversion efficiency of 100%. The notable increase in natural gas usage in 2030 and 2040 is driven by industrial and power generation demand, including non-energy applications.

Figure 2.13. Primary Energy Supply



BL = baseline, CN = carbon neutral, CN_HighGDP = carbon-neutral with high economic growth, H_2 = hydrogen, Mtoe = metric tonne of oil equivalent, NH_3 = ammonia.
Source: Author.

CN_HighGDP Scenario

The CN_HighGDP scenario assumes substantially higher economic growth, resulting in final energy consumption that is 1.4 times greater than in the CN scenario by 2050. Consequently, DACCS deployment accelerates to offset increased residual emissions, particularly from transport. In terms of the power mix, both offshore wind and gas-fired generation with CCS increase after 2040 to meet high demand. In 2040, gas-fired generation with CCS will be cost competitive because the costs of H_2 and NH_3 have not yet fallen sufficiently. Solar PV also increases in 2040 but remains stable in 2050, having already reached the assumed upper limit in the CN scenario. In the CN_HighGDP scenario, nuclear power – with reduced capital cost assumptions – is deployed up to the 13 GW upper limit assumed for 2050. The share of renewable energy generation reaches 68% in 2050, comparable to 71% in the CN scenario. Given the higher level of VRE deployment in this scenario, the importance of interregional grid interconnections and expanded transmission capacity becomes even more pronounced.

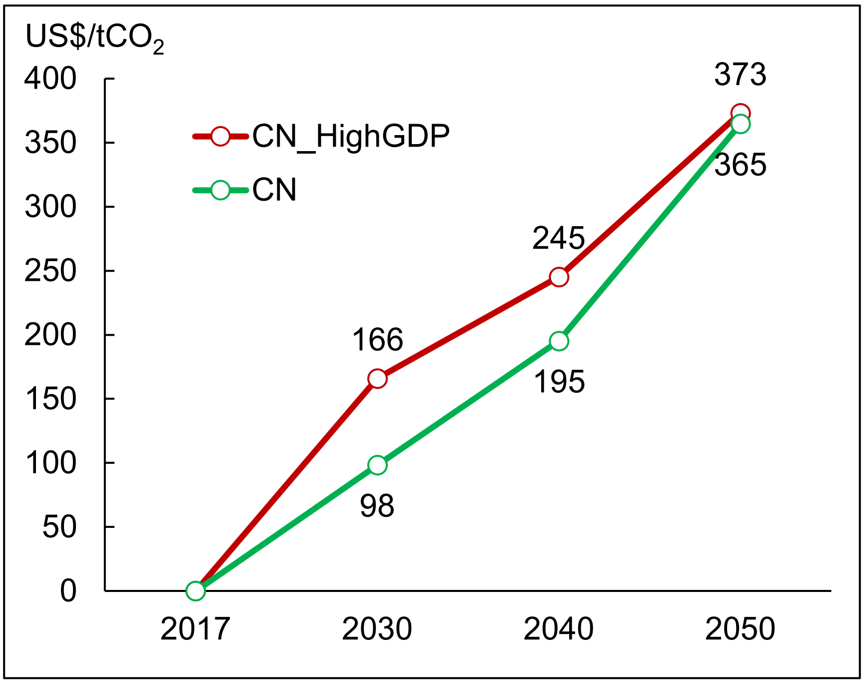
2.2. Financial Indicators

This section discusses three economic indicators. The marginal abatement cost (MAC) is defined as the cost of reducing an additional tonne of CO_2, and may be interpreted as the theoretical carbon price within the model. In the CN scenario, MAC increases almost linearly, reaching US$365 by 2050 (Figure 2.14), which is higher than the emissions allowance price of US$61 in the European Union (EU) Emissions Trading Scheme as of 1 April 2024 (World Bank, 2025).

Marginal electricity costs increase through to 2040, followed by a modest decline in 2050 under the CN scenario (Figure 2.15). Compared with the BL scenario, which relies on low-cost coal-fired power, the marginal electricity cost in 2040 rises by a factor of 2.3. This analysis defines the marginal electricity cost as the average across 2,190 time slots, with each slot's marginal cost reflecting the variable cost of the power source supplying the last kilowatt-hour. The decline in marginal electricity cost in 2050 is primarily due to a lower NH_3 fuel price and the inclusion of CO_2 costs – on top of fuel costs – for unabated natural gas-fired power generation in 2040.

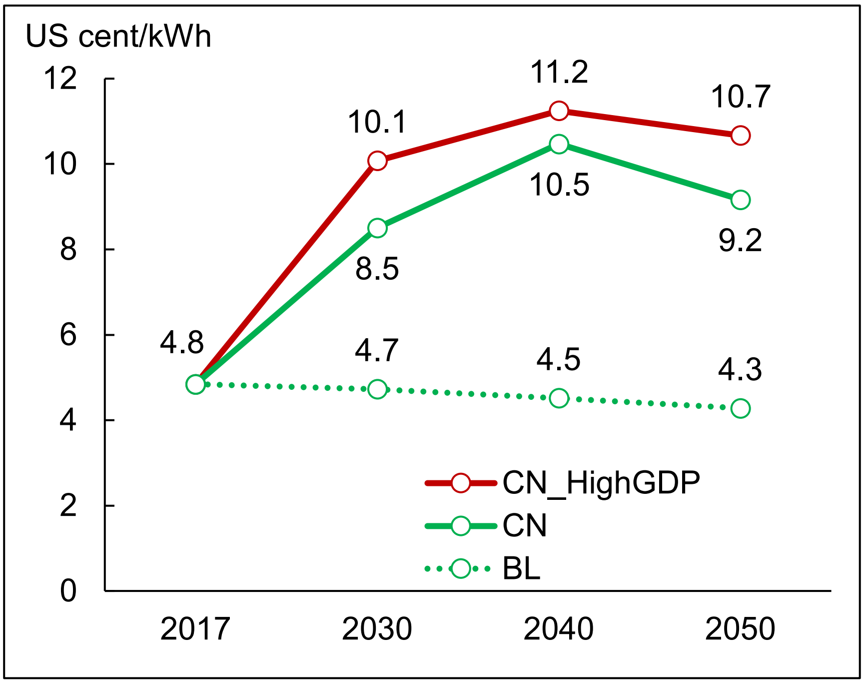
Concerning total cost – represented by the model's objective function – the annual additional costs relative to the BL scenario, expressed as a share of GDP, also rise almost linearly, peaking at 7.2% of GDP in 2050 (Figure 2.16). In that year, fixed costs for VRE and fuel costs for imported H_2 and NH_3 account for a significant share. In the CN_HighGDP scenario, all cost indicators exceed those of the CN scenario. The increases in MAC and marginal electricity costs are particularly pronounced, especially in 2030. Additional annual costs from the BL scenario, including incremental costs from higher economic growth, reach 12.3% of GDP in 2050.

Figure 2.14. Marginal Abatement Cost of Carbon Dioxide



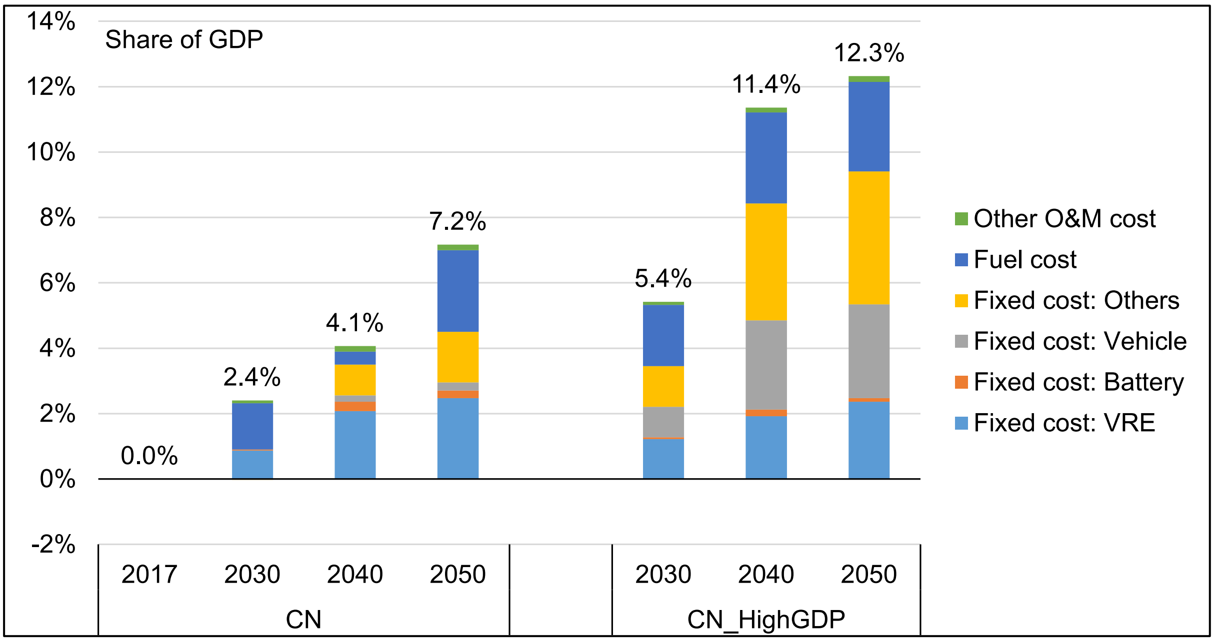
CN = carbon neutral, CN_HighGDP = carbon-neutral with high economic growth, tCO_2 = tonne of carbon dioxide.
Note: 2017 real price.
Source: Author.

Figure 2.5. Marginal Electricity Cost



BL = baseline, CN = carbon neutral, CN_HighGDP = carbon-neutral with high economic growth, kWh = kilowatt-hour.
Note: 2017 real price.
Source: Author.

Figure 2.16. Additional Annual Costs from the Baseline

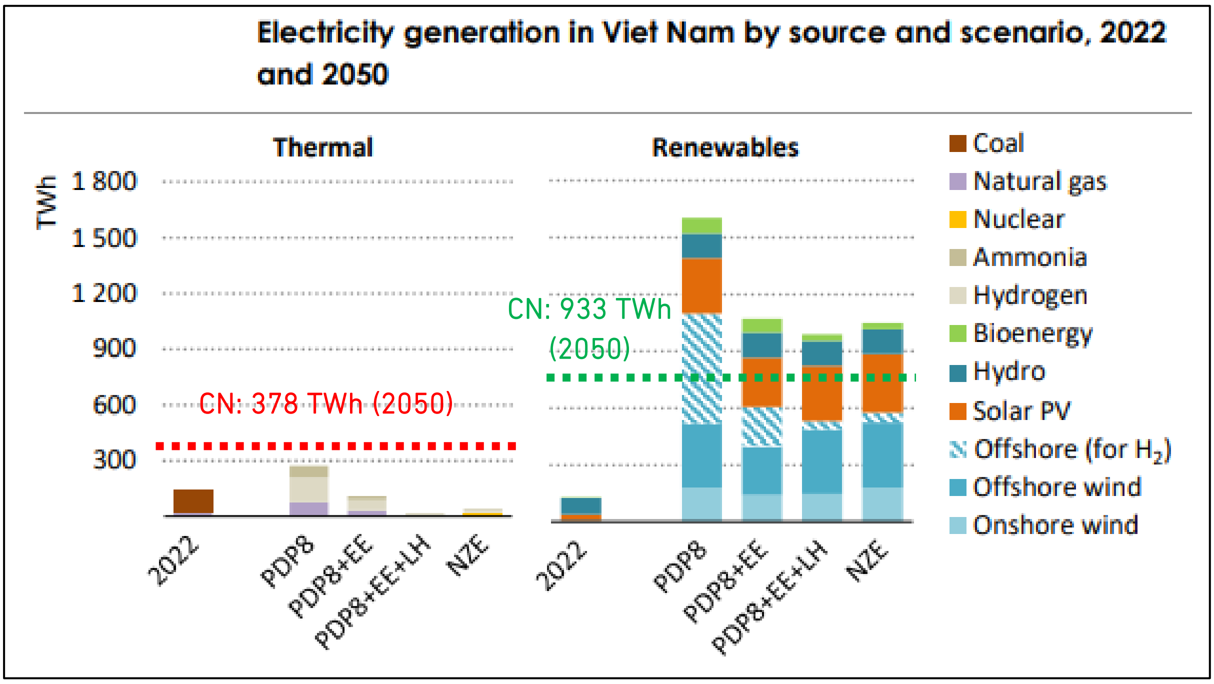


BL = baseline, CN = carbon neutral , CN_HighGDP = carbon-neutral with high economic growth, GDP = gross domestic product, O&M = operation and maintenance, VRE = variable renewable energy.
Note: Based on 2017 real prices. The annual cost of the CN_HighGDP scenario was estimated by dividing the increment from the BL scenario by the GDP assumption for the CN_HighGDP scenario.
Source: Author.

2.3. Comparison with Other References

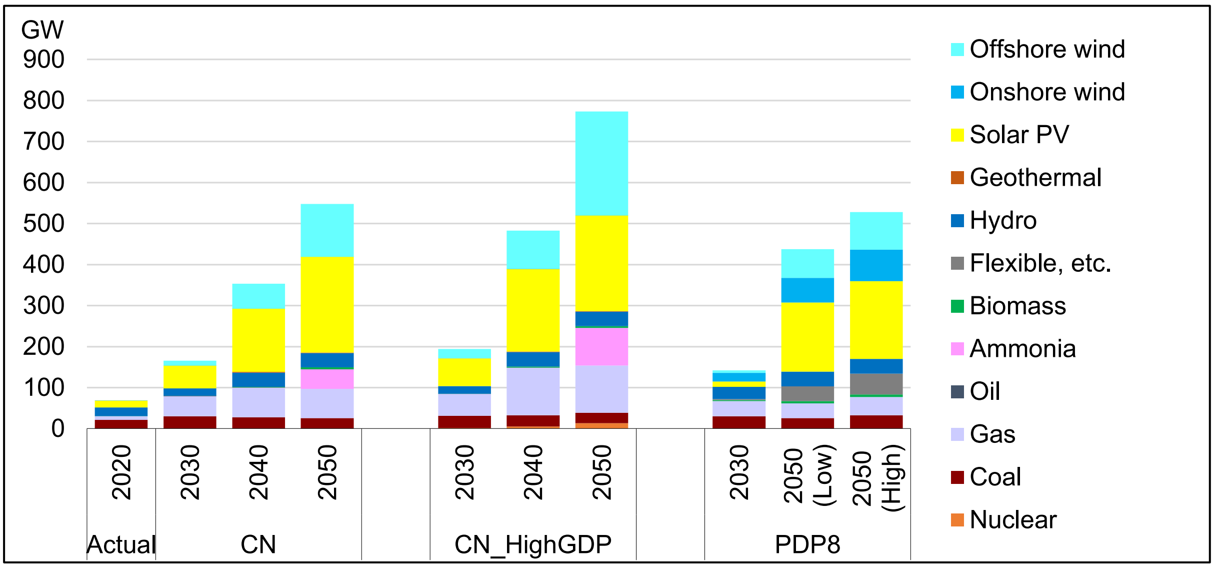
This analysis was validated through comparison with other reference studies. Compared with the IEA (2024) analysis on power generation, thermal power generation plays a more significant role in this study's CN scenario, whereas renewable power generation is slightly lower (Figure 2.17). Except for the IEA's PDP8 scenario, total generation is higher in the CN scenario, with a smaller share from renewable sources. Notably, the IEA's PDP8 scenario estimates a higher level of total generation than the CN scenario, primarily due to the substantial offshore wind capacity necessary for domestic green H_2 production. In contrast, this study assumes that H_2 and NH_3 can be imported. A comparison between the CN scenario and the government's PDP8 outlook of power generation capacity reveals that the CN scenario features a higher installed PV capacity in 2030 (Figure 2.18). By 2050, the total installed capacity and the share of key technologies, such as solar PV, wind, and thermal power, are broadly similar between the CN scenario and the PDP8 outlook. However, the CN scenario does not select onshore wind power due to its lower capacity factor and higher LCOE compared with offshore wind (Figure 1.11). Installed capacity in the CN_HighGDP scenario reaches 774 GW by 2050, 1.5 times higher than the PDP8 high case. In both CN and CN_HighGDP scenarios, PV capacity approaches its upper limit by 2050, whilst offshore wind capacity remains below its potential maximum, even in the CN_HighGDP scenario.

Figure 2.17. Power Generation Compared to the International Energy Agency Analysis



CN = carbon neutral, EE = energy efficiency, H_2 = hydrogen, LH = low hydrogen, PDP8 = Power Development Plan 8, PV = photovoltaic, NZE = net-zero emissions, TWh = terawatt-hour.
Source: Author's additions to International Energy Agency (2024).

Figure 2.6. Installed Power Generation Capacity Compared with the Power Development Plan 8 Outlook



CN = carbon neutral, CN_HighGDP = carbon-neutral with high economic growth, GW = gigawatt, PDP8 = Power Development Plan 8, PV = photovoltaic
Source: Author, based on PDP8.

Chapter 3

Key Implications

3.1. Electricity Demand and Supply

Energy Efficiency and Electrification

- Promoting energy efficiency and electrification is a core element in achieving carbon neutrality. When additional economic growth is factored in, it becomes necessary to enhance these efforts even more aggressively.
- In scenarios where economic growth and carbon neutrality are pursued simultaneously, electricity demand will surge rapidly, increasing societal dependence on electricity. Substantial investment in the power system is required to enhance its resilience.

Renewable Energy, Grid Reinforcement, and Flexibility

- Viet Nam possesses abundant renewable energy resources. Maximising their utilisation is crucial to achieving carbon neutrality. Under both the CN and CN_HighGDP scenarios, solar PV deployment will increase significantly in the short to medium term, whilst offshore wind capacity will expand substantially in the medium to long term. As a result, the share of renewable energy in electricity generation could reach approximately 70% by 2050.
- However, the expansion of VRE, coupled with the geographic concentration of optimal renewable sites (particularly the predominance of offshore wind in the south), will widen the temporal and spatial mismatch between electricity supply and demand. Beyond rapidly expanding generation capacity, strategic grid reinforcement and enhanced flexibility will become critical in the medium term. Priorities include enhancing north–south transmission lines, ensuring adequate balancing power sources, and deploying battery storage systematically. Discussions on fair cost-sharing mechanisms and transparent cost recovery schemes for these infrastructure investments are needed.

Role of Natural Gas as a Transition Fuel

- In both the CN and CN_HighGDP scenarios, the primary energy supply from natural gas is projected to increase until 2040. Subsequently, the transition to H_2 and NH_3 in the industrial and power sectors will gradually reduce gas consumption. This underscores the critical role of natural gas as a transition fuel, bridging the gap between growing energy demand and supply during the decarbonisation process.
- When developing gas and LNG infrastructure, designing facilities with the potential for future conversion to H_2 and NH_3 can help optimise total energy system costs in

the long term. Transition finance may also serve as an effective means to secure efficient and sufficient funding for gas infrastructure development.

Hydrogen and Ammonia

- H_2 and NH_3 are expected to play an increasingly vital role in decarbonising the industrial and power sectors in the latter stages of carbon neutrality transition.
- However, the future cost of H_2 and NH_3 supply chains remains highly uncertain. It is crucial to consider not only domestic production but also the potential for imports, whilst leveraging global technological advancements to drive cost reductions.

Carbon Capture and Storage

- CCS technology will play an important role in the medium to long term by enabling the continued utilisation of coal and gas assets and offsetting emissions from hard-to-abate sectors through negative-emission technologies such as BECCS and DACCS.
- To deploy CCS, detailed geological surveys and economic feasibility assessments must be conducted, alongside the establishment of regulatory frameworks to facilitate CCS projects. Strengthening regional collaboration for cross-border CO_2 transport and storage will also be critical in addressing storage capacity uncertainty and reducing costs through site optimisation. Exploring international cooperation, such as establishing joint CCS hubs within ASEAN, will be a key strategic approach.

Nuclear Power

- As a stable, long-term decarbonised energy source, nuclear power could support Viet Nam's growing electricity demand whilst enhancing power system stability. Although nuclear power requires large-scale investment and long construction timelines – introducing uncertainty in both costs and deployment pace – it could play a greater role through the adoption of SMRs and advanced nuclear technologies. The introduction of such technologies should be supported through international cooperation, particularly based on commercialisation efforts in developed countries.
- However, the deployment of nuclear power presents multiple challenges that cannot be fully resolved within the current energy system models. A more detailed analysis of nuclear energy utilisation, taking these complexities into account, will be presented in the next section.

3.2. Economic Challenges for Achieving Carbon Neutrality

- Under the CN scenario, MAC is projected to rise steadily, reaching US$365 per tonne of CO_2 by 2050. In the CN_HighGDP scenario, which incorporates higher economic growth and energy demand, decarbonisation technologies must be introduced earlier, before anticipated cost reductions from technological advancements are realised. Consequently, the short-term increase in MAC is more pronounced than in the CN scenario. This highlights the importance of strong and early incentives – such as carbon pricing – for low-carbon and zero-carbon technologies to support the energy transition amid increasing energy demand. However, the rapid introduction of carbon pricing could negatively impact industrial competitiveness and economic stability. A phased and predictable policy design is therefore crucial.

- The total increase in energy system costs relative to the BL scenario is projected to reach 7.2% of GDP in the CN scenario by 2050, and 12.3% in the CN_HighGDP scenario. To mitigate the social burden of the energy transition, efforts should focus on reducing investment risks and capital costs through public–private partnerships, and on lowering technology adoption costs via international cooperation.

Part 2
Potential Utilisation of Nuclear Power in Viet Nam

Nobuo Tanaka

Fengjun Duan

Kentaro Noma

Daisuke Kiuchi

Han Phoumin

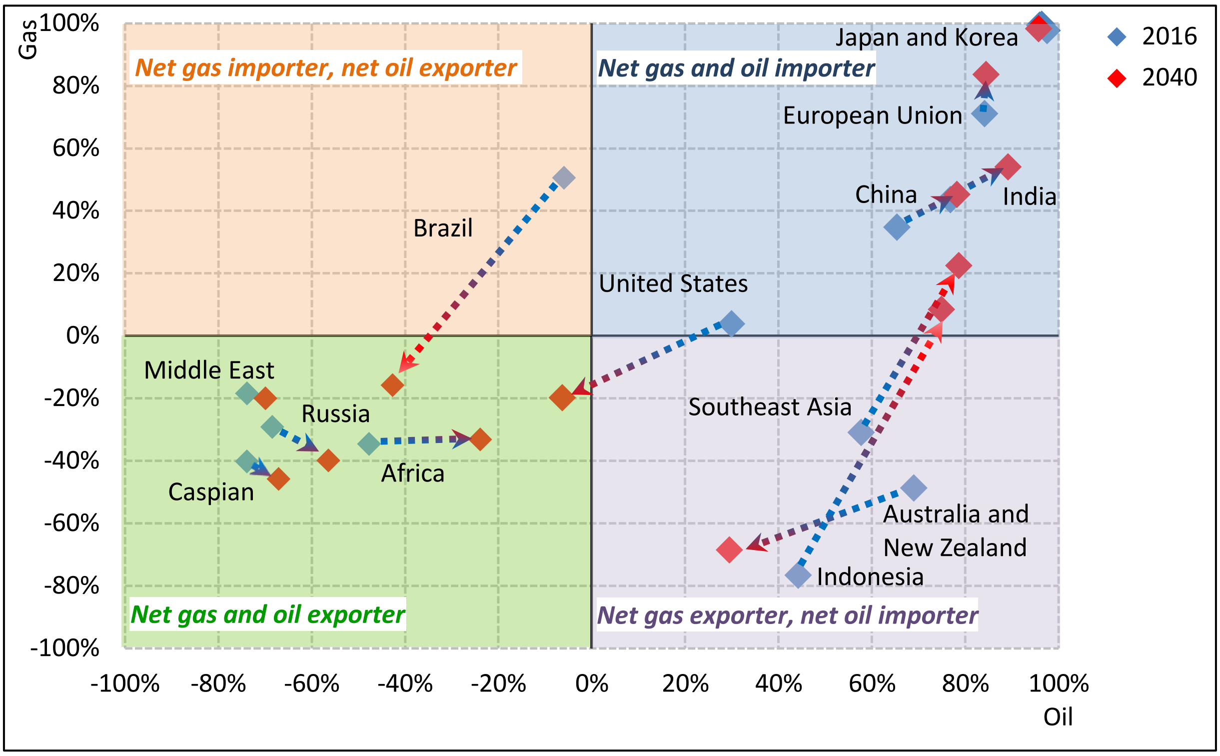
Chapter 4

Global Energy and Climate Crises

Dr. Fatih Birol, IEA executive director, has stated that the world is experiencing the first truly global energy crisis. The IEA was established in response to the first oil shock in 1974, when oil prices quadrupled. However, the Russian invasion of Ukraine has driven prices for all forms of energy – natural gas, oil, coal, and electricity – to unprecedented highs. As a result, energy security has become the top priority for many, if not all, governments. Simultaneously, extreme weather events are occurring with increasing frequency, far beyond historic trends. More than 100 countries have committed to achieving net-zero CO_2 emissions by the middle of this century. These dual crises – energy and climate – are propelling the world into an unparalleled struggle that will define the coming decades.

Figure 4.1 shows the import dependency of countries on oil (horizontal axis) and natural gas (vertical axis) in 2016 and 2040 under the IEA's Stated Policies Scenario. Countries in the blue area are net importers of both oil and gas, whilst those in green are net exporters. In 1973, Arab oil exporters imposed an embargo to undermine the pricing power of the so-called 'Seven Sisters' – the major Western oil companies – triggering the oil shock of 1974.

Figure 4.1. Oil and Gas Import Dependency of Countries

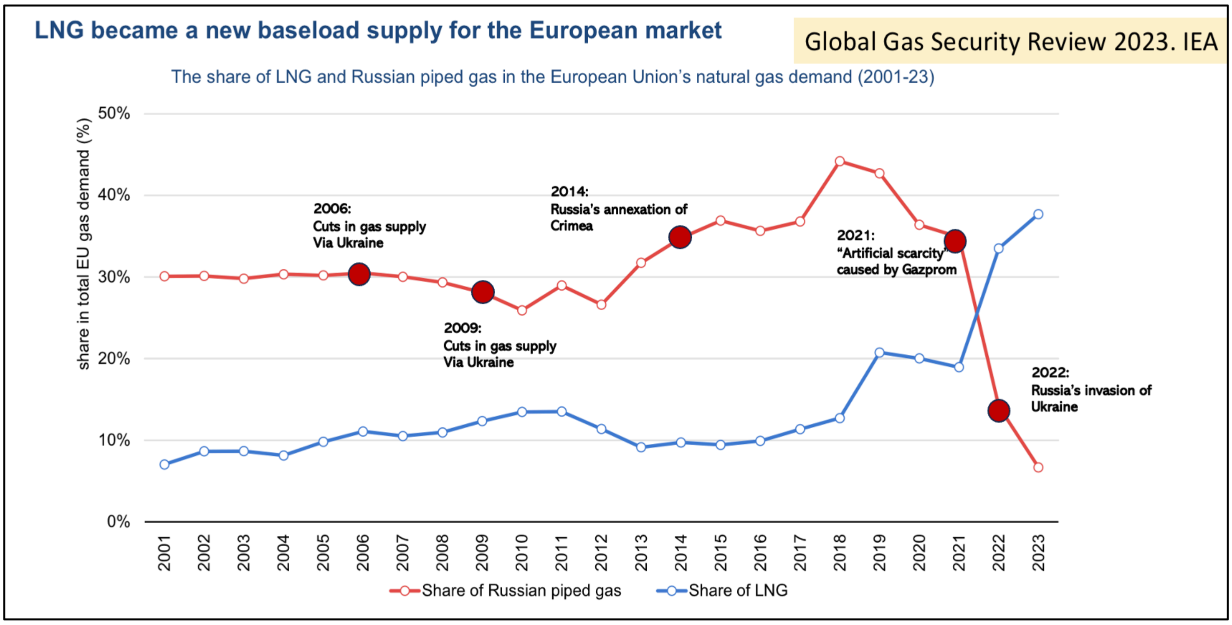


Source: International Energy Agency (2017).

Before the Shale Oil and Gas Revolution around 2010, the US was expected to become increasingly reliant on imported oil and natural gas. However, the shale revolution shifted the US from a net importer to a net exporter, moving from the blue to the green zone. Today, the US is the world's largest producer of oil and natural gas. This energy independence has been reinforced by President Trump's 'drill-baby-drill' policy, which sought to establish 'energy dominance'. In recent years, the US has drawn closer to Russia and the Middle East in what some have described as a 'fossil fuel alliance'. Russia, having lost its largest market for oil and gas – Europe – now faces economic isolation due to Western sanctions, a halt in foreign investment and technology, and a growing brain drain. Russia is amongst the least prepared nations for a net-zero CO_2 world. Europe, in contrast, has moved away from dependence on Russian pipeline gas towards LNG, with the US emerging as its largest LNG supplier. The fact that Saudi Arabia hosted peace negotiations on Ukraine involving the US and Russia could symbolically indicate the formation of a trilateral 'fossil fuel alliance'.

In response, Europe is accelerating the deployment of renewable energy and nuclear power to advance climate goals and energy independence. Following the Ukraine war, the EU launched the RePowerEU programme, which aims to achieve both de-Russianisation and decarbonisation. Through initiatives such as the Energy Union, the EU has built a collective energy security paradigm, interconnecting grid lines and gas pipelines across member states. This integration supports a broader electricity market and stabilises supply volatility by leveraging French nuclear, Nordic hydro, Polish coal, and, formerly, Russian gas. However, the EU's significant dependence on Russian pipeline gas ultimately proved detrimental, particularly in the context of the war in Ukraine.

Figure 4.2. Global Gas Security Review 2023



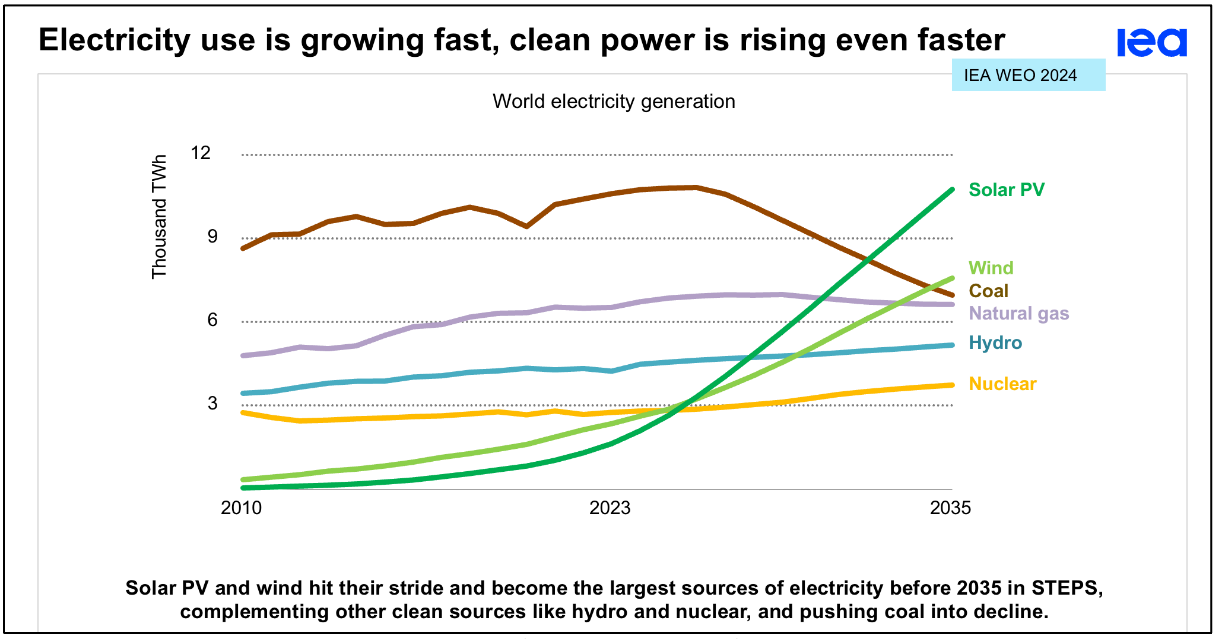
EU = European Union, IEA = International Energy Agency, LNG = liquefied natural gas.
Source: International Energy Agency (2023).

Complicating the story is the speed of decarbonisation. Although President Trump withdrew from the Paris Agreement, major tech firms continued to advance towards 100% renewable energy. Whilst many governments have committed to achieving net-zero CO_2 emissions by 2050, Apple, Facebook, Google, and Amazon (GAFA), along with Microsoft, are targeting net zero by 2030. These companies are requiring their suppliers – regardless of location – to adopt the same goal. The rapid expansion of artificial intelligence (AI) and data centres will drive a huge increase in demand for clean electricity in the coming years. The automotive sector is likely to follow suit. Green steel and semiconductors will become essential. According to the IEA, future investment in energy-intensive industries is expected to favour regions with abundant clean electricity and strong CCUS (World Energy Outlook, 2022). Industrial relocation is already underway, as manufacturers seek cleaner sources of power.

This energy transition is being driven by demand, not supply. The US' Inflation Reduction Act has attracted investment from the German steel industry to produce low-carbon steel using CCS and clean H_2. Whilst President Trump may stop subsidies for electric vehicles (EVs), he may retain other components of the act, as many Republican-led states are eager to continue CCS and clean H_2 projects. He may also support nuclear expansion, with proposals to add 200 GW of capacity and potentially triple the total by 2050.

Nuclear power has regained appeal amongst megatech firms as a low-carbon, dispatchable energy source. In particular, SMRs may see rapid growth if regulatory frameworks are put in place. GAFA and certain chemical industries are exploring SMRs as off-grid, in-house electricity solutions. Solar and wind are increasingly preferred by demand-side industries over fossil fuels (Figure 4.3). Although nuclear is also expanding, its growth is slower than that of solar and wind power.

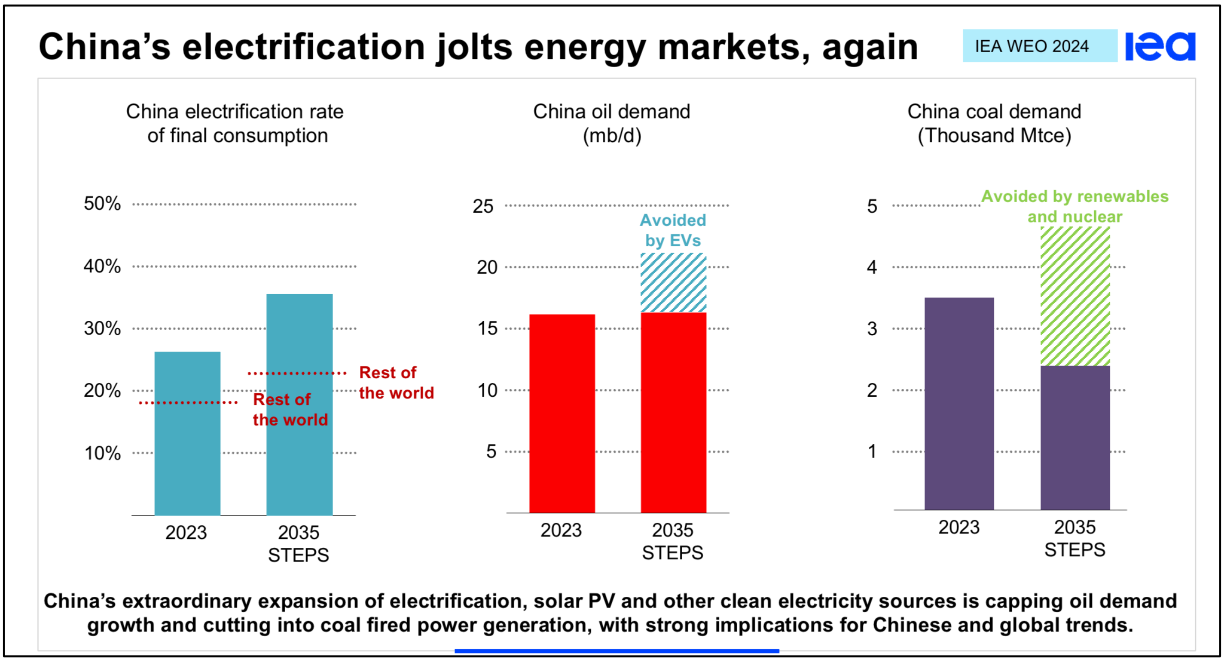
Figure 4.3. World Electricity Generation



PV = photovoltaic, TWh = terawatt-hour, WEO = World Energy Outlook.
Source: International Energy Agency (2024).

China stands to benefit strategically from this crisis. Its decarbonisation target is set for 2060, and its strategy revolves around electrification through wind, solar, H_2, battery storage, and EVs (Figure 4.4). Due to slower economic growth and rising EV adoption, China's oil demand may have peaked in 2023, much earlier than previously projected (around 2030 or earlier). China dominates the supply chain for critical decarbonisation technologies, including solar cells, wind turbines, EVs, electrolysers, and batteries.

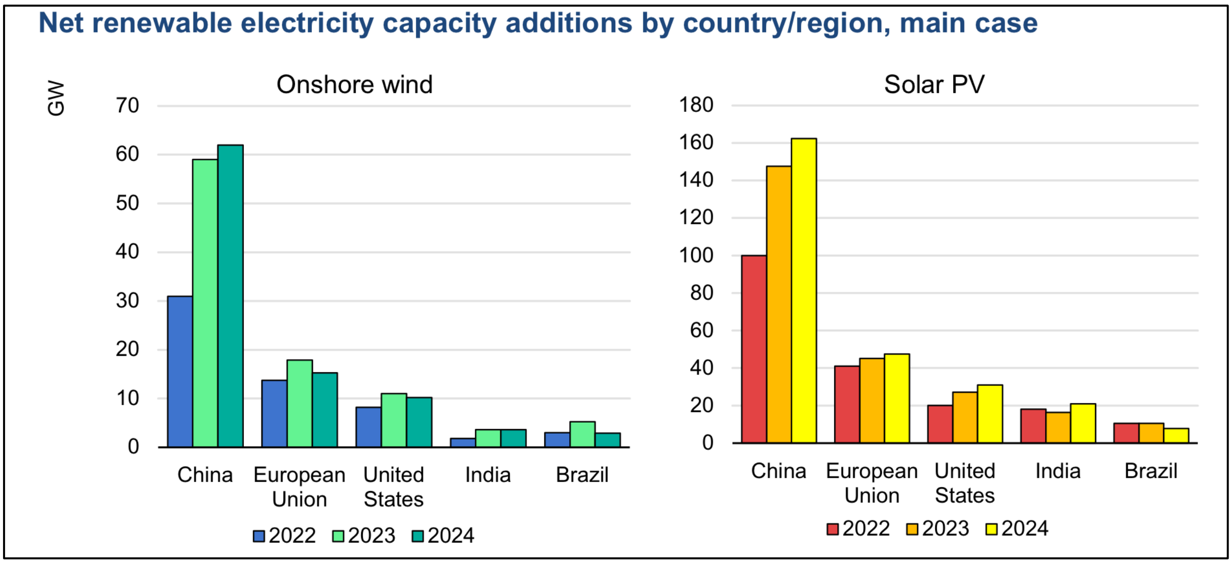
Figure 4.4. China's Electrification Jolts Energy Markets, Again



EVs = electric vehicles, mb/d = million barrels per day, Mtce = million tonnes of coal equivalent, STEPS = Stated Policy Scenario.
Source: International Energy Agency (2024).

China is emerging as a renewable energy superpower and is poised to co-lead the 'non-fossil fuel alliance' with Europe. Its strategy aims at energy independence by reducing fossil fuel imports from the US, Russia, and the Middle East. China is also investing heavily in nuclear power and is on track to become the world's largest nuclear power user, surpassing both the US and Europe by 2030.

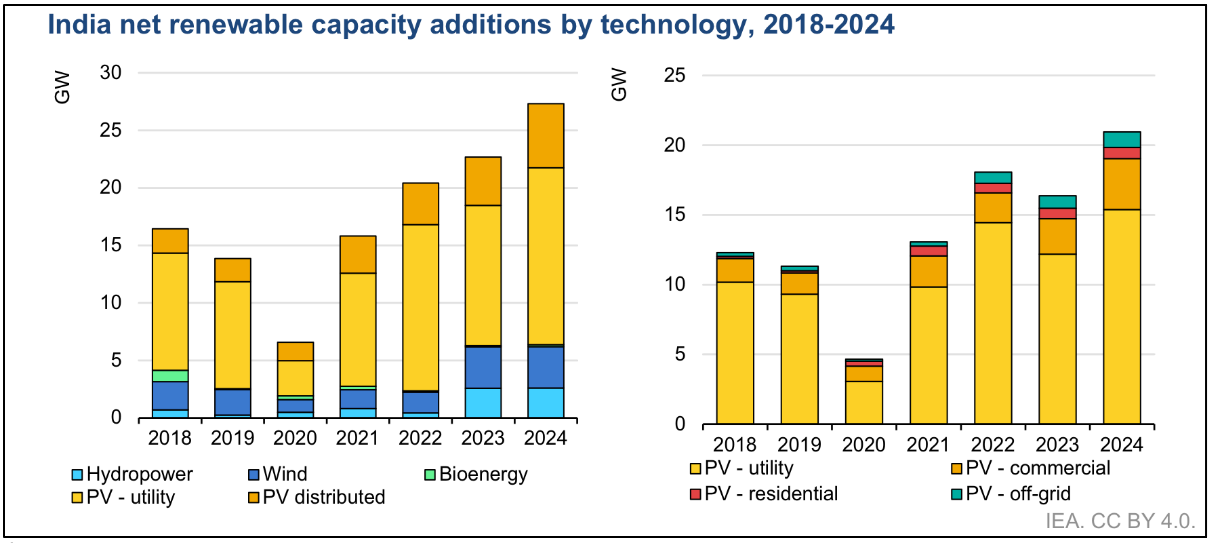
Figure 4.5. Net Renewable Electricity Capacity Additions by Country or Region



GW = gigawatt, PV = photovoltaic.
Source: International Energy Agency (2024).

India is following China's lead, investing heavily in solar and wind power. Amongst the major economies, India is the fastest-growing user of renewable energy. Its target year for achieving decarbonisation is 2070. By investing in both natural gas and renewables, India aims to strike a balance between economic growth and a gradual energy transition. India's intention to join the IEA may reflect its need to ensure a stable fossil fuel supply to sustain its economic growth.

Figure 4.6. India's Net Renewable Capacity Additions by Technology, 2018–2024



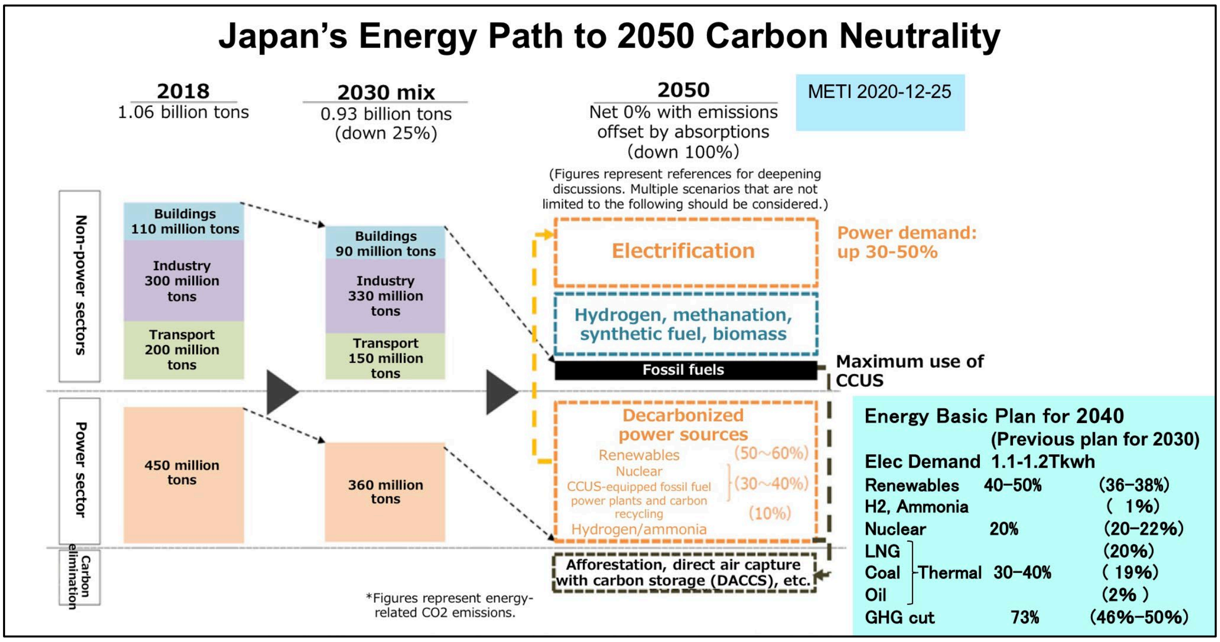
GW = gigawatt, PV = photovoltaic.
Source: International Energy Agency (2024).

Saudi Arabia possesses enormous potential for CCS in its depleted oil fields, alongside abundant solar energy. When DAC of CO_2 becomes cost competitive, Saudi Arabia – thanks to its cheap solar power – could become an ideal location for DACS. Carbon credits generated through DACS could support hard-to-abate sectors such as steel, cement, and petrochemicals. These industries may be quick to invest in building DACS facilities within the kingdom. Saudi Arabia can produce blue H_2 or NH_3 using its low-cost gas (as it begins to develop its shale gas resources) in combination with CCS, enabling the export of clean fuels. The US oil company Occidental Petroleum (Oxy), already independent of Middle Eastern oil, plans to produce 'clean oil' using DACS and renewable energy within the US. Aware of the impending peak in global oil demand, Saudi Arabia is preparing through its Vision 2030 initiative, spearheaded by Crown Prince Mohammed bin Salman. Saudi Arabia is also exploring nuclear power. The Republic of Korea (henceforth, Korea) attempted to export its SMART reactor (a small modular light water reactor), but the US insisted on stringent nuclear safeguards similar to those under the US–United Arab Emirates (UAE) 1-2-3 agreement – so called 'golden rules' of non-proliferation – which ultimately stalled the project.

Japan and Korea stand to benefit from the global energy transition, particularly if they work together on developing a clean H_2 supply chain and advanced nuclear power. Japan started importing LNG from Alaska in 1969, a costly operation at the time. However, over more than 50 years, Japan, alongside Korea and Taiwan, succeeded in commoditising LNG. Whilst the war in Ukraine may mark the end of the 'golden age of natural gas', as stated by the IEA in 2021, the golden age of LNG is expected to continue for decades. Meanwhile, Japan and Korea must now focus on developing a supply chain for clean H_2. Japan's Asia Zero Emission Community initiative aims to build H_2 and CCS infrastructure in Asian countries, with Korea actively collaborating on the project.

Another key area is joint development of advanced nuclear power. Japan has gradually restarted nuclear reactors following the nationwide shutdown in the aftermath of the 2011 Fukushima Daiichi disaster. Currently, 14 reactors are operational, contributing 8.5% of Japan's electricity generation, far below the 30% share before the accident. Despite shifting public opinion in favour of nuclear energy after Russia's invasion of Ukraine, the process of restarting reactors remains highly political and sensitive. Japan recently released its basic energy plan for 2040 (Figure 4.7), which envisions nuclear power supplying 20% of the electricity mix; renewables, 40%–50%; and thermal power, 30%–40%. To realise this scenario, Japan must present a clear vision for 'sustainable nuclear power', which is discussed in Chapter 6.

Figure 4.7. Japan's Energy Path to 2050 Carbon Neutrality and Basic Energy Plan



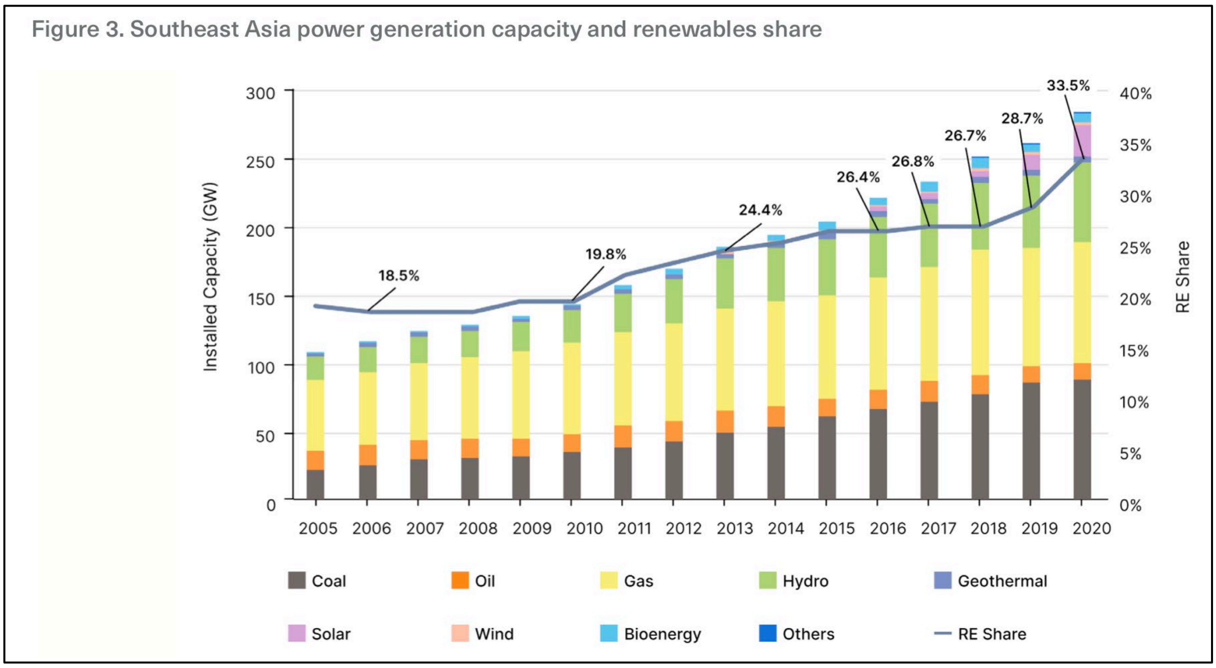
CCUS = carbon capture, utilisation, and storage; CO_2 = carbon dioxide; elec = electricity; GHG = greenhouse gas; H_2 = hydrogen, LNG = liquefied natural gas; METI = Ministry of Economy, Trade and Industry, Japan; TKwh = tera-kilowatt hour.

Source: Ministry of Economy, Trade and Industry, Japan (2020).

In Korea, the 10th Basic Plan for Long-term Electricity Supply and Demand aims to increase the share of nuclear power to over 30% of total electricity generation by 2036. Korea constructed four reactors at the Barakah Nuclear Power Plant in the United Arab Emirates (UAE) on schedule and within budget. It is now actively marketing its SMRs, including SMART, to countries such as Saudi Arabia.

What about ASEAN countries? For a successful transition to a lower-carbon economy, the deployment of renewables in the ASEAN region must be significantly accelerated. However, renewable energy penetration has been slower than in other regions, hampered by both country-specific and regional barriers to private cross-border investments.

Figure 4.8. Southeast Asia Power Generation Capacity and Renewables Share



GW = gigawatt, RE = renewable energy.
Source: International Energy Agency (2023).

To accelerate the transition to a lower-carbon economy, both international and domestic policy support for the ASEAN region are critical, alongside the establishment of more effective regulatory frameworks. To transition towards a more secure and sustainable growth model, ASEAN must dramatically increase energy investments and the share of capital allocated to clean energy technologies.

The investment levels required to meet sustainable development goals would support a shift in the energy mix whilst building on four essential pillars for achieving net-zero emissions by 2050: the widespread rollout of renewables; improvements in energy efficiency; electrification of end uses; and the deployment of low-emission fuels, including modern bioenergy, hydrogen-based fuels, and CCUS. This shift in the energy mix is necessary not only for securing a sustainable future but also for reducing vulnerabilities to climate change. Climate policy ambitions and investment risks vary across ASEAN countries (Figure 4.9).

Figure 4.9. Main Climate Policy Ambitions and Key Investment Priorities and Risks

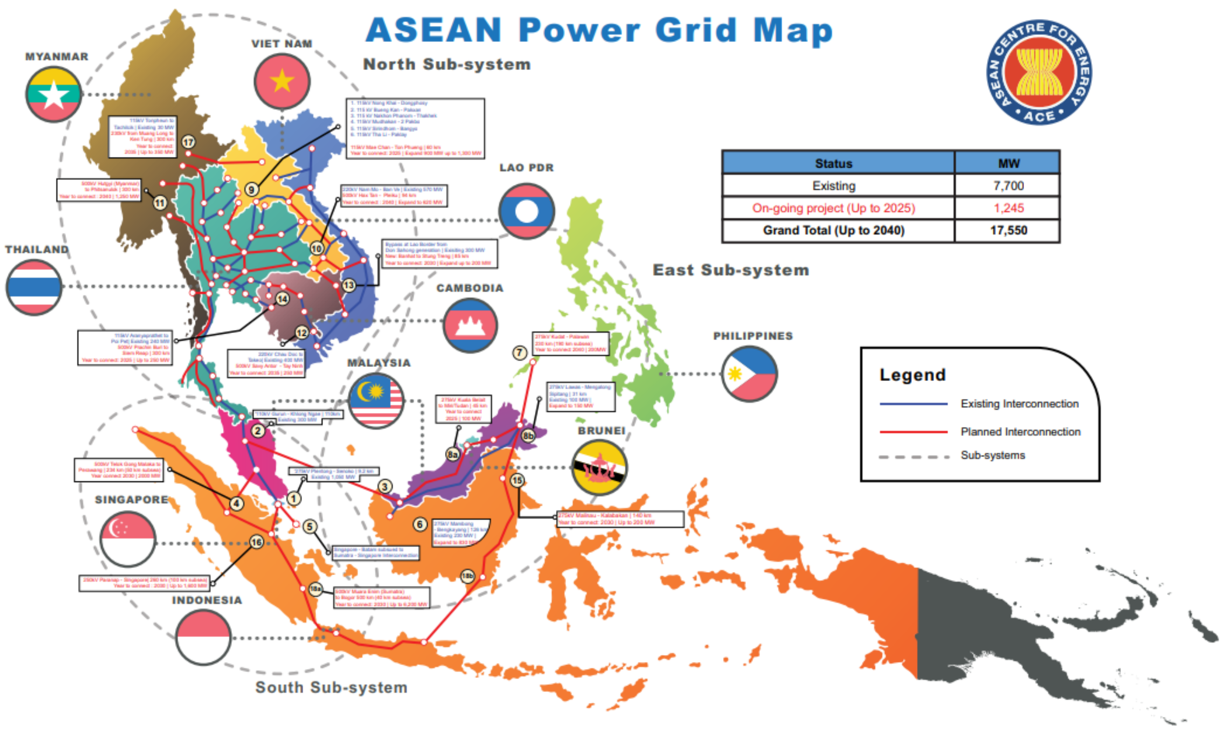
Market	Recent Policy Changes	Investment Priorities			
		Power sector sustainability	Project bankability	Financing	Integrated approaches
Indonesia	Planning for NZE by 2060. More renewable power in long-term plan, though coal still represents almost 65% of generation by 2030.	🔴	🟡	🟡	🔴
Malaysia	Government announced goal to become carbon neutral by 2050 and stop building new coal-fired plants.	🟢	🟡	🟢	🟢
Philippines	Updated nationally determined contribution in 2021	🔴	🟡	🟢/🟡	🟡
Singapore	Government announced Net-Zero Emissions by 2050 target in October 2022	🟢	🟢	🟢	🟢
Thailand	Announced intention to develop plan for NZE by 2065. Updated power expansion plan has reduced dependency on coal in favour of natural gas.	🟡	🟡	🟢	🟡
Vietnam	NZE by 2050 target announced at COP26. Substantial capital is mobilised to renewable power, especially solar, while coal capacity is still planned to expand by 2030.	🔴	🟡	🟢/🟡	🔴
Cambodia	Cambodia's Basic Energy plan recommends renewable power make up 65% of total generation by 2030.	🟡	🔴	🔴	🔴

🟢 Low risk/supportive factor for investment
🟡 Potential risk factor/barrier for investment
🔴 High potential risk factor/barrier for investment

COP 26 = 2021 United Nations Climate Change Conference, NZE = net-zero emissions.
Source: International Energy Agency (2023).

By interconnecting national power grids (Figure 4.10), ASEAN can enhance the integration and use of renewable energy, much like the EU's Energy Union initiative. Such connectivity would diversify energy supply and improve system resilience through complementarities, but it requires coordinated energy policy across member countries. ASEAN urgently needs a collective energy and sustainability strategy. Planning the location of renewables and nuclear power should be considered collectively rather than country by country. For example, the standardisation of nuclear reactor technologies can reduce construction costs. SMRs could also be deployed to provide backup power for intermittent renewable sources.

Figure 4.1. ASEAN Power Grid



Source: ASEAN Centre for Energy (2024).

According to the IEA, the carbon pricing required for a net-zero scenario by 2050 is estimated at US$250 per tonne of CO_2 for developed countries and US$200 per tonne for developing countries with net-zero commitments (Figure 4.11). Europe is leading the way with the EU Emission Trading System, where carbon prices currently stand at around €100 per tonne of CO_2. In the US, the Inflation Reduction Act offers carbon pricing incentives for CCS via the 45Q tax credit: US$85 per tonne of CO_2 stored in saline geologic formations from industrial and power sector sources, and US$180 per tonne from DAC projects. Japan plans to implement a hybrid carbon pricing system combining emissions trading and a carbon surcharge. Meanwhile, several ASEAN countries, including Thailand, Malaysia, Singapore, and Indonesia, are beginning to consider carbon pricing mechanisms. For nuclear power expansion, carbon pricing can serve as a positive incentive for industrial users.

Figure 4.11. Carbon Dioxide Price Assumptions for the International Energy Agency Scenarios

USD (2021) per tonne of CO_2	2030	2040	2050
Stated Policies Scenario			
Canada	54	62	77
Chile, Colombia	13	21	29
China	28	43	53
European Union	90	98	113
Korea	42	67	89
Announced Pledges Scenario			
Advanced economies with net zero emissions pledges[1]	135	175	200
Emerging market and developing economies with net zero emissions pledges[2]	40	110	160
Other emerging market and developing economies	-	17	47
Net Zero Emissions by 2050 Scenario			
Advanced economies with net zero emissions pledges	140	205	250
Emerging market and developing economies with net zero emissions pledges	90	160	200
Other emerging market and developing economies	25	85	180

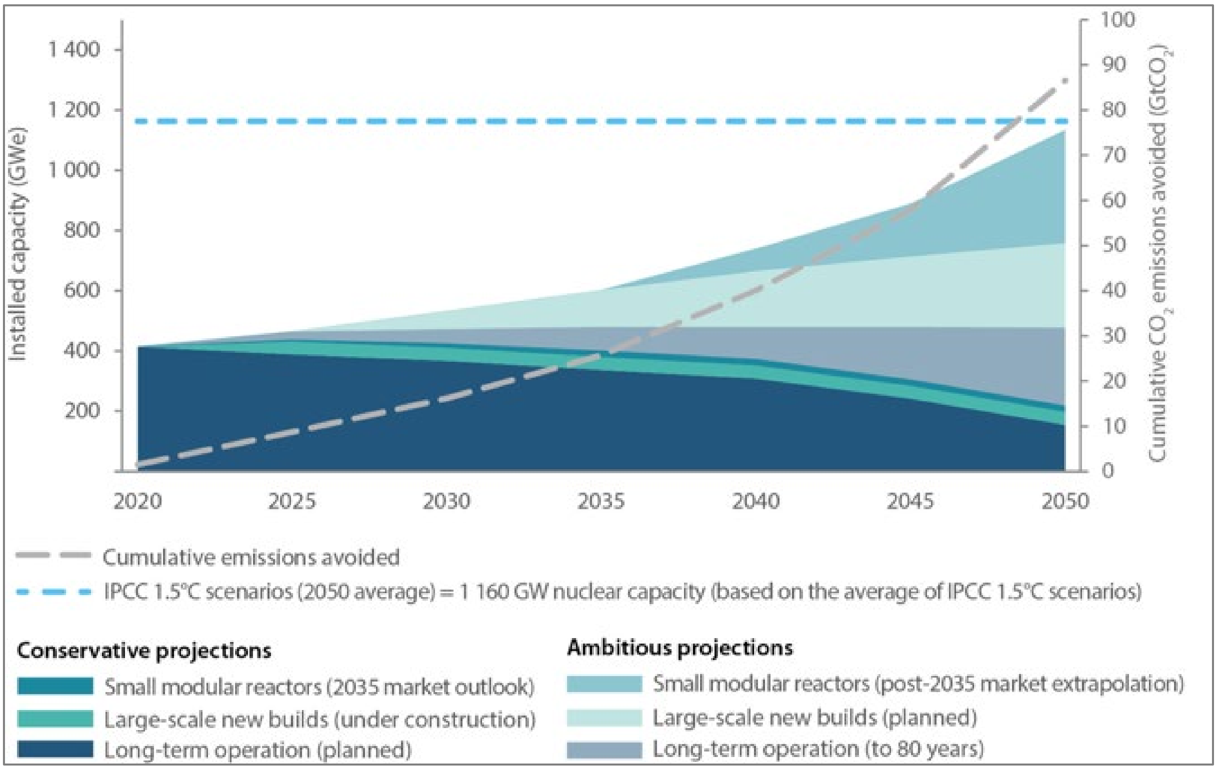
CO_2 = carbon dioxide.
Source: International Energy Agency (2022).

Chapter 5

The Path to a New Era for Nuclear Energy: A Review

At COP 28 in Dubai, several countries committed to tripling global nuclear capacity by 2050. To realise this ambitious target (Figure 5.1), the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (OECD) states that it will be necessary to extend the operational life of existing reactors to 80 years, ensure the timely completion of all the reactors currently under construction or planned, and accelerate the deployment of SMRs.

Figure 5.1. Full Potential of Nuclear Contributions to Net Zero

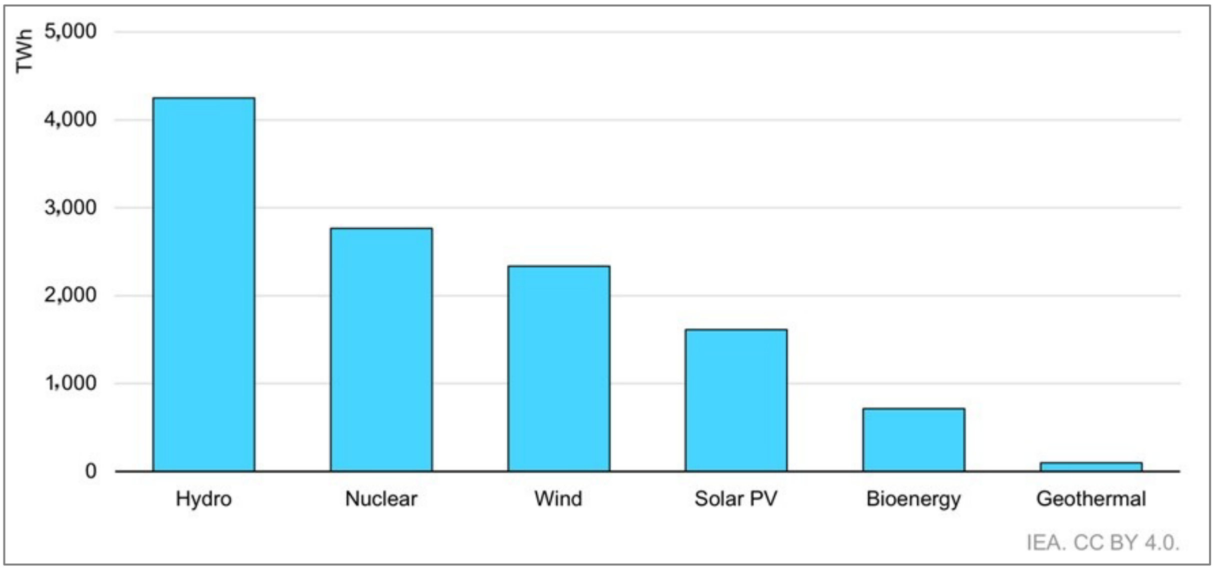


CO_2 = carbon dioxide, $GtCO_2$ = gigatonnes of carbon dioxide, GW = gigawatt, GWe = gigawatt electrical, IPCC = Intergovernmental Panel on Climate Change
Source: International Energy Agency (2025).

The Path to a New Era for Nuclear Energy (IEA, 2025) offers a timely and comprehensive assessment. Dr. Fatih Birol, IEA executive director, states in the foreword: ‘It’s clear today that the strong comeback for nuclear energy that the IEA predicted several years ago is well underway, with nuclear set to generate a record level of electricity in 2025’. More than 70 GW of new nuclear capacity are under construction globally, one of the highest levels in the last 30 years. More than 40 countries have announced plans to expand the role of nuclear power in their energy systems. SMRs, in particular, present significant growth potential. However, governments and industry must still overcome considerable challenges. These include ensuring that new projects are delivered on time and within budget, whilst addressing issues related to financing and supply chains.

In 2023, nuclear energy accounted for just over 9% of global electricity generation, with more than 410 reactors operating across more than 30 countries. This marks a decline from its peak share of around 18% in the late 1990s (Figure 6.2). Although the absolute amount of nuclear power generated has grown modestly over the past decade, electricity demand has increased faster, thereby reducing nuclear's share in the overall energy mix. Nonetheless, in 2023, nuclear energy remained the second-largest source of low-emission electricity after hydropower.

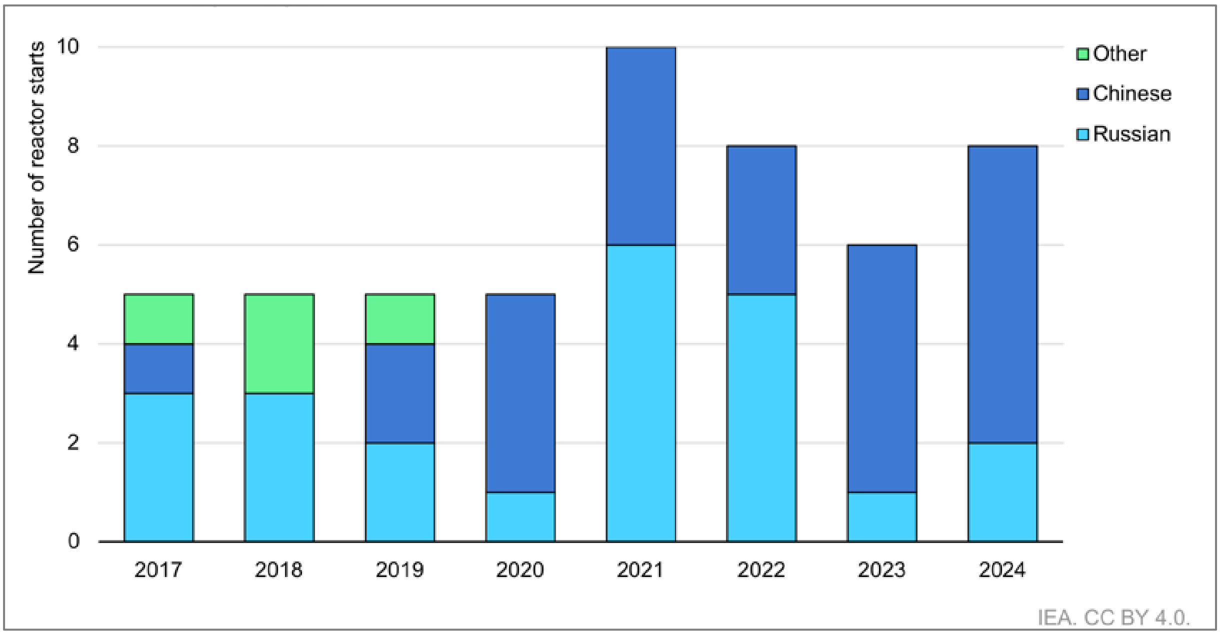
Figure 5.2. Global Low-emission Electricity Generation by Source



PV = photovoltaic, TWh = terawatt hour.
Note: Other low-emission sources not shown generate smaller amounts of electricity and include concentrating solar power, marine power, and plants equipped with carbon capture, utilisation, and storage.
Source: International Energy Agency (2025).

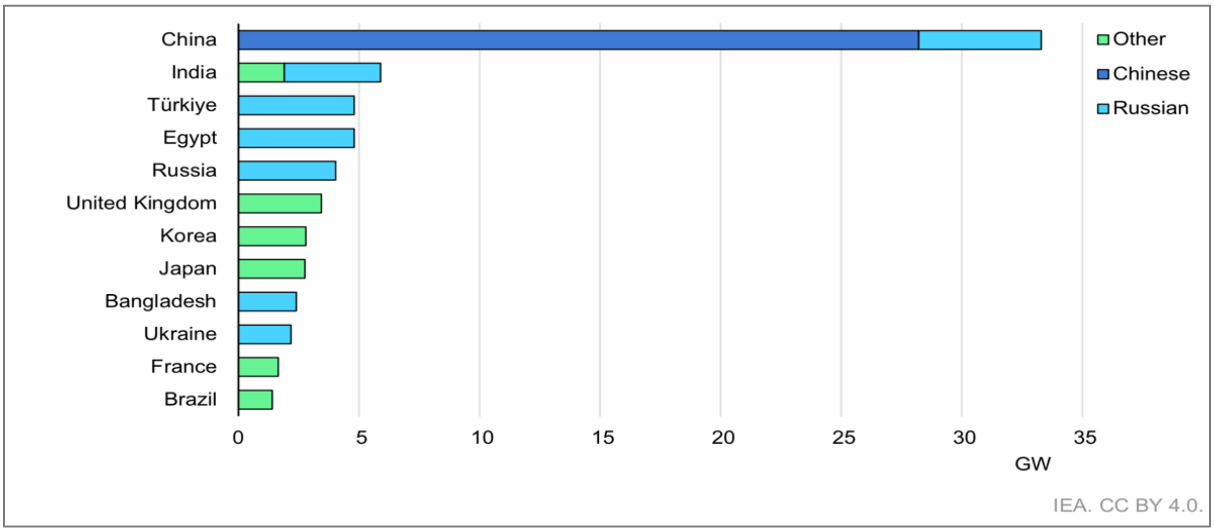
Most of the current global nuclear power fleet is in advanced economies and consists of plants built several decades ago. However, the global landscape is shifting. Today, most nuclear construction is occurring in China, which is on course to overtake both the US and Europe in installed nuclear capacity by 2030. Russia also remains a major player in the international nuclear technology landscape. Of the 52 reactors that began construction worldwide in 2017–2024, 25 are of Chinese design and 23 Russian (Figure 5.3, Figure 5.4).

Figure 5.3. Nuclear Power Plant Construction Starts by National Origin of Technology



Source: International Energy Agency (2025).

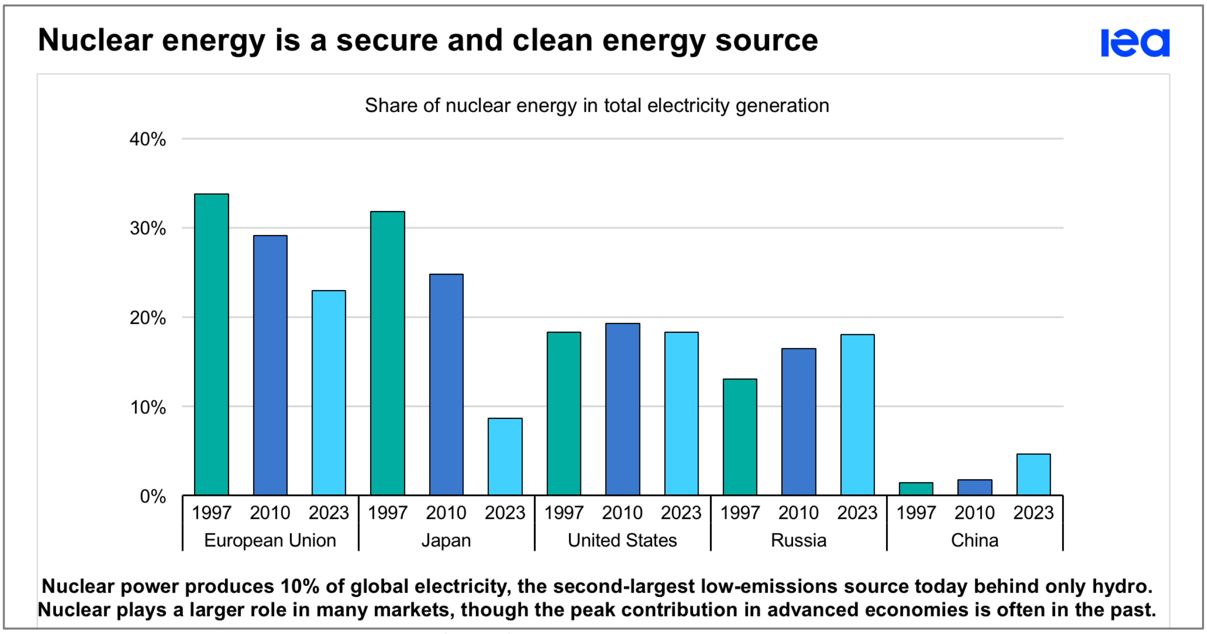
Figure 5.4. Nuclear Power Capacity Under Construction by Region and National Origin of Technology



Source: International Energy Agency (2025).

Nuclear energy is a well-established technology that has provided electricity and heat to consumers for well over 50 years. However, it has encountered several challenges in recent years. Looking back to 1997 – almost 30 years ago – when nuclear energy was at a high point in advanced economies, Europe stood out as a frontrunner, meeting over one-third of its total electricity needs through nuclear generation. At the same time, nuclear energy accounted for more than 30% of electricity generation in Japan and close to 20% in the US. These figures were significantly higher than those in Russia and certainly in China, where nuclear provided just 1% of electricity at the time (Figure 5.5).

Figure 5.5. Nuclear Energy as a Secure and Clean Energy Source



Source: International Energy Agency (2025).

Over the past 30 years, the energy landscape, electricity systems, and the role of nuclear energy have evolved. In advanced economies, electricity demand has increased by more than 20%, whilst nuclear power generation has declined by more than 10%.

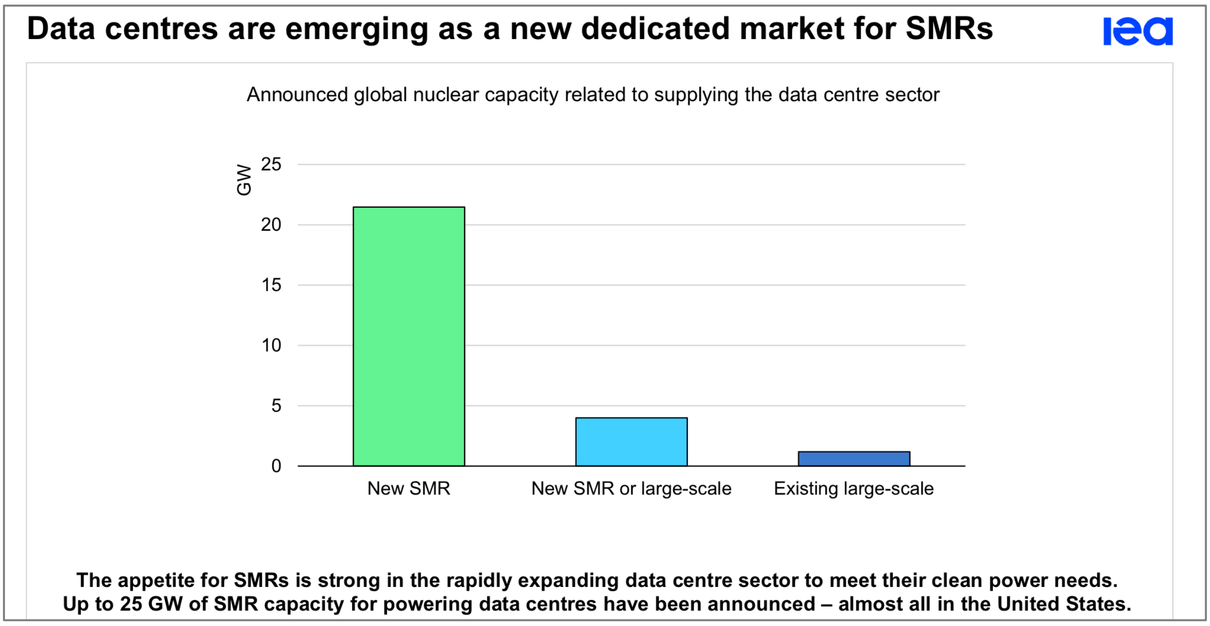
In the EU, nuclear power's share of electricity generation steadily declined to 23% by 2023, as many reactors were permanently shut down. In Japan, the share declined slowly until 2010, then dropped sharply following the accident at the Fukushima Daiichi plant, although it is now starting to climb again as reactors are restarted. In the US, nuclear's share has remained relatively stable.

In contrast, electricity demand in emerging markets and developing economies has tripled over the same period, whilst nuclear power generation has more than doubled. In Russia, nuclear power's share has steadily climbed. In China, the sector has grown substantially: it now ranks third globally in terms of operational nuclear capacity.

Several signs indicate that further change is underway, driven by growing policy support, rising investment, and technological innovation.

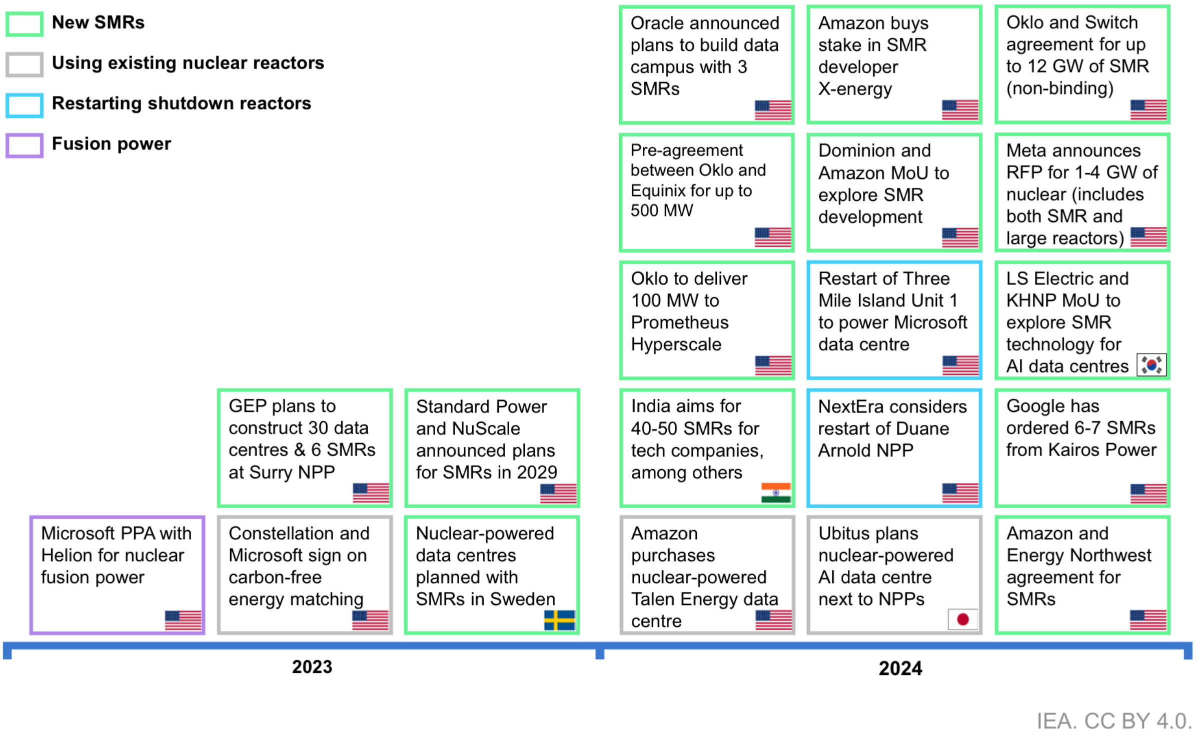
One of the most notable developments is the rising demand for clean and stable power from data centres, which is emerging as a new driver for nuclear energy growth. The typical load profile of a data centre is flat and stable, making it well suited to nuclear power's consistent output. Recently, data centres have shifted from merely consuming nuclear electricity to actively supporting new nuclear projects, particularly through growing interest in SMRs. Thanks to their modular design, SMRs can offer a more localised energy solution by being built close to demand. The IEA's bottom-up research identifies plans for up to 25 GW of SMR capacity, the vast majority of which is located in the US (Figures 5.6 and 5.7). However, interest is growing globally, with new announcements and initiatives in various countries such as India, Sweden, Korea, and the United Kingdom (UK).

Figure 5.6. Data Centres are Emerging as a New Dedicated Market for Small Modular Reactors



Source: International Energy Agency (2025).

Figure 5.7. Recent Announcements and Agreements Related to the Procurement of Nuclear Energy for Data Centres

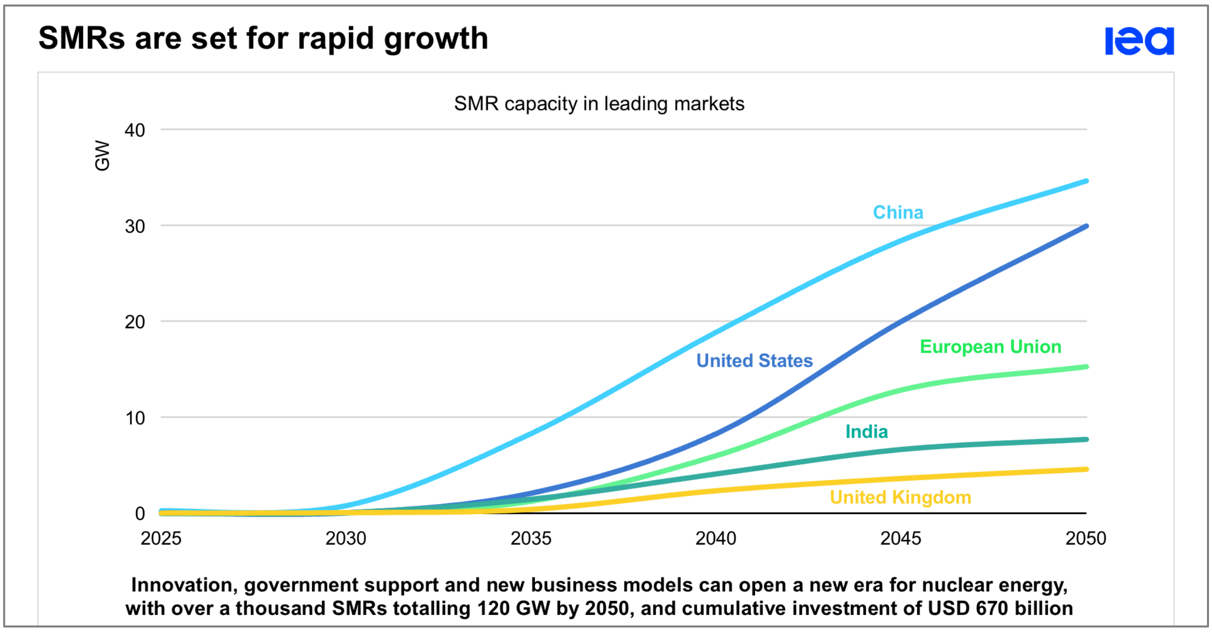


AI = artificial intelligence, GW = gigawatt, MW = megawatt, NPP = nuclear power plant, PPA = power purchase agreement, RFP = request for proposal, SMR = small modular reactor.
Source: International Energy Agency (2025).

The strong credit ratings of large technology companies further support this trend by creating favourable conditions for financing SMR projects. This synergy between the financial stability of the tech sector and the flexibility of SMR technology is generating strong momentum behind deployment.

Beyond data centres, SMRs are also being considered to help meet rising electricity demand and decarbonise industrial heat across a wide range of sectors, not only in the US, but increasingly in other regions as well (Figure 5.8).

Figure 5.8. Small Modular Reactors are Set for Rapid Growth



GW = gigawatt, SMR = small modular reactor.
Source: International Energy Agency (2025).

Building on these announcements, policies, and plans, the IEA has developed an in-depth outlook for SMRs.

The US leads global innovation in SMR technology. Several companies are actively developing the technology, whilst major technology companies plan to deploy SMRs to meet the growing electricity demand of data centres.

China is already operating and building SMRs, putting it on track to achieve the largest SMR capacity globally. It has developed three prominent designs for applications in electricity generation, heating, and desalination. The leading SMR, the ACP100 by China National Nuclear Corporation, is scheduled for completion by 2026.

Within the EU, several countries, including France, the Czech Republic, Finland, Sweden, Poland, and Romania, have expressed interest in or are planning to install SMRs alongside large-scale reactors, complementing continued growth in renewables. In India, SMRs have been identified as an important tool for decarbonising industrial power use, notably in the iron and steel sectors, and for replacing coal-fired power plants.

The UK intends to build a mix of large- and small-scale reactors to deliver its energy security plan. The government is providing financial support to Rolls-Royce, a leading company in SMR development.

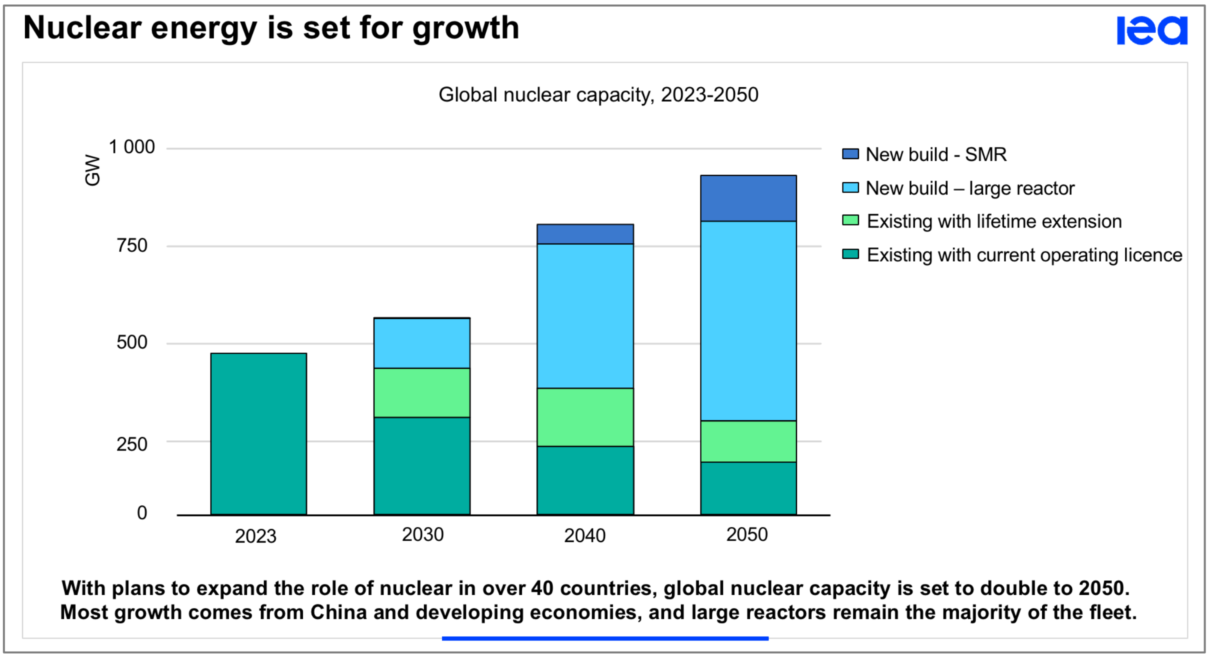
Together, these markets are expected to account for almost 80% of global SMR capacity by 2050. In addition, several developing economies, including countries in Southeast Asia and Africa, are exploring SMRs as a cost-effective option, due to their smaller scale and lower upfront capital requirements.

By 2050, about 1,000 SMRs are expected to be deployed globally, delivering a total capacity of 120 GW of capacity, supported by cumulative investments of about US$650 billion.

This projected growth depends heavily on innovation driving down SMR costs, which are projected to reach parity with large hydro and offshore wind by 2040. Should cost reductions occur faster, an additional 70 GW of SMR capacity could be unlocked by 2050.

Under a rapid growth scenario, global nuclear capacity more than doubles to 870 GW by 2050, supported by current policies and plans in over 40 countries. Most new capacity would come from large-scale reactors, with more than 500 GW expected to be constructed between now and 2050 (Figure 5.9).

Figure 5.9. Nuclear Energy is Set for Growth



GW = gigawatt, SMR = small modular reactor.
Source: International Energy Agency (2025).

Emerging markets and developing economies will drive the bulk of this growth, accounting for two-thirds of new capacity. China leads this growth, contributing over one-third of global additions. By 2030, China is expected to overtake both the US and Europe to host the largest nuclear fleet in the world.

Lifetime extensions will also play an important role, comprising around 150 GW, or 20%, of global capacity by 2040. As of 2024, all US reactors that have operated for at least 30 years have applied for an additional 20-year operating licence, with over one-fifth applying for a second 20-year extension. In Japan, regulations allow reactors to operate beyond 60 years, with several restarts currently underway. Similar policies in France and other European countries are enabling many reactors to remain operational for 60, or even 80, years.

The US government plans to add 35 GW of new capacity by 2035 – including plants already under construction – and aims to deploy 200 GW of nuclear capacity by 2050, effectively tripling the country's nuclear generation. The Advanced Reactor Demonstration Program provides over US$3 billion in funding for SMRs and other advanced reactor technologies.

In advanced economies, the growth of SMRs and timely, on-budget construction of new large-scale reactors will only just offset the impact of ageing fleet. As a result, total capacity in 2050 will be slightly higher than today.

SMRs are gaining momentum and represent a growing share of the nuclear market. By 2050, SMRs are projected to account for 15% of total global nuclear capacity.

However, even with this increase, nuclear power's share of electricity generation is expected to decline slightly, remaining below 10% through to 2050. This is due to electricity demand rising faster, driven by electrification and the development of energy-intensive technologies, such as AI and data-driven demand centres.

The nuclear landscape is also shifting in terms of market leadership. From early 2017 to September 2024, 52 nuclear reactors began construction globally. China led with 25 domestically designed reactors, followed by Russia with 23 of its own. In contrast, advanced economies started with just four reactors, two in the UK (based on European designs) and two in Korea (using national technology).

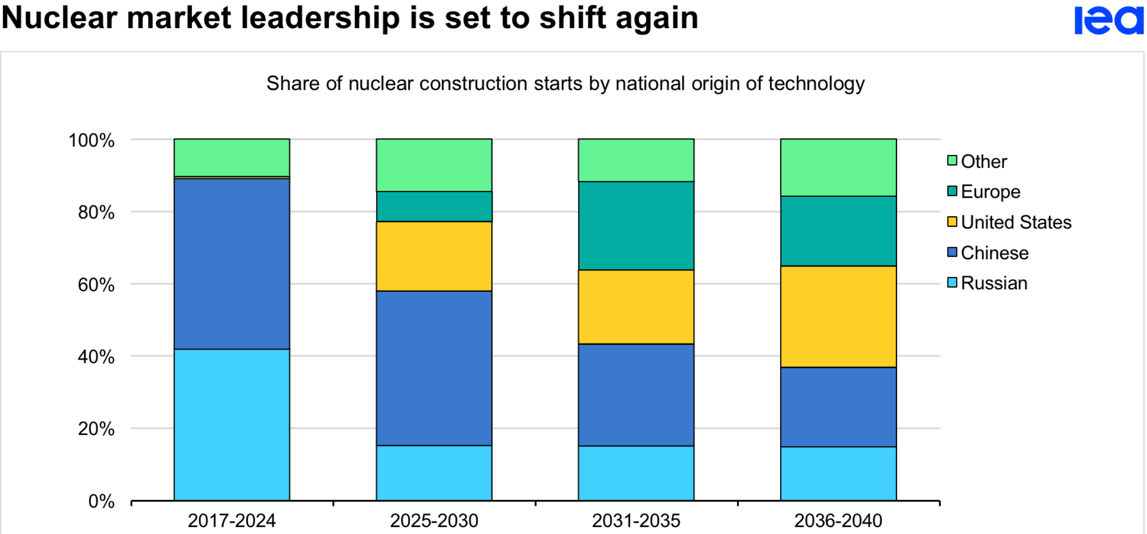
The rise of SMRs, alongside a new wave of large-scale reactor construction, opens the possibility for advanced economies to reclaim leadership in nuclear technology.

The share of reactor designs originating from Europe, the US, Japan, and Korea is set to increase from 10% in recent years to 45% by 2030 and over 60% thereafter.

Whilst large-scale reactors remain the key driver of this shift, the widespread deployment of SMRs further reinforces the trend.

Advanced economies are projected to dominate the SMR market, accounting for over 60% of installations from 2025 to 2040 (Figure 5.10).

Figure 5.10. Nuclear Market Leadership is Set to Shift Again



Reversing the recent trend, a new wave of construction in advanced economies for both large and small reactors opens the possibility for Europe, the United States and Japan to reclaim market share.

Source: International Energy Agency (2025).

Several leading developers in these regions are spearheading innovation in SMR technology, with plans to install reactors domestically and export them to other countries.

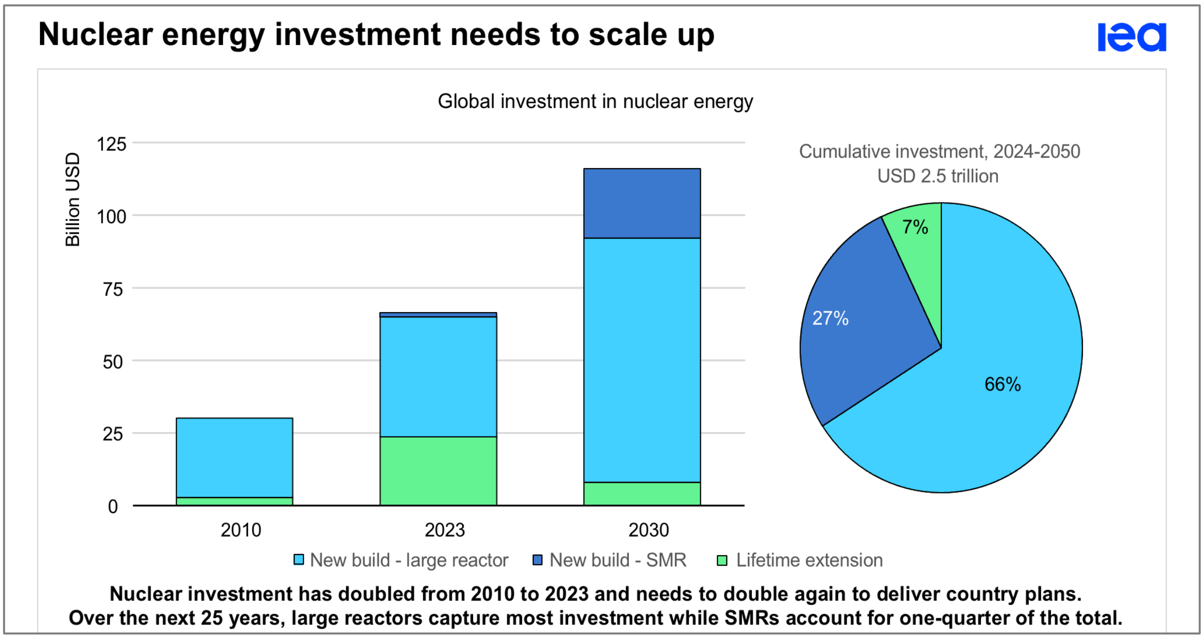
China's capacity additions are expected to peak in the 2030s before declining, resulting in a reduced share of the global market towards 2040, despite continued construction both within China and abroad.

A more competitive and diverse nuclear market brings significant benefits, especially for countries seeking to step up deployment of nuclear technologies as part of their broader energy strategies.

Since 2010, global investment in nuclear energy has more than doubled, reaching more than US$60 billion. This increase is largely driven by growth in large-scale reactor projects, due to both a larger number of reactors under construction in 2023 and cost overruns in advanced economies. A similarly significant increase has occurred in investments for lifetime extensions of existing large reactors, following recent decisions in the US, France, and Japan that recognise the high cost-effectiveness of these extensions.

To achieve the rapid growth projected for nuclear energy, global investment must double from 2023 to 2030, reaching US$120 billion. Most of this investment will be directed towards large-scale reactor construction. However, even by 2030, a significant amount – US$25 billion – will support the first wave of SMRs scheduled to come online in the 2030s. Lifetime extensions represent a smaller portion, primarily because of the current high level of activity in this area. Over the next 25 years, cumulative global investment in nuclear energy is expected to reach US$2.5 trillion. Of this total, two-thirds will go to large reactors, over one-quarter – US$650 billion – to SMRs, and less than 10% to lifetime extensions (Figure 5.11).

Figure 5.11. Nuclear Energy Investment Needs to Scale Up



SMRs = small modular reactors.
Source: International Energy Agency (2025).

How are these investments financed?

Investing in nuclear energy, particularly in large-scale power plants, requires a significant upfront financial commitment, with profitability often taking 20–30 years to achieve. This extended timeline, combined with high construction costs – often exceeding US$10 billion – can deter private investors, especially during the lengthy construction phase. Rebuilding a consistent track record of delivering projects on time and within budget is also essential.

Establishing a favourable financing environment for nuclear projects hinges in part on ensuring stable cash flows once operations begin, which is critical for servicing debt and paying dividends. This requires a combination of pricing and revenue guarantee mechanisms to ensure stable and adequate cash inflows, alongside robust de-risking strategies to reduce or transfer the risk of unexpected cash outflows.

Several recent nuclear projects exemplify how pricing guarantees can enhance financial stability. Long-term power purchase agreements with fixed prices are a common means of reducing risks related to wholesale market price volatility.

The contract for difference model offers another approach to revenue assurance. Under this scheme, developers and operators are guaranteed a fixed price – the 'strike price' – for the electricity they generate.

The regulated asset base (RAB) model, originally established for other infrastructure sectors, is now increasingly applied to nuclear projects. It combines revenue guarantee with de-risking mechanism under the national regulatory framework. In 2022, the UK Parliament passed the Nuclear Energy (Financing) Bill, establishing the legal foundation for a new financing framework that includes the RAB model for new nuclear power plants. On the cash outflow side, export credit agencies (ECAs) play an important role in managing or transferring risks related to cost overruns, delays, and regulatory changes during the construction phase. ECAs are government-backed institutions that provide loans, guarantees, and insurance for companies involved in international projects. In the nuclear sector, ECAs can offer credit insurance and guarantees, thereby lowering risks for private investors and lenders and improving access to long-term, low-cost financing.

ECAs often collaborate with multilateral development banks to provide both financial support and additional credibility to nuclear projects, particularly in emerging markets. This partnership is particularly beneficial in regions with nascent financial systems or less-developed energy markets (Table 5.1).

Table 5.1. Business Models Adopted for Selected Recent Nuclear Projects

Project	Cash inflow	Cash outflow
Barakah (UAE)	Long-term PPA Fixed-price agreement with EWEC	Costs are primarily borne by the construction consortium and risk is mitigated through Korean Export-Import Bank (KEXIM) and government-backed loans
Akkuyu (Türkiye)	Intergovernmental agreement guarantees fixed-price PPA for 15 years Government commitment to purchase a significant portion of the output	Equity provider bears the main construction risk, supported by Russian Export credit agencies (ECAs) and intergovernmental collaboration
Hinkley Point C (UK)	Contract for difference provides guaranteed strike price for electricity	Equity investors EDF and China General Nuclear Power Corp. (CGN) bear the risk
Olkiluoto 3 (Finland)	Mankala principle ensures cost-based PPA with over 60 stakeholders Financial stability achieved through shareholder commitment to purchase electricity at cost	Risk of cost overruns and delays managed through co-operative financing model Shareholders absorb financial risks proportionate to their ownership
Sizewell C (UK)	Regulated asset base model allows operators to start recovering investments during the construction phase	Shifts some risk to government, reducing the burden on developers

EDF = Électricité de France, EWEC = Emirates Water and Electricity Company, PPA = power purchase agreement, UAE = United Arab Emirates, UK = United Kingdom
Source: International Energy Agency (2025).

On the other hand, SMRs could present a compelling alternative by potentially reducing the payback period by up to 10 years (Figure 5.12).

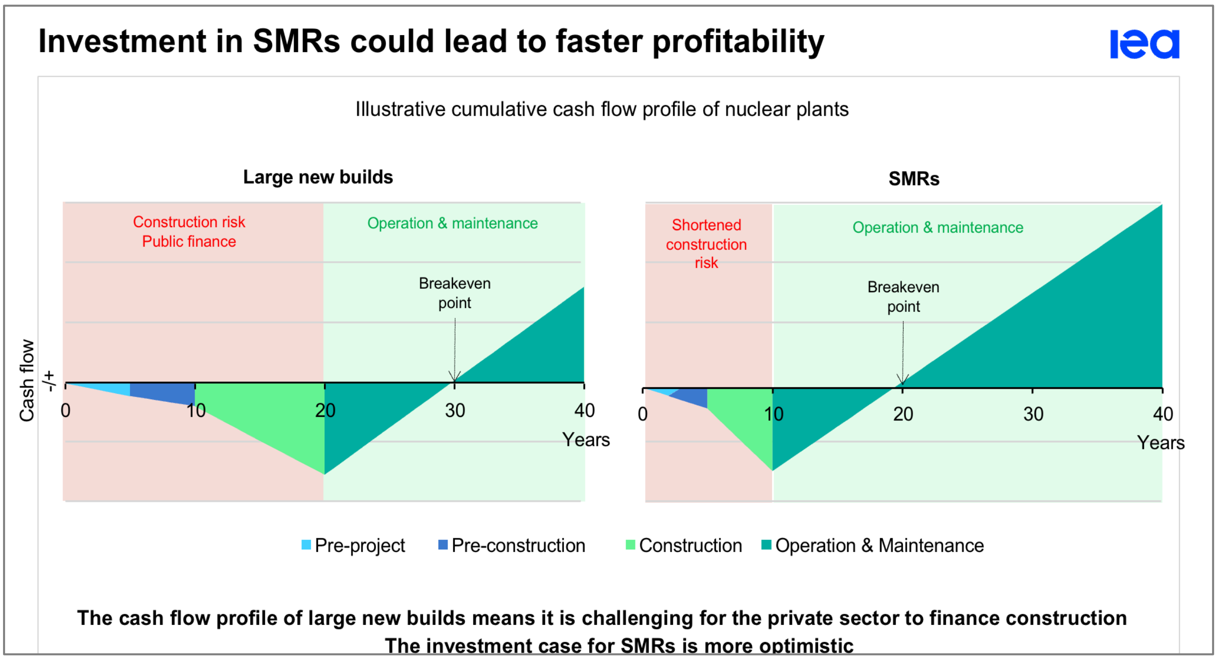
If, by 2040, SMRs achieve the same cost per megawatt as conventional nuclear projects, they could attract greater investment by generating earlier cash flows. This shorter timeline would free up capital for new projects and help build market momentum.

Unlike traditional large plants, SMRs require a lower upfront investment – about US$2 billion – making them more accessible to private investors. Their smaller scale also simplifies the financing process.

However, for SMRs to reach their full potential, it is crucial that initial projects progress steadily and become operational as quickly as possible. The shorter construction periods, standardised designs, and earlier cash flow prospects allow developers to potentially refinance even during the construction phase.

By contrast, new-build large-scale nuclear projects often struggle to attract private investors early in their development due to lengthy and capital-intensive construction timelines, and will likely continue to rely on public support.

Figure 5.12. Investment in Small Modular Reactors Could Lead to Faster Profitability

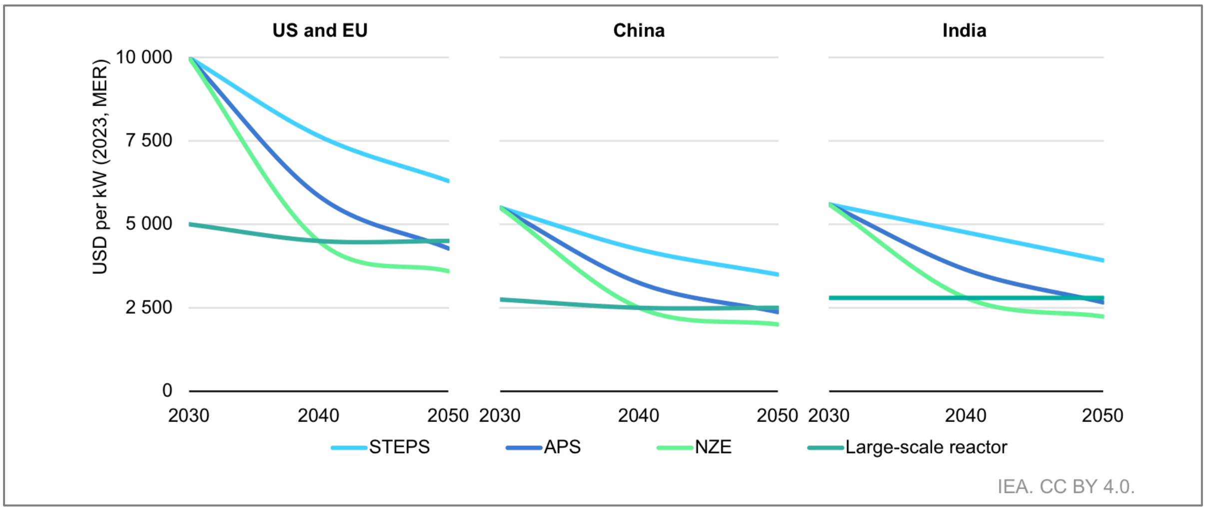


Source: International Energy Agency (2025).

The cost of building SMRs will be a critical factor in determining the pace of technology deployment. Future costs remain highly uncertain, as most first-of-a-kind projects have yet to be completed. In our analysis, the construction costs per unit of capacity for first-of-a-kind SMRs are estimated to be double those of large-scale reactors delivered on time and within budget. This equates to about US$10,000 per kW in advanced economies and less than US$6,000 per kW in China and India (Figure 5.13). Costs are projected to decline as deployment scales up and industry experience increases, particularly as a greater portion of each plant can be prefabricated off-site, yielding significant efficiency gains. In the announced pledges scenario (APS), SMR costs fall significantly during the 2030s and reach parity with large-scale reactors in the 2040s, at under US$5,000 per kW. In the NZE scenario, this cost reduction occurs even faster due to more rapid deployment. Conversely, under STEPS, more limited innovation and policy support result in slower cost reductions.

Despite projected cost declines, SMR costs in the US and Europe in 2050 under the APS and NZE scenarios remain well above the targets set by several leading developers. For example, GE Hitachi is targeting US$2,250 per kW, Moltex Energy aims for US$2,000 per kW, and Westinghouse projects US$3,400 per kW.

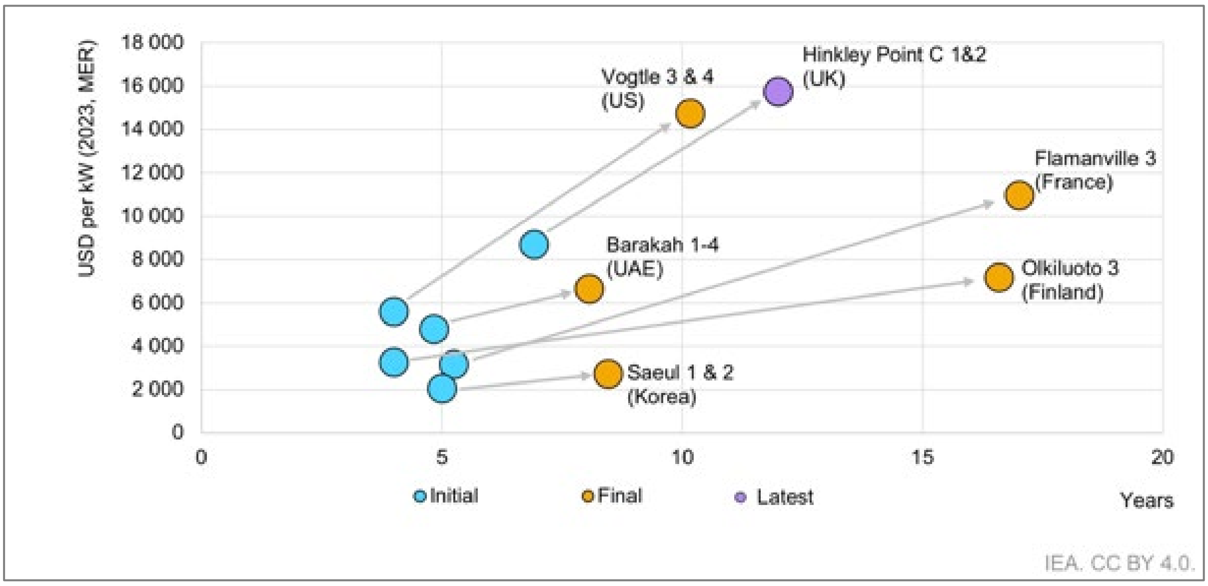
Figure 5.13. Capital Costs of Small Modular Reactors in Major Markets by Scenario, 2030–2050



APS = announced pledges scenario, EU = European Union, MER = market exchange rate, NZE = net-zero emissions by 2050 scenario, SMR = small modular reactor, STPES = stated policies scenario, US = United States.
Note: The cost of large-scale reactors is projected to be the same in all three scenarios.
Source: International Energy Agency (2025).

One of the conclusions of *The Path to a New Era of Nuclear Energy* is that many actions are required. The industry must deliver projects on time and within budget. Huge cost overruns have happened in Europe and the US, culminating in the collapse of Westinghouse (owned by Toshiba) and AREVA (Figure 5.14).

Figure 5.14. Initial and Latest Capital Cost Estimates and Construction Time for Selected Recent Nuclear Projects



kW = kilowatt, MER = market exchange rate, UAE = United Arab Emirates, UK = United Kingdom, US = United States.

Notes: Cost estimates exclude interest. Gross installed capacity is considered. Construction time refers to the period from the start of construction to grid connection. For plants with multiple reactors, the average construction time is shown. Construction of Hinkley Point C is ongoing.

Source: International Energy Agency (2025).

One of the cost elements that makes nuclear particularly challenging is regulatory backfit requirements. Meeting stringent regulations across all aspects of nuclear operations is a fundamental requirement. However, these regulations, whilst critical to safety, also contribute significantly to project risk. An important component of this risk is backfit requirements, regulatory mandates that compel operators to retrofit or upgrade facilities in line with new safety standards or technological advancements. Whilst such measures ensure nuclear power plants remain at the forefront of safety management – reducing both the risk and impact of accidents – they can also impose substantial financial and operational burdens, creating uncertainty around long-term plant viability.

Following the Fukushima accident, all nuclear power plants in Japan were shut down. New restart regulations were introduced under a newly created regulatory agency. Restarting these plants remains difficult, despite the huge additional costs incurred to comply with updated equipment standards. This situation illustrates how such requirements can make building new plants extremely difficult, if not impossible. Governments can help clear the path by taking several key steps: setting long-term visions and strategic policies for nuclear energy, de-risking investments to attract finance, fostering innovation in SMRs, and streamlining regulatory processes to enable a more supportive and sustainable nuclear power landscape.

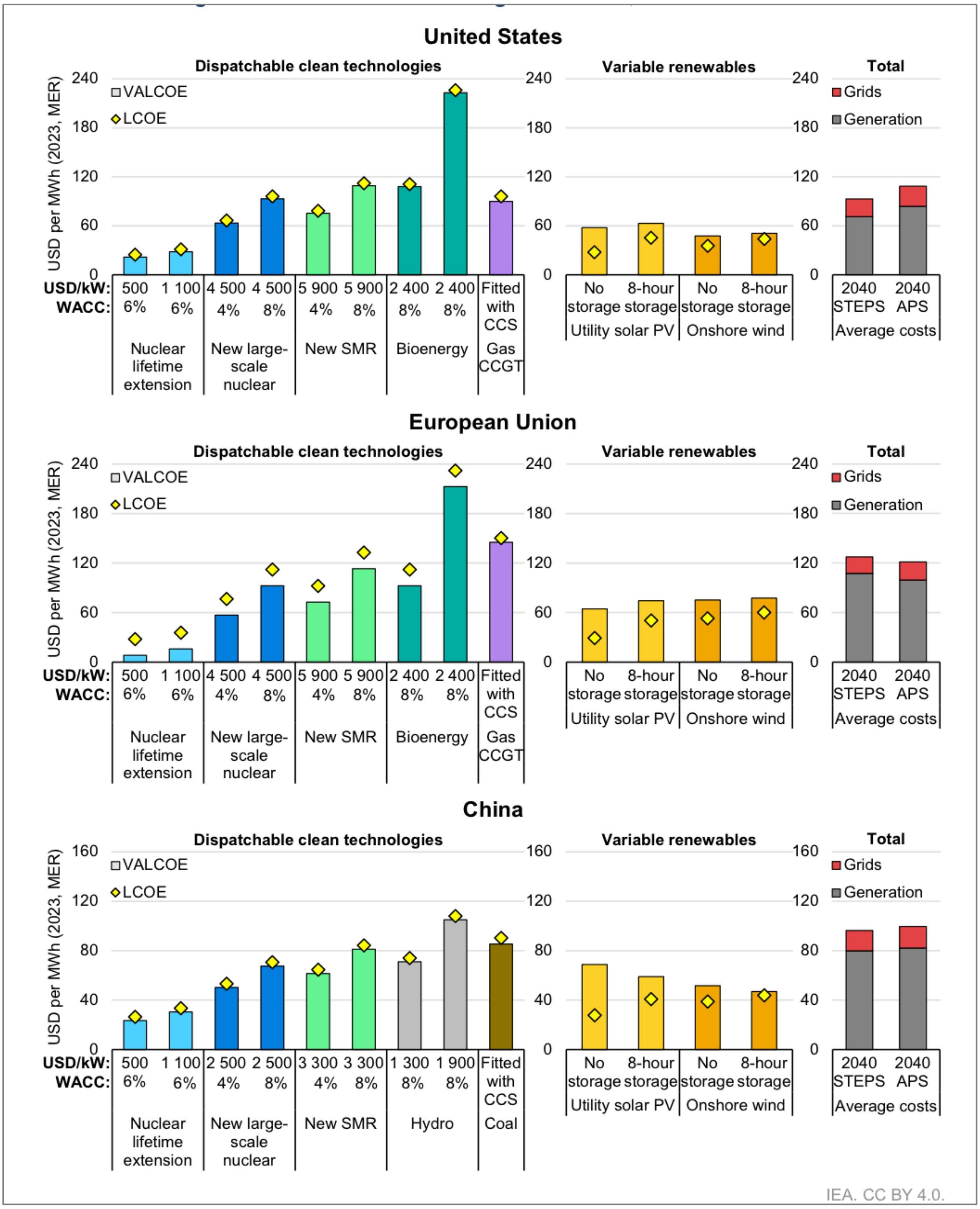
Finally, let us consider the IEA's cost comparison of different technologies. The prospects of the nuclear industry depend critically on whether both large- and small-scale reactors can be delivered on time and within budget. Capital and financing costs represent a large share of nuclear energy's total generation costs, so construction delays or cost overruns can severely undermine its competitiveness.

Nuclear energy's competitiveness also depends on comparison with alternative technologies. For dispatchable generation technologies that supply bulk power, the LCOE is a useful measure of competitiveness. The LCOE represents the average cost of generating electricity over the asset's lifetime, accounting for capital, operational, fuel, carbon, and decommissioning costs. Whilst nuclear plants are capital-intensive, they generally benefit from low fuel costs compared with other dispatchable baseload sources such as fossil fuels. In addition, nuclear energy achieves high-capacity factors – often around 75% – which helps lower the LCOE.

The IEA notes that the lifetime extension of existing nuclear plants is the most cost-effective option compared with renewables in all regions. However, the LCOE of new SMRs is about 20% higher than that of new large-scale reactors. Nonetheless, SMRs may still appeal to investors due to their lower upfront capital requirements and other advantages, including shorter construction periods. In general, the projected LCOEs for nuclear energy in 2040 under the APS are competitive with other low-emission dispatchable technologies, such as hydropower (in China) and bioenergy (in the US and the EU). This remains true even when accounting for relatively high financing costs (e.g. 8% weighted average cost of capital) for nuclear (Figure 5.15).

Furthermore, projected LCOEs are also competitive with new unabated fossil fuel plants in 2040 under the APS, including coal-fired plants (in China) and natural gas-fired plants (in the US and the EU). In this scenario, significant carbon pricing – US$175 in the US and the EU and US$110 in China – reflects growing efforts to decarbonise electricity generation. However, considering these ambitions, comparisons with unabated fossil fuels may not hold as much relevance for new investment decisions by 2040.

Figure 5.15. Cost Comparison of Nuclear and Other Technologies in United States, Europe, and China



CCGT = combined-cycle gas turbine, CCS = carbon capture and storage, kW = kilowatt, LCOE – levelised cost of electricity, SMR = small modular reactor, VALCOE = value-adjusted levelised cost of electricity, WACC = weighted average cost of capital.

Notes: Average nuclear capacity factor assumed at 75%–90%. Biomass assumed at 50%, and hydro at 25%. WACC for solar PV assumed at 4%–5%. Biomass fuel costs range from US$5 per gigajoule (GJ) to US$20 per GJ. Coal capacity factors assumed at 50%, gas CCGT at 30%–50%. Technology costs and VALCOE for solar PV are from International Energy Agency (IEA) (2024), World Energy Outlook 2024.

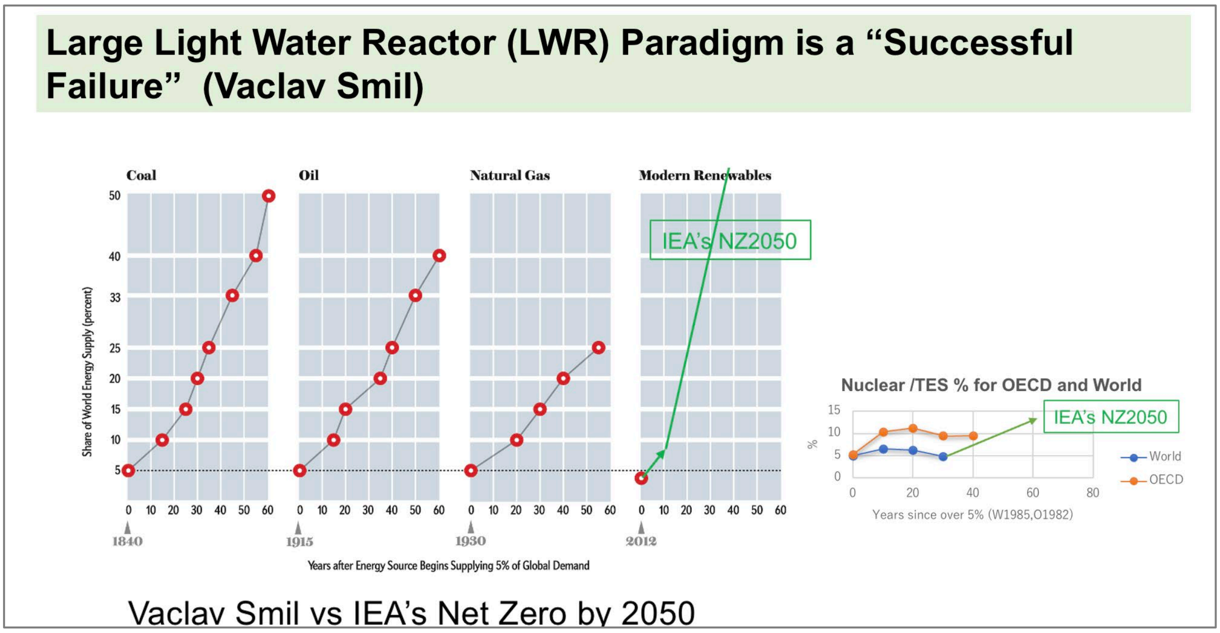
Source: International Energy Agency (2025).

Chapter 6

Sustainable Nuclear Power

Vaclav Smil, a prominent professor of energy history at the Manitoba University, Canada, describes the history of nuclear power as a 'successful failure'. By this, he means that nuclear power continues to attract global attention and resources, yet repeatedly fails to meet expectations. His graph on energy transition shows that historical shifts in energy sources have taken considerable time. Coal hit 5% of the global energy supply in the 1840s and took 60 years to reach 50%. Oil reached only 40% over a 50-year period, whilst natural gas managed just 25% in the same period. Smil wonders how fast renewables can grow in comparison. To illustrate this, I have included the IEA's net-zero scenario trajectory for renewables, represented as a steep upward curve. Is such accelerated growth possible? I have also added the nuclear trajectory on the right-hand side. Since nuclear power hit 5% of global energy in the 1980s, its growth has remained virtually flat. Whilst the IEA's net-zero scenario envisages a doubling of nuclear power, COP28 statements call for a tripling by 2050. Yet, compared with the historical growth of fossil fuels – let alone the projected surge of renewables – nuclear expansion remains modest (Figure 6.1).

Figure 6.1. Vaclav Smil vs International Energy Agency's Net Zero Scenario

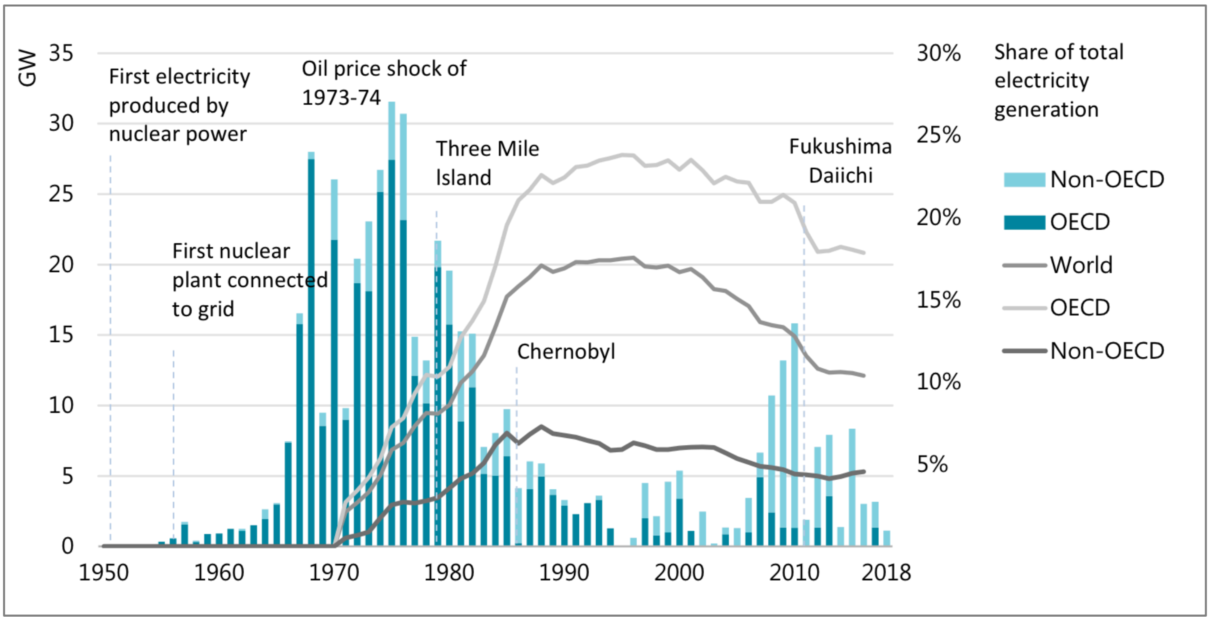


Source: Innovation for Cool Earth Forum (2024).

Why is this the case? The biggest reason lies in a repeated pattern of mistakes and accidents. Incidents such as Three Mile Island in the US (1979), Chernobyl in Ukraine

(1986), and Fukushima in Japan (2011) triggered global safety concerns, discouraging further deployment of nuclear power (Figure 6.2).

Figure 6.2. Reactor Construction Starts and Share of Nuclear Power

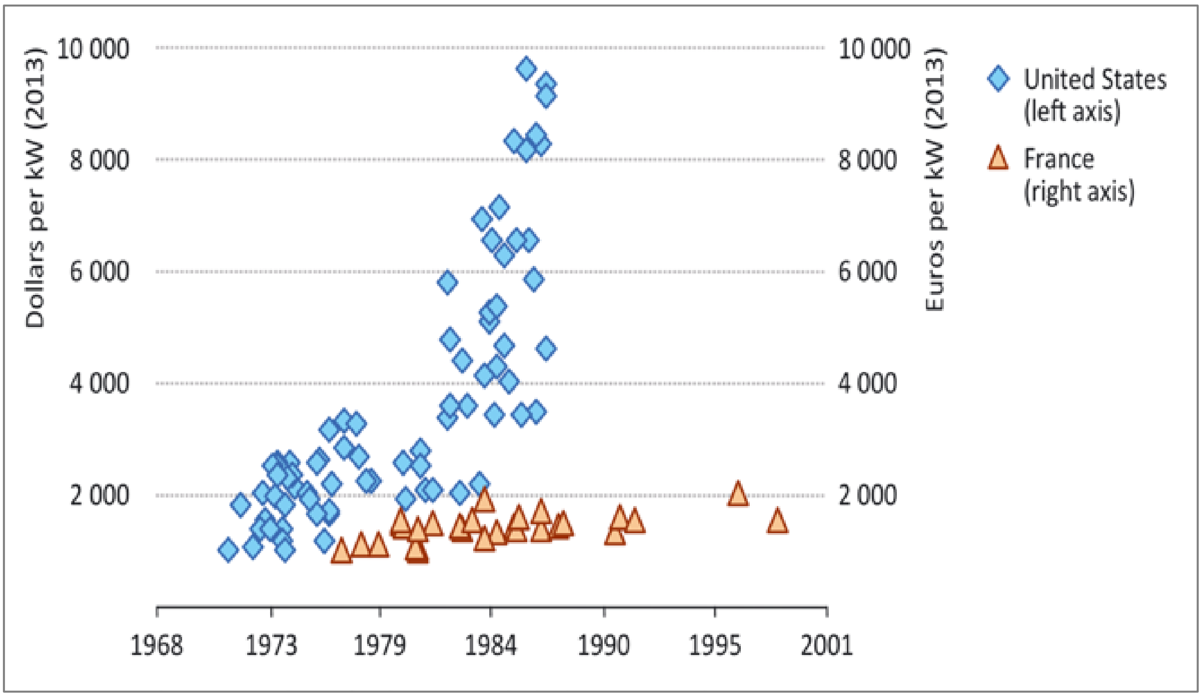


GW = gigawatt, OECD = Organisation for Economic Co-operation and Development.
Source: International Energy Agency (2019).

No technology is without risk. Human error happens. Although passive safe or fail-safe technologies exist, it is important to reduce the possible consequences of an accident. One effective method is to reduce the core volume of the reactor, thereby potentially shrinking the emergency planning zone (EPZ) to the plant boundary, if approved by regulators. SMRs are designed for this purpose. For example, the EPZ for Nuscale's VOYGR reactor is confined within the plant itself. Toshiba's 4S reactor claims a 20-meter EPZ, as submitted to the US Nuclear Regulatory Commission. In theory, such designs eliminate the need for neighbourhood evacuation plans.

The second major issue is cost. As the IEA reveals, delays in construction have led to significant cost overruns in Europe and the US. In contrast, China and Russia have performed better in adhering to construction timelines, whilst Korea made a remarkable success with the Barakah Nuclear Power Plant in the UAE. A comparative analysis of construction costs between the US and France for nuclear power plants underscores that standardisation is more important than scale of reactor. SMRs aim to address this issue through modularity and streamlined design (Figure 6.3).

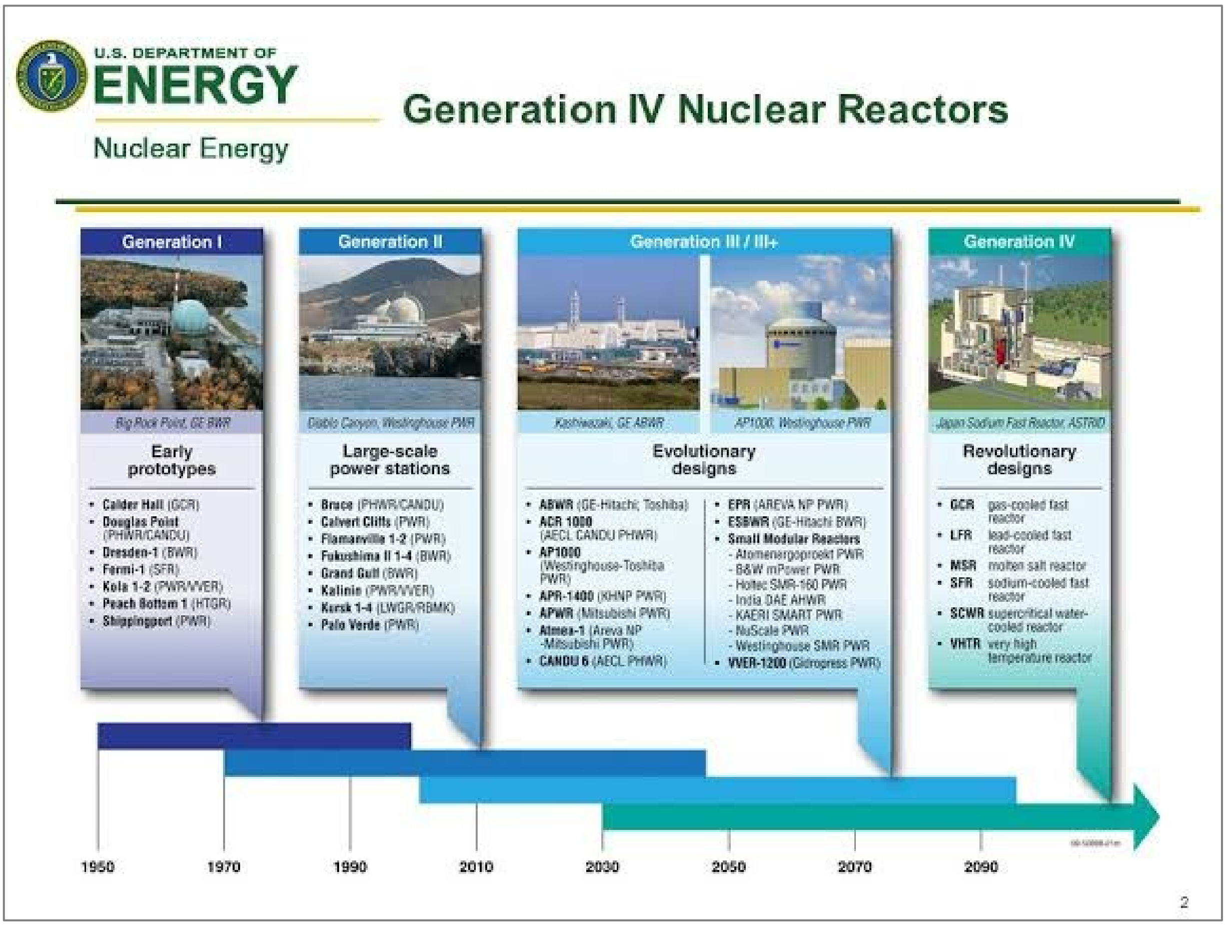
Figure 6.3. Historical Overnight Construction Costs for Nuclear Power Plants in France and the United States



kW = kilowatt.
Note: Overnight costs are shown for the year in which plants became operational.
Source: International Energy Agency (2014).

The evolution of nuclear reactor technology shows that large light water reactors (LWRs) dominate Generations II and III. A safer version, known as Generation III+, has been developed, but with increased capacity, implying potentially greater consequences in the event of an accident. Although the probability of an incident may be lower, the 'tail risk' is larger, given the increased nuclear core size. According to the IEA, large reactors are still being built, albeit with significant risks. The golden age of large LWRs is ending, as the era of innovative SMRs begins (Figure 6.4).

Figure 6.4. Generation IV Nuclear Reactors



Source: United States Department of Energy.

Another limitation of LWRs is the finite nature of uranium resources. Current known reserves are sufficient to sustain today's level of nuclear power generation for only about 60 years. Notably, 99% of natural uranium is uranium-238 (U238), which is not fissionable. Only 0.7% consists of fissionable uranium-237 (U237), which must be enriched to about 5% for use in LWRs. The IEA cautions that enrichment capabilities are restricted to a small number of countries, with Russia accounting for 40% of global capacity. Generation IV fast neutron reactors offer a solution to this limitation. These reactors not only generate power but also convert U238 into fissionable plutonium-239. Fast breeder reactors go a step further, increasing the supply of usable fuel. This means that natural uranium could potentially sustain nuclear power generation for 6,000 years, 100 times longer than current LWR technology allows. This innovation offers a compelling solution to long-term energy security.

The third major challenge is the disposal of radioactive waste. It takes about 300,000 years for the toxicity of spent nuclear fuel, particularly minor actinide, which have extremely long half-lives, to decline to the level of natural uranium. Direct disposal of this waste requires geologically stable repositories capable of maintaining their integrity over these vast timescales. Onkalo, Finland's deep geological repository, 500 metres underground, is designed to contain spent fuel safely for 100,000 years. In Sweden, the planned spent fuel repository at Forsmark will be located in Söderviken, 500 metres deep within 1.9-billion-year-old bedrock. France plans a similar facility at Bure-Saudron in the Meuse/Haute-Marne region. In the US, Yucca Mountain in Nevada has long been considered a candidate site, although development has stalled due to opposition from the state governor. Japan has initiated preliminary studies in three localities: two in Hokkaido and one in Kyushu.

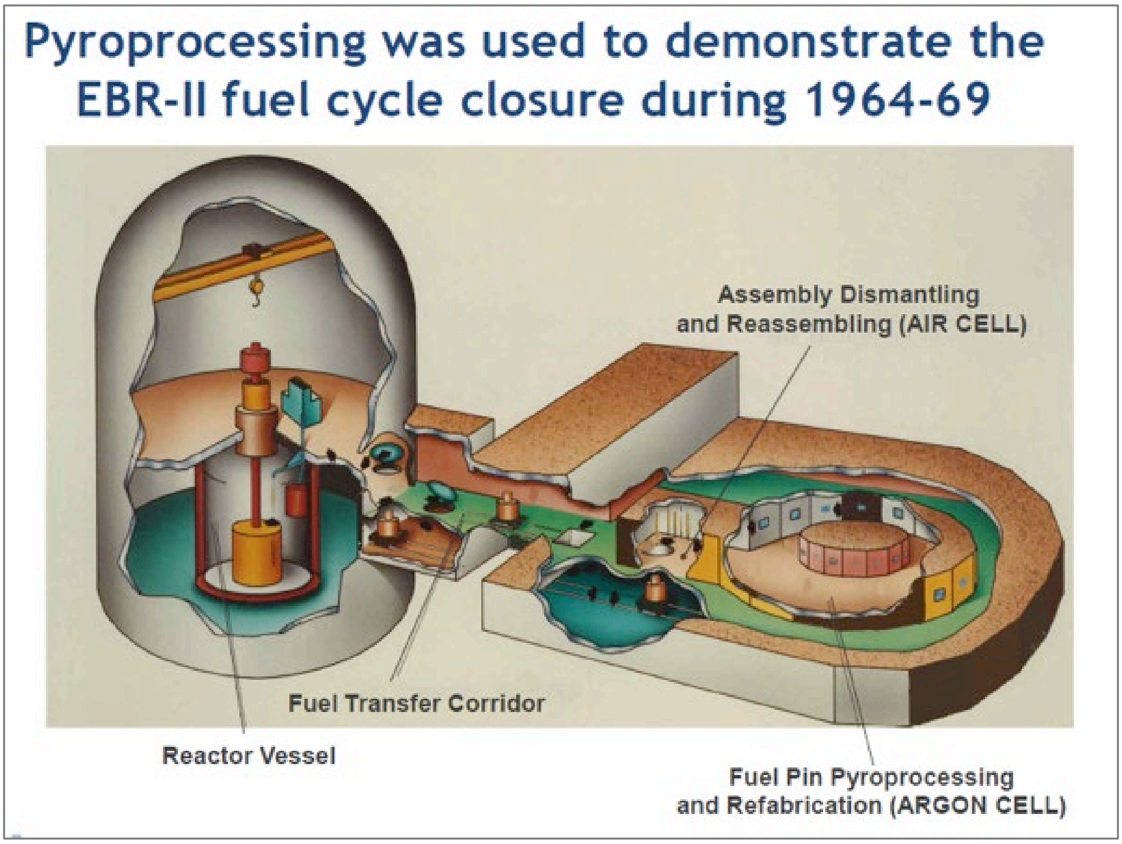
Unlike Finland and Sweden, which plan direct disposal of spent fuel from their LWRs, France and Japan have adopted a nuclear fuel cycle approach. This involves reprocessing spent fuel to separate plutonium, which can then be used either in fast neutron reactors or as mixed oxide fuel in LWRs. Through this method, the volume and toxicity of high-level radioactive waste can be significantly reduced, bringing the toxicity period down to about 9,000 years. The remaining waste is vitrified and stored in geological structures.

The US approach at Yucca Mountain is based on temporary, retrievable storage. However, the US may adopt reprocessing in the future to use plutonium as fuel in fast neutron reactors. The US Department of Energy operates the Waste Isolation Pilot Plant in Carlsbad, New Mexico, where transuranic waste generated by defence activities is permanently disposed of.

Siting a waste repository remains politically sensitive. Nonetheless, it is irresponsible to continue relying on nuclear power without a clear and viable waste management strategy.

A promising alternative is the integral fast reactor (IFR), developed by Argonne National Laboratory in the US, along with its associated pyro-processing (Figure 6.5). This closed fuel cycle system reduces the waste's toxicity to about 300 years rather than 9,000 years for PUREX-based reprocessing or 300,000 years for direct disposal (Figure 6.7).

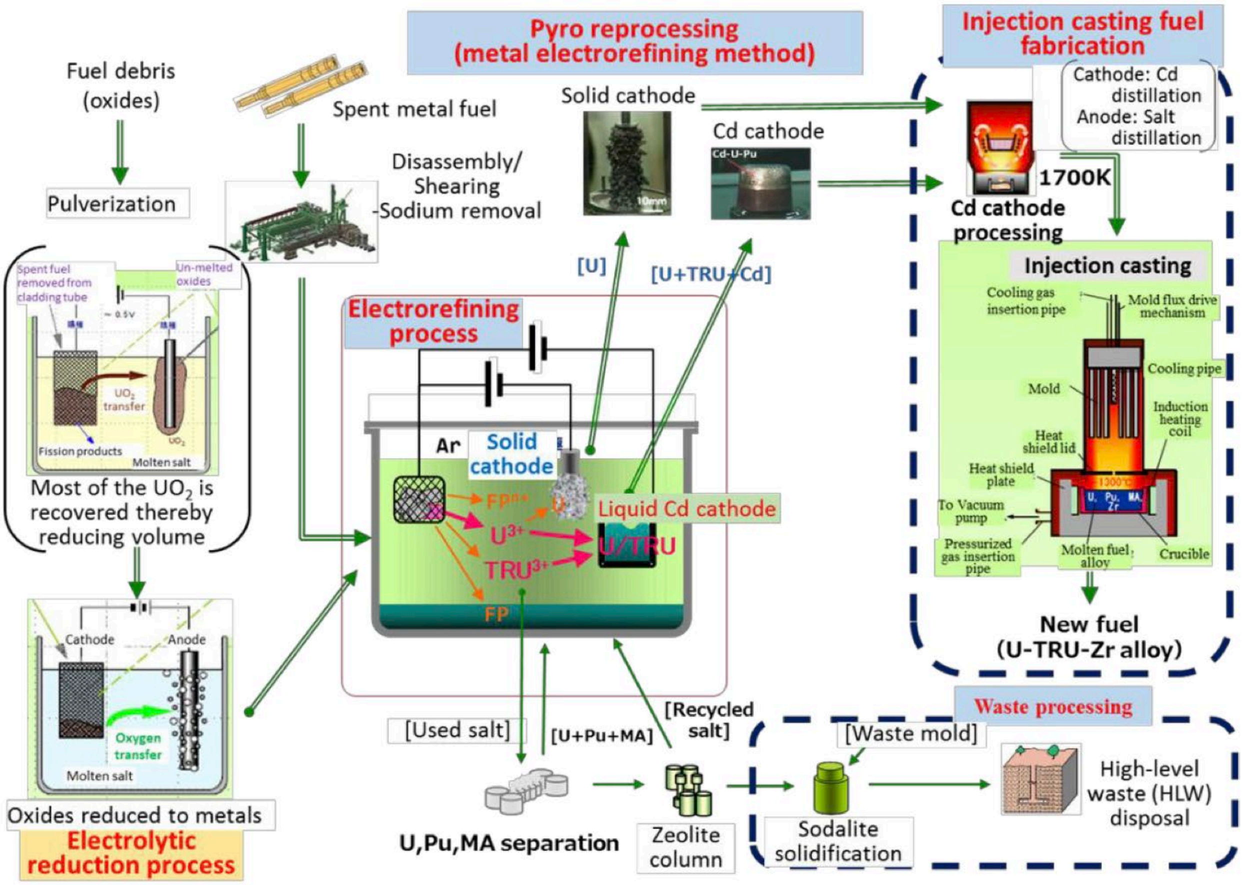
Figure 6.5. Integral Fast Reactor Developed at Argonne National Laboratory, United States



Source: Charles E. Till and Yoon IL Chang: Plentiful Energy, 2011.

The reprocessing method, known as pyro-processing, separates uranium, plutonium, and minor actinides through a metal electrorefining process. These elements are then recycled as fuel in a fast reactor that is co-located with the pyro-processing plant, forming a fully integrated, closed-loop system (Figure 6.6).

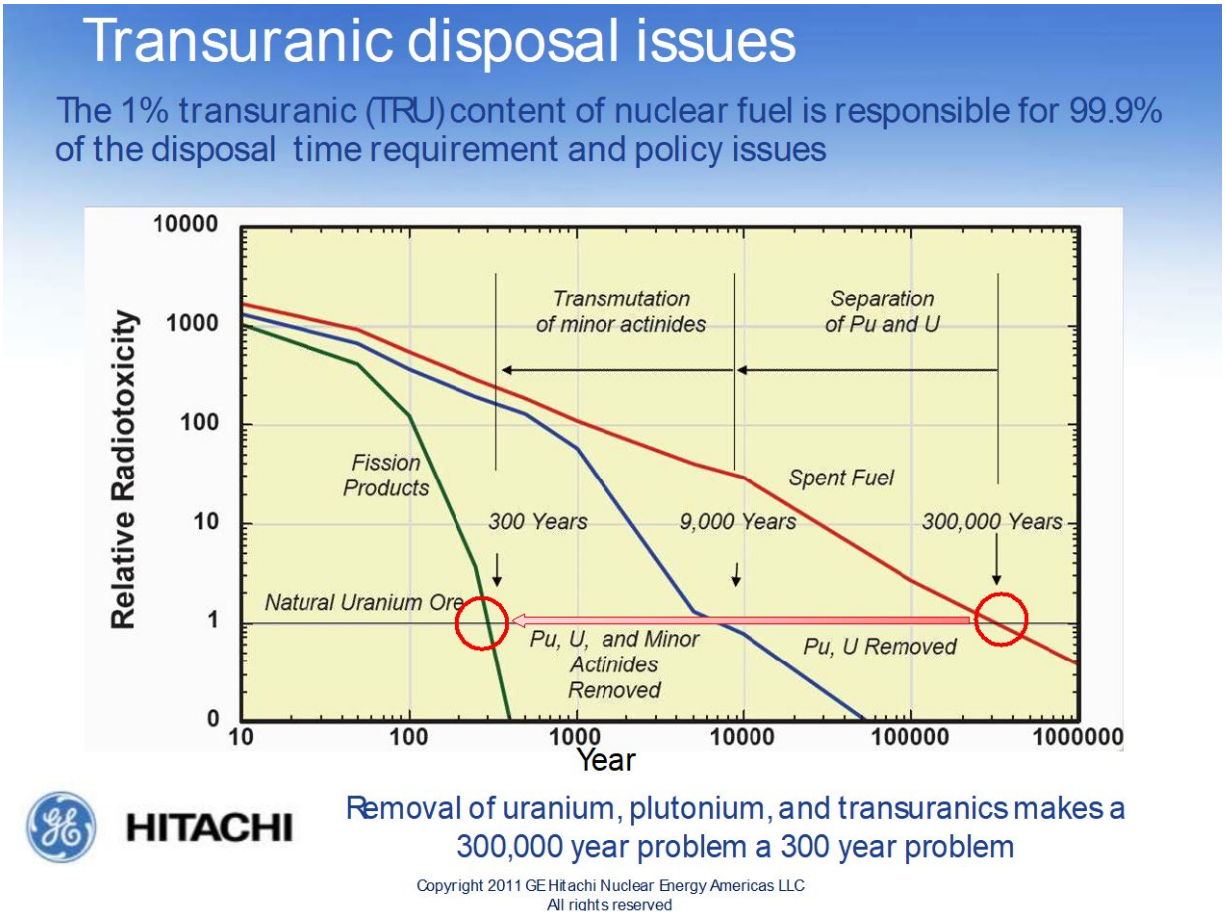
Figure 6.6. Technical Feasibility of an Integral Fast Reactor as a Future Option for Fast Reactor Cycles – Integration of a Small Metal-fuelled Fast Reactor and Pyro-processing Facilities



MA = minor actinide, Pu = plutonium, TRU = transuranic, U = uranium, UO2 = uranium dioxide, Zr = zirconium

Source: Sasakawa Peace Foundation (2016).

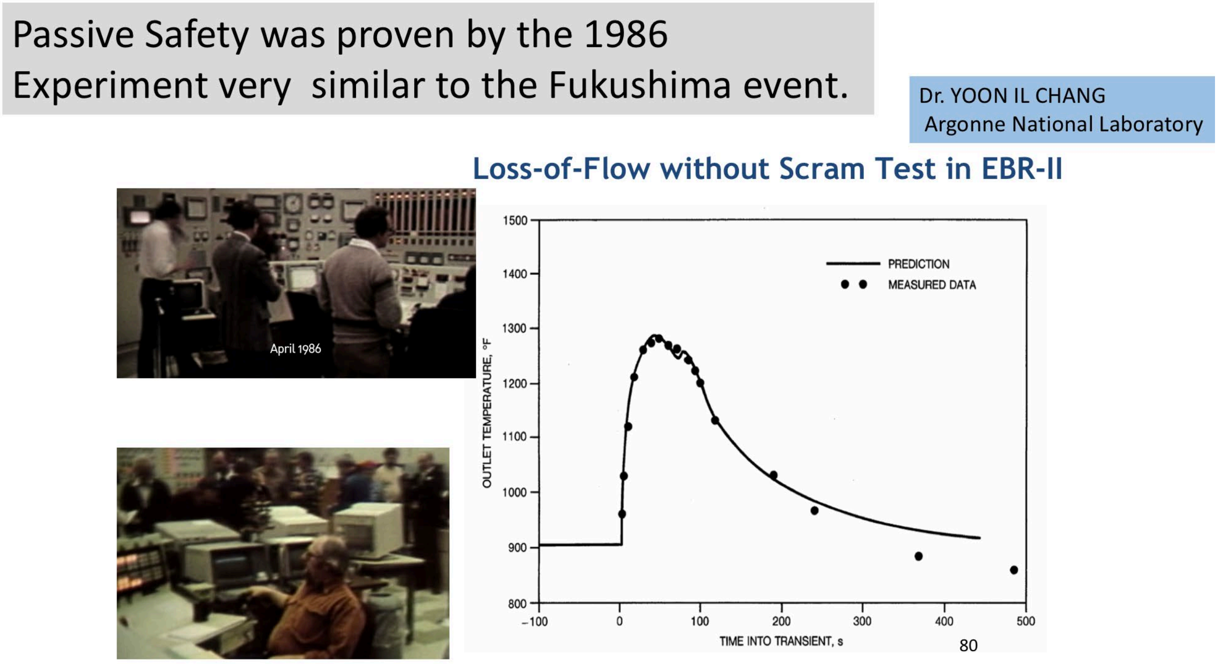
Figure 6.7. Transuranic Disposal Issues



Pu = plutonium, U = uranium.
Source: GE Hitachi (2011).

In 1986, the passive safe features of the EFR's fast reactor design were demonstrated at the EBR-II reactor in Idaho. The extreme test simulated a complete loss of coolant flow caused by a total blackout, without triggering a safety control rod actuator mechanism (SCRAM) or an emergency shutdown. Remarkably, the reactor safely shut itself down without any human intervention, an even more demanding scenario than the Fukushima accident, where SCRAM was initiated by the earthquake. The EBR-II, a fast neutron reactor using metallic fuel and a sodium coolant, successfully validated its passive safety mechanisms, as originally designed (Figure 6.8). Whilst safety is a necessary condition for sustainability, it is not sufficient on its own. The potential consequences of an accident cannot be eliminated, which is why reactor core size remains a critical factor in determining the scale of impact.

Figure 6.8. Loss-of-flow Without SCRAM Test in EBR-II, 1986



SCRAM = safety control rod actuator mechanism.
Source: Yoon Il Chang (2011).

The fourth element of sustainability is proliferation resistance. LWRs are considered proliferation-prone technologies because they rely on enrichment and reprocessing as basic technological processes. To mitigate the risk of proliferation, we must redesign the current non-proliferation treaty regime and International Atomic Energy Agency (IAEA) surveillance system, in parallel with the development of proliferation-resistant technologies.

The IFR is designed to be proliferation resistant through two key features. First, its pyro-processing method separates plutonium together with highly radioactive minor actinides, making it considerably more difficult to extract pure plutonium for use in nuclear weapons. In contrast, the PUREX process is specifically designed to separate pure plutonium, which is suitable for bomb production. Second, the IFR operates as a closed system of integrated facilities (Figure 6.5), meaning that plutonium is never transported outside the site. This significantly reduces the risk of seizure by terrorists.

In summary, the key innovations of the IFR include the following:

1. **Metal fuel and pyro-processing.** Uranium resource utilisation is improved by a factor of 100 compared with current commercial reactors, rendering nuclear power an almost limitless energy source.
2. **Unique inherent passive safety.** Demonstrated successfully, this feature significantly reduces the impact of accidents, particularly when deployed as an SMR.

3. **Reduced radiological hazard.** The lifetime of nuclear waste radiological risk is reduced from about 300,000 years to about 300 years.
4. **Proliferation-resistant and economic fuel cycle closure**. This is enabled through pyro-processing.

International collaboration on IFR development is ongoing. The IFR was originally developed by Argonne National Laboratory and is located at Idaho National Laboratory (INL). The Korea Atomic Energy Research Institute has long pursued its development in partnership with INL. Dr. Takashi Nagai, a physician and a survivor of the Nagasaki atomic bomb tragedy, spoke positively about nuclear technology, expressing hope that it could transform destruction into fortune (Figure 6.9).

The development of IFR technology offers a strong opportunity for expanded international cooperation.

Figure 6.9. Statement by Dr. Takashi Nagai

Statement by Dr. Takashi NAGAI after Nagasaki atomic bomb. "How to turn the devil to the fortune."

Dr. Takashi Nagai, a Professor at Nagasaki University in 1945 when the atomic bomb was dropped, exemplifies the resilience, courage and believe in science of the Japanese people. Despite having a severed temporal artery as a result of the bomb, he went to help the victims even before going home. Once he got home, he found his house destroyed and his wife dead. He spent weeks in the hospital where he nearly died from his injuries. But just months after the atom bomb dropped, he said:

"Everything was finished. Our mother land was defeated. Our university had collapsed and classrooms were reduced to ashes. We, one by one, were wounded and fell. The houses we lived in were burned down, the clothes we wore were blown up, and our families were either dead or injured. What are we going to say? We only wish to never repeat this tragedy with the human race. We should utilize the principle of the atomic bomb. Go forward in the research of atomic energy contributing to the progress of civilization. Devil will then be transformed to fortune.(Wazawai tenjite Fukutonasu) The world civilization will change with the utilization of atomic energy. If a new and fortunate world can be made, the souls of so many victims will rest in peace."

Source: Takashi Nagai.

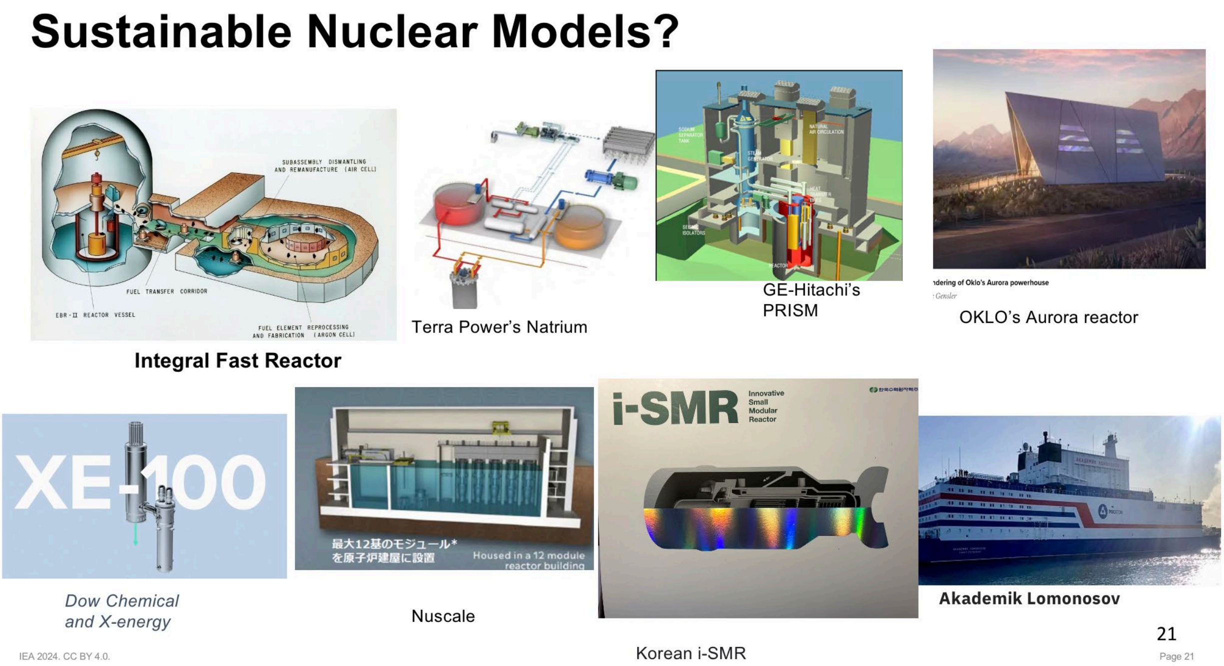
Chapter 7

Small Modular Reactors as Sustainable Nuclear Technology Models

A wide variety of SMRs are emerging. The IEA's report highlights that the private sector increasingly regards nuclear energy as an investible source of firm, competitive, and clean power capable of supporting energy-intensive operations around the clock. Notably, major technology firms in the US are entering into power purchase agreements with developers to secure electricity for data centres and AI operations. SMRs meet the criteria for minimal accident impact due to their compact size and many incorporate passive safety features.

Several SMRs are based on IFR technology (Figure 7.1). Microsoft-backed TerraPower's Natrium reactor is planned to replace a coal-fired power plant in Wyoming. OKLO's Aurora reactor, an SMR-type derivative of the IFR, employs a sodium-cooled fast reactor with commercial pyro-processing. GE-Hitachi's PRISM, the ARK-100, and Toshiba's 4S reactor are also designed as SMR applications of IFR technology. The 4S reactor's EPZ is designed with a radius of just 20 m. Korea Hydro & Nuclear Power's i-SMR is based on LWR technology, but the company is actively exploring IFR as a future option.

Figure 7.1. Sustainable Nuclear Models? Nobuo Tanaka's Presentation

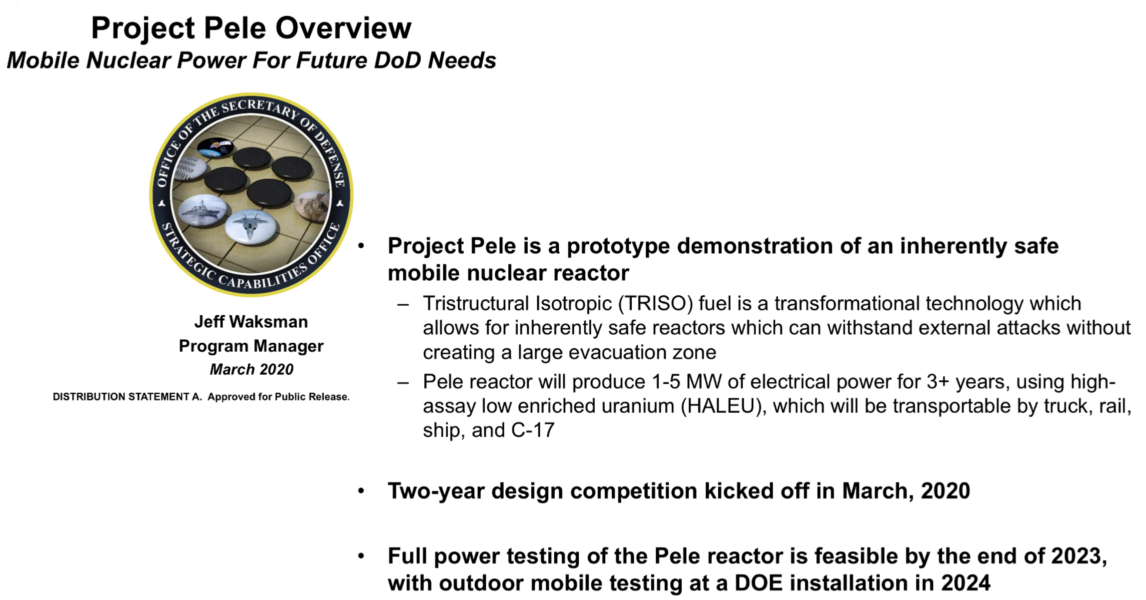


Source: Author, from Nabuo Tanaka's presentation.

Non-IFR SMRs with similar features are also under development. NuScale's VOYGR is an LWR with an EPZ contained entirely within the plant. X-energy's XE-100, a high-temperature gas reactor (HTGR), is being deployed by Dow Chemical for use at its industrial facilities. The US Department of Defense is developing the mobile Project PELE reactor, also an HTGR, through BWX Technologies (Figure 7.2). HTGRs have demonstrated passive safety in helium coolant loss scenarios, as confirmed by experimental results in China and Japan. China's high-temperature gas-cooled reactor–pebble-bed module (HTR-PM) and Japan Atomic Energy Agency (JAEA) high-temperature engineering test reactor both validated this passive safety feature in 2024.

Google and Kairos Power are developing a molten salt reactor. Amongst floating nuclear power options, ThorCon Power in Indonesia is pursuing molten salt reactor technology, whilst Rosatom's Akademik Lomonosov is based on LWR technology. LWRs offer inherent passive safety when deployed at sea, as the surrounding water provides abundant emergency cooling. Island nations may particularly benefit from floating nuclear solutions to electrify remote islands. These units can be constructed in dockyards and deployed upon completion, allowing for more efficient project timelines. In addition to LWRs, some companies are considering molten salt reactors for floating applications, as molten salt solidifies upon contact with water, helping to contain potential contamination in the event of an emergency.

Figure 7.2. Overview of the United States Department of Defense's Project PELE



Source: United States Department of Defense.

According to the IEA study, China is projected to become the leading market for SMRs by 2050. Several SMRs are expected to commence operation in the late 2020s, total installed capacity reaching about 35 GW by 2050. The country's first SMR, the HTR-PM – a

Generation IV high-temperature gas-cooled design – was successfully brought online in 2023. Additional units of this type are planned, alongside various large-scale reactors. Two other SMR designs, the ACP100 and NHR200, are also under development. These three SMR types are suitable for multiple applications, including district heating, industrial heat, and electricity generation.

Chapter 8
Secure Supply Chains

The global prospects of the nuclear industry depend critically on the resilience of its supply chains. Resilient supply chains can adapt quickly to operational disruptions through flexible contingency planning and accurate forecasting across all segments. Government policy must avoid 'stop-and-go' cycles, which are detrimental to industries that require long-term visibility to justify major investments in supply infrastructure.

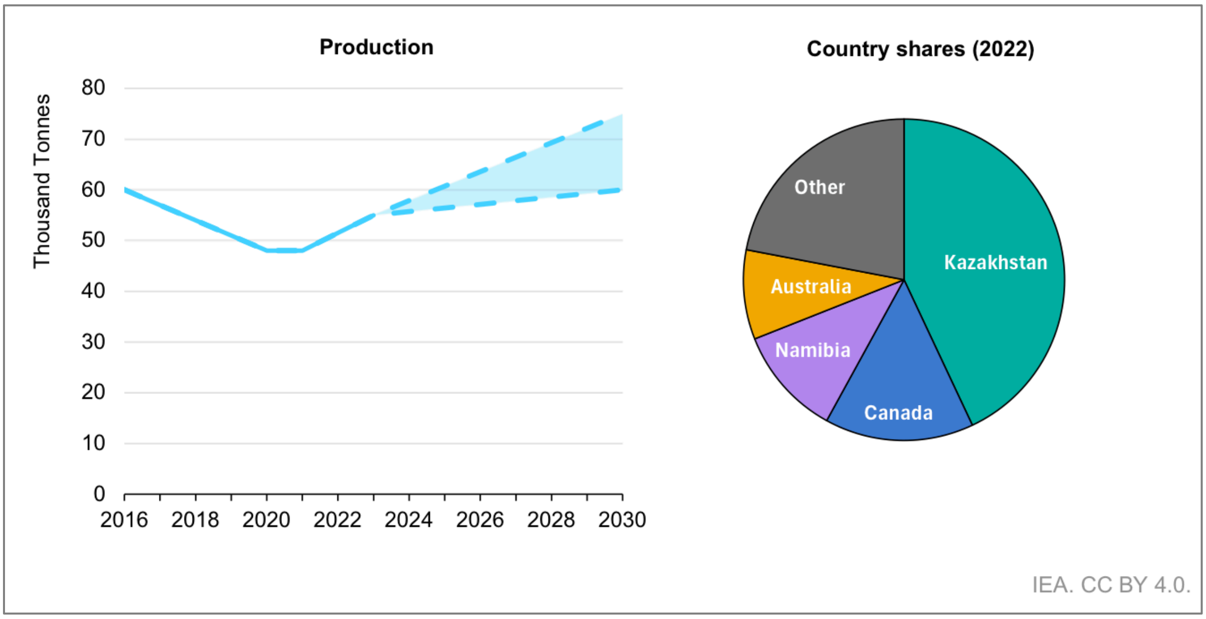
Strategic supply chain planning must be undertaken well in advance, finding the optimal balance between global and local components. Local supply chains benefit from familiarity with local culture, regulatory standards, and industry codes, providing clear advantages in certain market contexts. However, global supply chains also offer significant benefits: they expand the pool of suppliers, and international providers may be more economically viable due to access to more cost-effective sources of energy, raw materials, or labour. In some cases, the use of foreign suppliers is sometimes necessary. For example, global capacity for forging large ingots (over 500 tonnes), required for manufacturing major reactor components, is currently sufficient to meet demand for 30 large reactors per year, but this capacity exists only in France, Italy, and South Africa.

Adopting new technologies is key to improving the reliability and competitiveness of nuclear supply chains. These include modular construction, additive manufacturing, and advanced manufacturing processes such as new welding technologies and digital innovations. For example, digital twins represent a major advancement, enabling continuous online monitoring by receiving sensor data or running real-time simulations. Efficiency gains in supply chain logistics are amongst the many advantages offered by these technologies.

Traditionally, operators maintain large inventories of spare components in preparation for unexpected failures, although much of this stock remains unused. Modern digital tools can help estimate the probability of component usage, thereby optimising procurement and inventory management.

In 2022, four countries accounted for over three-quarters of global uranium production from mines: Kazakhstan (43%), Canada (15%), Namibia (11%), and Australia (9%). Current market projections indicate that existing mine output will be sufficient to meet global uranium requirements for the next several years. Nevertheless, as nuclear capacity increases, demand will rise. According to the IAEA, global uranium demand is expected to rise from 61,000 tonnes to 77,000 tonnes by 2030 (Figure 8.1).

Figure 8.1. Global Uranium Production from Mines, 2016–2030



Source: International Energy Agency (2025).

The IEA report highlights the significant concentration risk in uranium fuel enrichment. Today, over 99% of global enrichment capacity is controlled by just four companies: China National Nuclear Corporation, with 15%; Russia's Rosatom, with 40%; Urenco (a British–German–Dutch consortium), with 33%; and France's Orano, with 12%. Some of these entities are pursuing expansion. 'Russia accounts for 40% of global capacity, the single largest share', said Dr. Fatih Birol. 'Highly concentrated markets for nuclear technologies, as well as for uranium production and enrichment, represent a risk factor for the future and underscore the need for greater diversity in supply chains'.

Next-generation nuclear technologies may necessitate new supply chains for advanced fuel. Several reactor designs under development will require high-assay low-enriched uranium (HALEU). To meet this demand, some countries are increasing their production capacity. In the US, the Department of Energy has created a HALEU consortium and co-funded a demonstration production facility in Piketon, Ohio. Another type of HALEU, the tristructural isotropic particle fuel (TRISO), which is used in high-temperature gas-cooled reactors, is also entering production. As with all nuclear fuels, robust safeguards must be implemented to minimise the risk of proliferation.

Reprocessed plutonium from spent LWR fuels can serve as an abundant source of fuel, potentially offering 100 times more energy than enriched uranium, for use in advanced fast reactors. Moreover, plutonium does not require further enrichment. However, due to its potential misuse, stricter proliferation management is essential.

Chapter 9

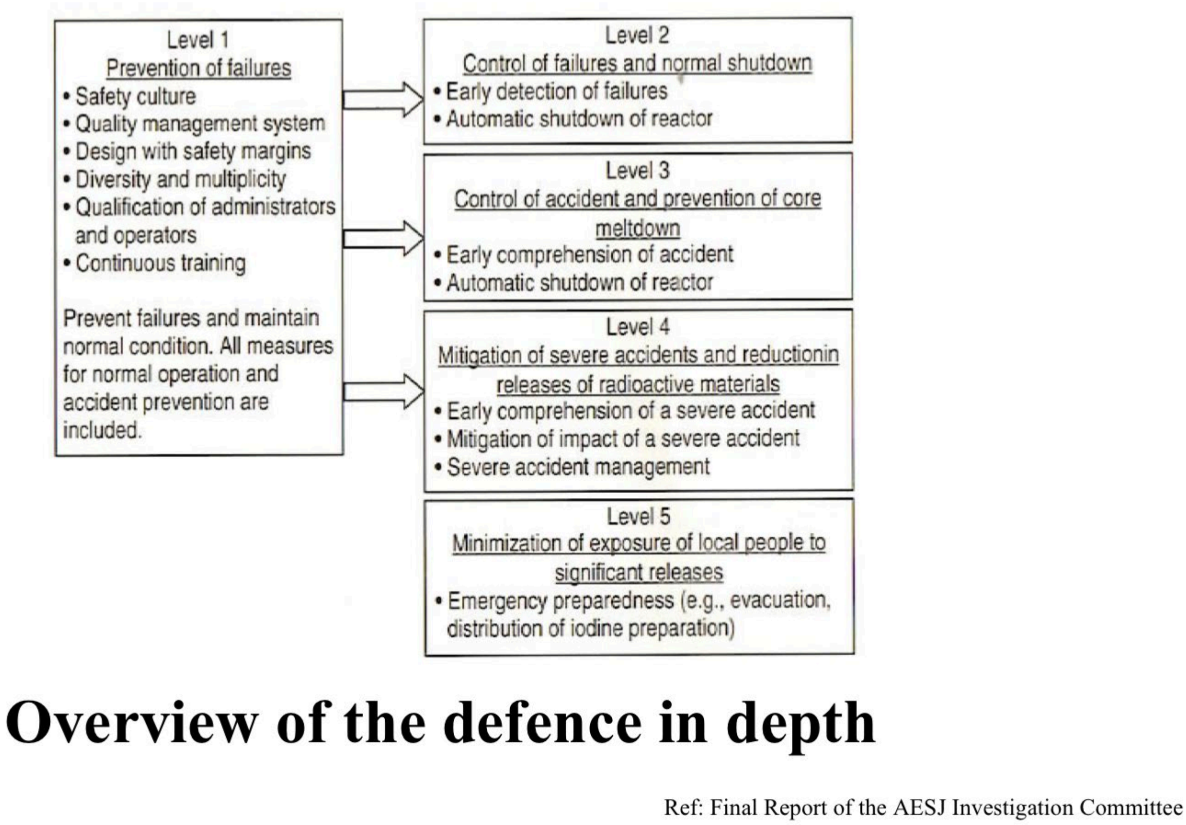
Planning Human Resources and Regulation

According to the IEA, the global nuclear energy industry employs about 1.1 million people. Of this total, around 400,000 are engaged in operations, whilst more than 600,000 are involved in the construction of new reactors. In advanced economies, a shortage of qualified personnel is emerging as a critical challenge, particularly as a large portion of the existing workforce is set to retire in the coming years. If not properly addressed, this issue could become a major bottleneck for nuclear expansion plans. It is therefore essential to conduct comprehensive national and regional workforce assessments. These will provide a clearer vision of skillsets at risk, enabling better planning and training for the skilled workforce required to support the future of the nuclear energy industry.

In France, for example, more than 40,000 workers are directly employed in nuclear power generation. Across the extended nuclear supply chain – encompassing reactor design, construction, operation, the fuel cycle, and research and development (R&D) – the industry accounts for more than 200,000 jobs, representing about 7% of the country's industrial employment. To support its entire programme, including fleet operations and the EPR2 and SMR new-build initiatives, the French nuclear industry plans to recruit about 10,000 people each year over the next 10 years. Reactor operators and engineers must be trained and educated by the original designers. However, the reactor is only one component of the broader nuclear system. Regulatory authorities must understand international rules and safety practices. Other sectors of the industry, such as uranium mining, fuel conversion, fabrication, fuel transport, waste management, and fuel cycle R&D, require specialised training and education. The IAEA and the World Association of Nuclear Operators play key roles in providing essential knowledge and resources.

Regulatory bodies must be independent of operators and technically proficient in the entire nuclear system. One of the contributing factors to the Fukushima accident was the phenomenon known as 'regulatory capture', where regulators became overly dependent on the expertise and safety data provided by the regulated entities. In many cases, operators and designers were more knowledgeable than the regulators themselves. This imbalance can result in gaps in safety planning. Japan's regulatory authority, for instance, did not fully adopt the IAEA's defence-in-depth approach because TEPCO, the plant operator, deemed it unnecessary. As a result, only three of the IAEA's five defence-in-depth levels were implemented, leaving no preparation for a complete station blackout (Figure 9.1).

Figure 9.1. Five Defence-in-Depth Levels of the International Atomic Energy Agency



Source: International Atomic Energy Agency.

Box 1. Lessons Learnt from the Fukushima Accident

Dr. Yoichi Fujiie, former chairman of the Atomic Energy Commission of Japan, who, along with Dr. Yoon Il Chang of Argonne National Laboratory, also educated the author on the integral fast reactor, summarised the key lessons from Fukushima as follows:

- Accident management procedures to prevent and mitigate severe accidents must be prioritised and incorporated into safety regulatory frameworks.
- A comprehensive, in-depth design strategy must address external hazards, including both design basis conditions and design extension conditions, ensuring a balanced approach to prevention and mitigation. The design base for external events must be well examined using the best available science and historical data to prevent site-specific vulnerabilities.
- Mitigation measures must also address scenarios beyond the design base. These measures should be based on the latest scientific knowledge and expert judgment and ensure the continued operation of safety functions even after design limits are exceeded.
- Effective accident management procedures must be identified and well examined to prevent core damage and avoid the release of radioactive materials by maintaining critical safety functions.

It is important to note that no acute and latent fatalities resulting from radiological effects have been observed, nor are they expected to occur, thanks to the robust seismic design, the successful reactor shut down, and the commendable efforts of those involved in managing the crisis.

Source: Dr. Yoichi Fujiie.

The IAEA defines international safety rules for reactors and sets safeguards to manage proliferation risks. These rules serve as models for member states, which are encouraged to adopt them into national regulatory frameworks. The IAEA also conducts site visits, helping member states assess and enhance the safety of their nuclear installations by comparing practices to international standards and providing tailored recommendations for improvement. In addition to international guidelines, most national regulatory bodies enforce their own requirements. The industry also self-regulates by sharing operational experiences and conducting peer reviews. The World Association of Nuclear Operators, for instance, conducts peer review missions at every nuclear power plant every 3 years and issues performance rankings.

In parallel, safeguards must be observed to address the risk of nuclear proliferation. These are legally binding agreements verified by the IAEA to ensure nuclear materials are used solely for peaceful purposes. The entire nuclear supply chain, including the transport of nuclear fuel, is subject to IAEA monitoring. The US is particularly stringent regarding proliferation risks. As such, enrichment services and spent fuel reprocessing are generally prohibited when the US is involved in fuel cycle agreements.

Box 2. Admiral Hyman G. Rickover of the United States Navy: Father of the United States Nuclear Submarine Fleet

Admiral Hyman G. Rickover, regarded as the father of the United States nuclear submarine programme, directed the original development of the naval nuclear fleet. He interviewed and recruited every officer and crew member, believing that any compromise in selection could jeopardise the safety of the submarine and its personnel. Rather than recruiting from conventional submarine crews, he selected nuclear engineers with a strong grasp of the underlying technology. Rickover maintained uncompromising standards: even small mistakes were grounds for immediate dismissal. His firm discipline laid the foundation for one of the safest submarine fleets in the world. After retiring from service, many of his officers and crews went on to work in nuclear power plants, equipment manufacturing, and regulatory agencies, contributing to the high safety standards of the US civilian nuclear industry. His legacy is chronicled in the book *Against the Tide* by Dave Oliver.

Chapter 10

Commitment of a Political Leader

How can a government avoid 'stop-and-go' policies? A clear long-term vision and strong commitment are essential for the successful deployment of nuclear power.

Consider the case of Germany, which decided to phase out both nuclear and coal-fired power whilst relying on inexpensive natural gas imported via pipeline from Russia.

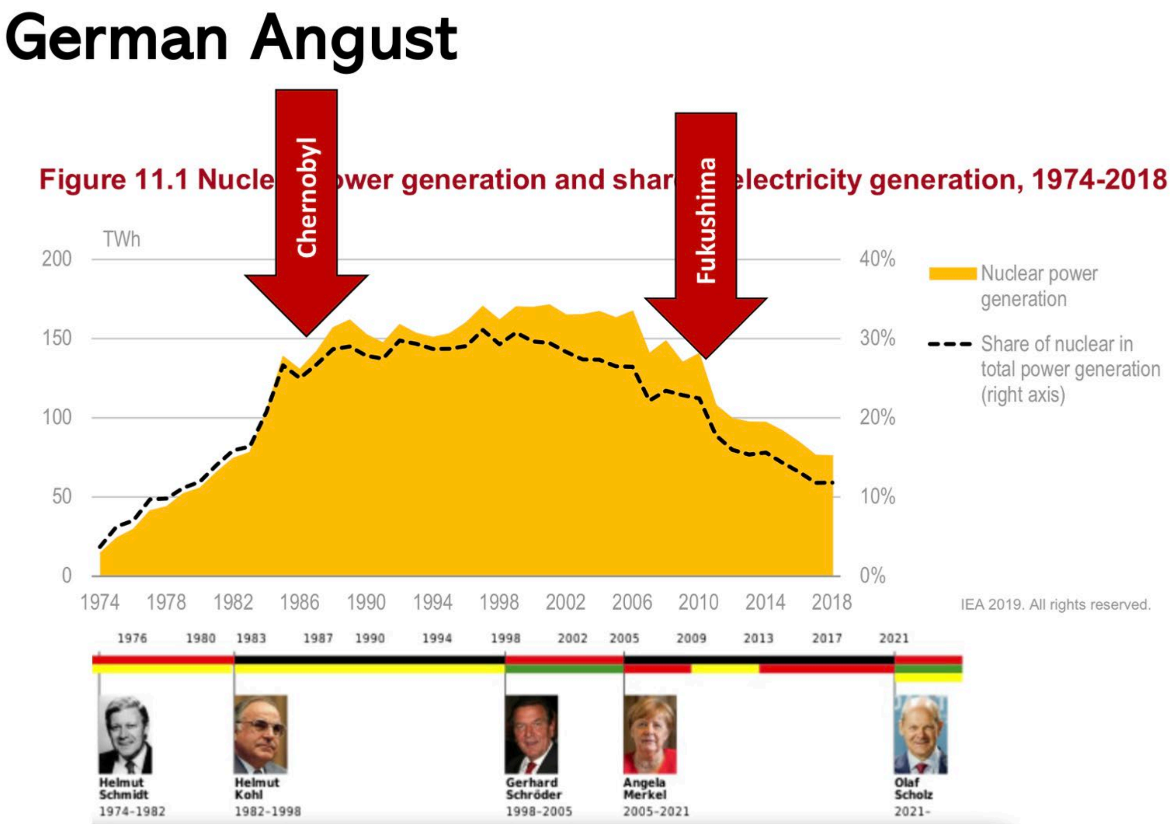
Figure 10.1. Discussion on Energy with Chancellor Merkel and German Industrial Leaders

Source: Author.

In 2008, the German government opted to phase out nuclear energy, largely due to a coalition with the Social Democratic Party, which opposed nuclear power. However, in 2009, the Christian Democratic Union achieved a strong electoral victory and formed a coalition with the Free Democratic Party, leading to a reversal of the phase-out decision. Yet, following the Fukushima accident in 2011, the German government reinstated its nuclear phase-out policy (Figure 10.2). This represents a textbook example of a 'stop-and-go' energy policy, which a government should avoid.

Energy infrastructure projects span decades. Frequent shifts in policy – on, off, and on again – create uncertainty that hampers long-term investment. The IEA consistently calls for stable and predictable energy policies across its member states. Nuclear energy policy is no exception.

Figure 10.2. Nuclear Power Generation and Share in Electricity Generation in Germany



Source: International Energy Agency (2019).

In Japan, Hidankyo, the association representing survivors of the atomic bombings of Hiroshima and Nagasaki, was awarded the Nobel Peace Prize, an acknowledgement that the Nobel Peace Committee perceives the risk of nuclear proliferation as a pressing global threat.

In light of this, I urge the governments of Japan and India to engage in joint diplomacy. Suppose India commits to renouncing nuclear weapons and joins the Treaty on the Prohibition of Nuclear Weapons. In that case, it can collaborate with Japan to advocate for permanent seats on the United Nations Security Council as representatives of non-nuclear weapon states. If Prime Minister Modi aspires to lead the Global South, this would be a meaningful step towards moving beyond Cold War–era nuclear deterrence mindsets and making a genuine contribution to global peace.

Yuval Noah Harari, author of *Sapiens,* has identified three existential challenges facing humanity in the 21st century: nuclear war, ecological collapse, and technological disruption through AI and algorithmic control. He argues that nationalism and populism are incapable of addressing such global issues. Instead, the world needs leaders with a truly global identity and outlook.

Chapter 11

An Optional Approach to Utilising Nuclear Energy in Viet Nam: Technology Selection and Strategic Implementation

Viet Nam's commitment to achieving carbon neutrality by 2050, coupled with its rapidly growing energy demand, necessitates a diversified energy portfolio. Whilst renewable energy sources such as solar and wind, along with LNG, dominate current strategies, nuclear energy remains a viable long-term option for providing stable, low-carbon baseload power and supporting industrial decarbonisation.

Nuclear R&D in Viet Nam began in the 1960s. The Da Lat research reactor (Da Lat Nuclear Research Institute, 2024), commissioned in 1963 with assistance from the US and later reconstructed in 1984 with support from the Soviet Union and IAEA, played an essential role in the country's early nuclear development. In 2006, Viet Nam announced its first nuclear power programme to diversify its energy mix. Following the enactment of the Atomic Energy Law in 2008, the government launched an ambitious plan to build 14 reactors by 2030 and selected two sites in Ninh Thuan Province for the first projects. It established the necessary institutional framework, including the National Nuclear Safety Council, the Vietnam Atomic Energy Agency, and the State Steering Committee for the Ninh Thuan Nuclear Power Project. Concurrently, Viet Nam signed intergovernmental agreements with Russia and Japan to facilitate technology transfer and nuclear power plant construction. In parallel, the country promoted human resources development by sending students to Russia and conducting personnel training programmes in cooperation with GE Hitachi Nuclear Energy (GE Hitachi Nuclear Energy, 2015). / However, in 2016, the nuclear power plan was cancelled due to economic and financial constraints.

After an 8-year hiatus, the Vietnamese government has decided to revive its nuclear energy ambitions to meet its climate goals. Although earlier experiences in research, development, and capacity-building have laid the groundwork for adopting nuclear energy, Viet Nam should initially prioritise the importation of foreign reactor technologies. At the same time, it should continue to promote domestic R&D for future expansion. This dual approach will support the urgent objectives of decarbonisation and energy security whilst building national expertise for the long term.

11.1. Candidate Technologies

As discussed in the previous chapters, nuclear technology is undergoing significant advancements. Whilst conventional reactor technologies continue to dominate the market, new designs are emerging, with a focus on improving safety, efficiency, and sustainability. The main technologies across three reactor categories – mature commercial reactors, small modular light water reactors, and advanced reactors – are summarised in Table 11.1, Table 11.2, and Table 11.3, respectively.

Table 11.1. Mature Commercial Reactors (Generation III+)

Reactor Technology	Type	Developer	Status
ABWR	BWR	GE Hitachi, Toshiba (Japan/USA)	Operational (4) in Japan; under construction (5) in Japan and Taiwan
AP1000	PWR	Westinghouse (USA)	Operational (6) in China and the US; under construction (6) in China
APR1400	PWR	KEPCO (Korea)	Operational (8) in Korea and the UAE; under construction (2) in Korea
ATMEA1	PWR	MHI (Japan) & Framatome (France)	No operational units; proposed in Türkiye
EPR	PWR	Framatome/EDF (France) & Siemens (Germany)	Operational (4) in China, Finland, and France; under construction (2) in the UK
ESBWR	BWR	GE Hitachi (USA)	No operational units; design certificated in the US
HPR1000	PWR	CGN/CNNC (China)	Operational (7) in China and Pakistan; under construction (26) in China and Pakistan
VVER1200 /AES-2006	PWR	Rosatom (Russia)	Operational (6) in Russia and Belarus; under construction (19) in Russia, Türkiye, Egypt, Hungary, Bangladesh, and China

BWR = boiling water reactor, CNNC = China National Nuclear Corporation, EDF = Électricité de France, KEPCO = Korea Electric Power Corporation, MHI = Mitsubishi Heavy Industries, PWR = pressurised water reactor, UAE = United Arab Emirates, UK = United Kingdom, USA = United States of America.
Source: Author.

Table 11.2. Leading Small Modular Light Water Reactors

Reactor technology	Type	Output (MWe)	Developer	Status
ACP100	PWR	125	CNNC (China)	Under construction since 2021; expected completion by 2026
BWRX-300	BWR	300	GE Hitachi(Japan/USA)	Selected for Canadian site; expected deployment by 2028
RITM-200	PWR	55	Rosatom (Russia)	Operational on floating platforms in Russia; land-based version under development
Rolls-Royce SMR	PWR	470	Rolls-Royce (UK)	Backed by the UK government; first plant planned for the 2030s
VOYGR	PWR	77	NuScale (USA)	First design certified by the US NRC in 2022; first plant expected in the early 2030s

BWR = boiling water reactor, CNNC = China National Nuclear Corporation, Mwe = megawatt electrical, PWR = pressurised water reactor, UK = United Kingdom, USA = United States of America, US NRC = United States Nuclear Regulatory Commission.
Source: Author.

Table 11.3. Leading Advanced Reactors

Reactor Technology	Type	Output (MWe)	Developer	Status
Natrium	SFR	345	TerraPower (USA)	Demonstration plant planned in Wyoming; expected completion by late 2020s
BN800	SFR	880	Rosatom (Russia)	Operational in Russia since 2016
PRISM	SFR	311	GE Hitachi (Japan/USA)	Selected for DOE's Versatile Test Reactor (VTR) Programme in 2018
HTR-PM	HTGR	210	INET (China)	Demonstration project operational in China since 2021
HTTR	HTGR	30(t)	JAEA (Japan)	Research reactor operational in Japan since 1998; demonstration plant planned in mid-2030s
Xe-100	HTGR	80	X-energy (USA)	Selected for US DOE demonstration programme; expected deployment by 2028

Reactor Technology	Type	Output (MWe)	Developer	Status
4S	LMFR	10	Toshiba (Japan)	Licensing activity initiated with the US NRC in 2007
Aurora	FR	1.5	OKLO (USA)	Safety design strategy approved by DOE in 2024; supply agreement with utility and industry
BREST-OD-300	LFR	300	NIKIET (Russia)	Under construction since 2021; expected completion by 2027
ThorCon	Floating MSR	250	ThorCon (USA/Indonesia)	Pre-licensing in 2022; expected construction from 2028

DOE = United States Department of Energy, FR = fast reactor, HTGR = high-temperature gas-cooled reactor, INET = The Institute of Nuclear and New Energy Technology, JAEA = Japan Atomic Energy Agency, LFR = lead fast reactor, LMFR = liquid metal fast reactor, MSR = molten salt reactor, MWe = megawatt electrical, SFR = sodium-cooled fast reactor, USA = United States of America, US NRC = United States Nuclear Regulatory Commission.
Source: Author.

Most reactors built since 2000, and those currently under construction, are Generation III+ LWR designs (Table 11.1), with outputs exceeding 1000 MWe per unit. These reactors feature significant improvements over earlier generations. Safety is enhanced through passive safety systems that rely on natural cooling processes. Higher operating temperatures, extended operational life, and longer fuel cycles improve overall reactor efficiency. Additionally, standardised designs and flexible output capabilities support improved economic performance. Extensive construction and licensing experience with these technologies may ease deployment in newcomer countries such as Viet Nam. However, several major challenges persist.

As described in Chapter 6, the first challenge is risk management. Accidents at Three Mile Island, Chernobyl, and Fukushima have demonstrated that no technology is entirely risk-free. Given the large scale of these reactors, safety enhancements must be complemented by robust frameworks such as the IAEA's concept of defence-in-depth to reduce the potential impact of accidents. The second challenge relates to the high upfront investment and long construction timelines, which introduce cost overrun risks and high overnight capital costs. Table 11.4 lists selected recent global construction experiences. Despite differing labour and financial conditions, countries such as Korea, China, and Russia have managed to achieve shorter construction periods and lower overnight costs through multiple deployments and design standardisation. The third, and most enduring, challenge concerns the treatment of radioactive waste. Both spent fuel and reprocessed waste pose heavy environmental burdens, and without reliable long-term solutions, public acceptance will remain a critical obstacle.

Table 11.4. Selected Recent Construction Experiences of Generation III+ LWR

Reactor Technology	Site Country	Construction Start	Construction Time (Month)	Overnight Cost (US$/kW)
AP1000	USA	2013	120–124	14,700
	China	2009	104–110	3,154
APR1400	Korea	2008~	87–126	2,700
	UAE	2012~	97–104	4,540
EPR	Finland	2005	199	7,200
	France	2007	204	11,000
	China	2009~	103–110	3,222
HPR1000	China	2015~	56–88	2,500
	Pakistan	2015~	67–72	3,080
VVER1200 /AES-2006	Russia	2008~	98–126	3,000–3,500
	Belarus	2013~	84–109	4,200

kW = kilowatt, LWR = light water reactor, UAE = United Arab Emirates, USA = United States of America.
Source: Author.

SMRs are emerging as a promising nuclear technology, offering compact designs, enhanced safety features, and greater deployment flexibility compared with traditional large-scale reactors. Defined by the IAEA as reactors with capacities below 300 Mwe, SMRs – particularly small modular light water reactors (SMLWRs) (Table 11.2) – are leading this innovation wave. Benefitting from the technological maturity of larger designs, SMLWRs offer advantages beyond size. Modular, factory-fabricated components enable shorter construction times, more manageable financing, and deployment in smaller grids or off-grid areas. These features help address several challenges faced by large LWRs. Notably, the smaller fuel inventory allows for a narrower EPZ, thereby reducing potential impacts in an emergency. Whilst further validation through practical deployment is needed, factory fabrication may also reduce overnight costs.

Globally, SMRs are gaining interest as countries seek reliable, low-carbon energy sources to complement renewables. In the digital age, they are well-positioned to power AI systems and data centres. Major technology companies such as Amazon (X-energy, 2024) and Google (Kairos Power, 2024)4 have recently shown high interest and invested in SMR R&D. Nevertheless, considerable challenges remain. The lack of commercial deployment means that high first-of-a-kind costs, immature supply chains, and potential licensing delays pose obstacles to adoption, particularly for newcomer countries. Moreover, being based on LWR technology, SMRs face the same long-term challenge of radioactive waste management as their larger counterparts.

Advanced nuclear reactors go beyond traditional LWR designs, offering improved safety, efficiency, versatility, and sustainability. Leading technologies (Table 11.3) include sodium-cooled fast reactors, HTGRs, and lead-cooled fast reactors. These often employ innovative coolants such as liquid metals and gases, and support diverse applications, from electricity generation and industrial heat to H_2 production. Their inherent safety features are rooted in reactor physics, whilst innovative fuels such as TRISO (in HTGRs) and metallic fuels (in fast reactors) help reduce waste volumes. However, TRISO fuel is designed for direct disposal and cannot, on its own, provide a comprehensive solution to waste management. From a backend perspective, the IFR concept, which incorporates pyro-processing (Chapter 6), represents a more sustainable solution by reducing long-lived fission products and closing the fuel cycle. Despite their potential, most advanced reactor technologies remain at the demonstration stage. Regulatory complexity, funding constraints, and public acceptance continue to pose significant barriers to widespread deployment.

11.2. Potential Options for Different Usages

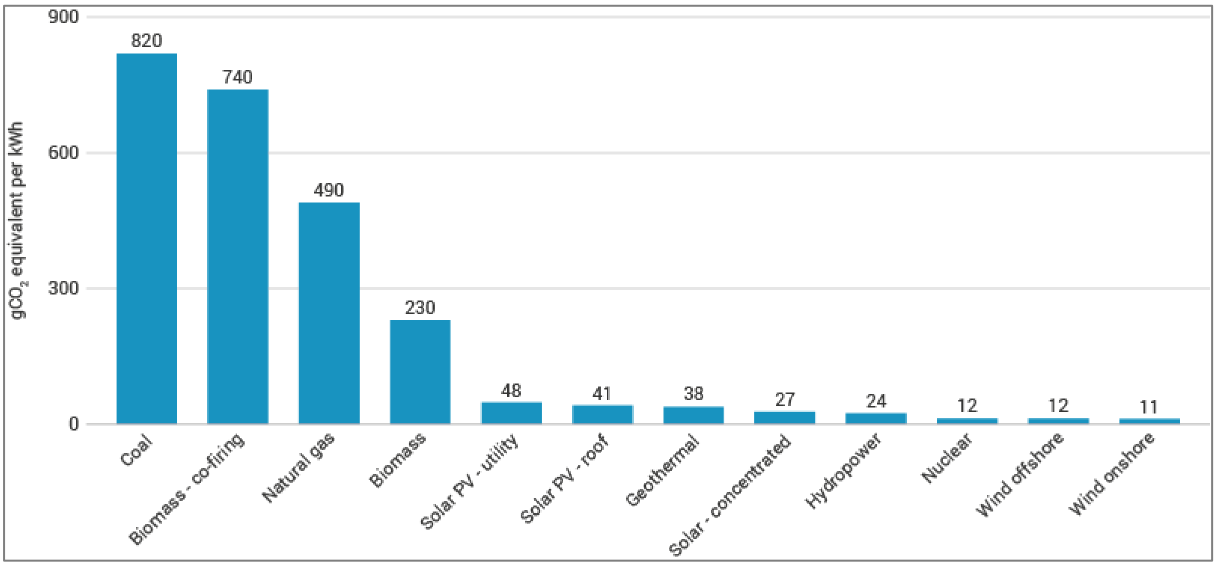
To achieve Viet Nam's ambitious climate goals, nuclear energy can be utilised in various ways, including power generation, industrial heat supply, and H_2 production.

11.2.1. Option for power generation

According to the PDP8 Implementation Plan, Viet Nam's total power generation capacity – 77.8 GW in 2022, including 25.3 GW from coal-fired plants – is projected to expand to a carbon-free energy fleet of approximately 490–590 GW by 2050. During the process, nuclear energy could contribute by adding new capacity or replacing coal-fired capacity.

As noted by the Intergovernmental Panel on Climate Change (IPCC), nuclear power has amongst the lowest life-cycle CO_2 emissions of all current power generation technologies (Figure 11.1) (Steffen Schlömer, 2014). Moreover, it can provide a reliable, year-round, 24/7 electricity supply. Thus, introducing nuclear power is a rational option for building additional capacity, both in terms of decarbonisation and grid stability. At the same time, retiring existing coal-fired power plants is essential for achieving the national climate goal. A coal-to-nuclear transition, amongst other options, offers advantages such as repurposing infrastructure, including steam-cycle components, heat-sink components, and transmission components. Comprehensive research by the US Department of Energy (INL, 2022) suggests that such repurposing could reduce overnight capital costs by 15% to 35%, compared with a greenfield project.

Figure 11.1. Average Life-cycle Carbon Dioxide–equivalent Emissions



gCO_2 = gramme of carbon dioxide, kWh = kilowatt-hour, PV = photovoltaic.
Source: World Nuclear Association (2024).

The operational technologies for power generation include mature commercial reactors and SMLWRs. Large, gigawatt-scale conventional reactors are particularly suitable where bulk, grid-based electricity is required. Although their construction costs have recently increased, they still offer the lowest cost per unit of electricity (MIT CANES, 2024) and remain the most mature option for capacity expansion. These reactors benefit from economies of scale and consistently achieve capacity factors exceeding 90% worldwide.

SMLWRs, meanwhile, hold strong potential for both grid-based and behind-the-meter resilient electricity supply. They offer several advantages over large reactors, particularly where bulk power is not optimal. They are also better suited for replacing smaller coal-fired power plants. Although not yet commercially demonstrated and with potentially higher projected unit costs than large reactors, SMLWRs require lower upfront capital investment and offer faster construction timelines. These advantages make them particularly attractive for meeting rapidly growing electricity demand from emerging digital industries, including AI and data centres.

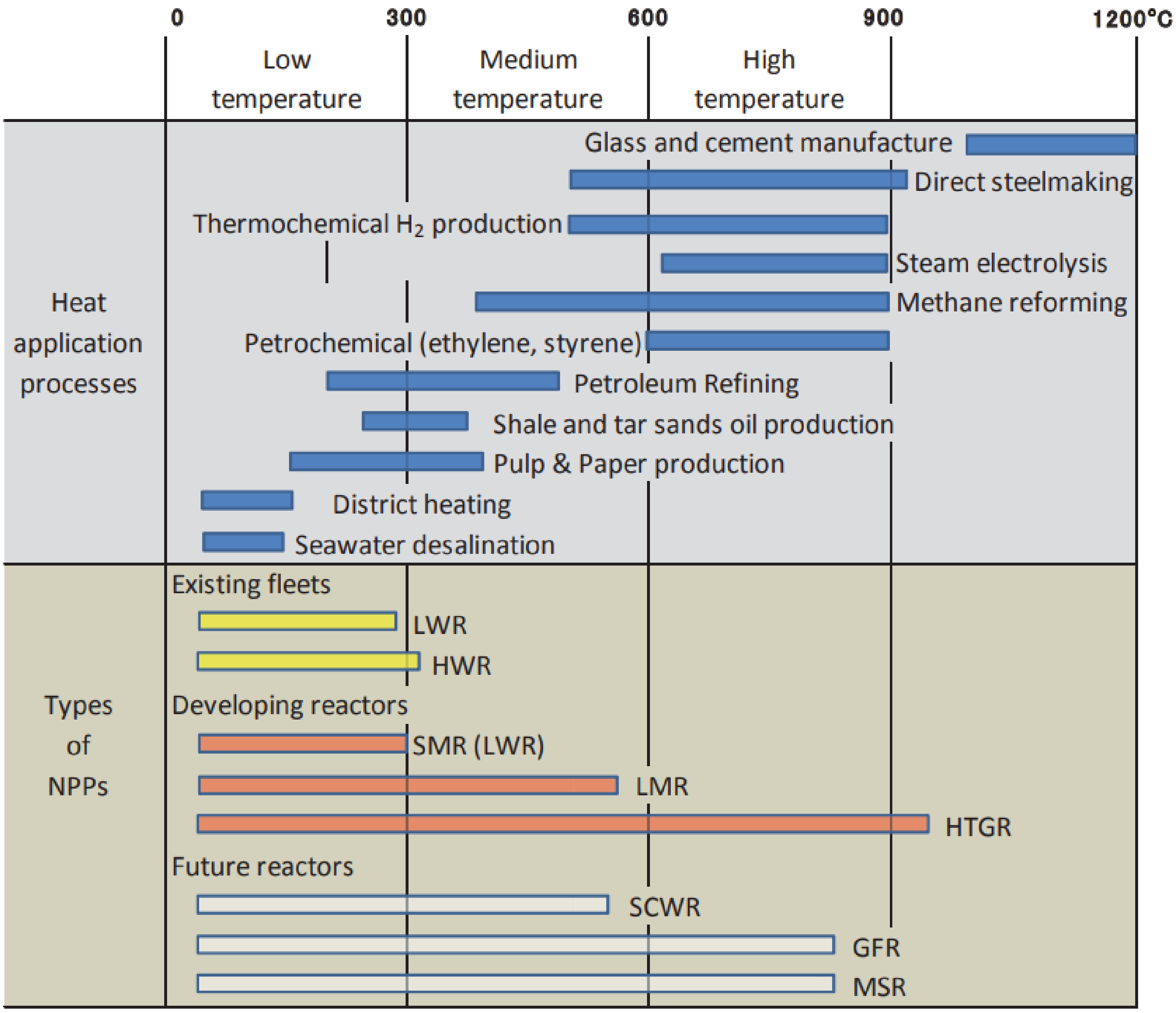
11.2.2. Options for industrial heat supply

Decarbonising the industrial sector, which accounts for more than 30% of Viet Nam's national CO_2 emissions, is essential for realising climate goals. Carbon-free heat sources are important to high-temperature industrial processes such as steel, cement, and chemical manufacturing. Compared with alternative fuels, nuclear reactors can provide direct process heat, thereby improving overall energy efficiency.

The Next Generation Nuclear Plant project (2005–2011) examined various potential industrial applications of HTGRs (INL, 2011). In 2024, China commissioned the first industrial nuclear steam project using a conventional LWR, which supplies steam at 1.8 megapascals and about 250°C to a nearby petrochemical plant (WNN,2024).11F

Given the high temperature requirements of most industrial processes (Figure 11.2), the potential of both large and small modular LWRs is limited. Advanced reactors, especially HTGRs, offer more suitable technological options.

Figure 11.1. Temperature Ranges of Heat Application Processes and Types of Nuclear Reactors



GFR = gas-cooled fast reactor, H_2 = hydrogen, HTGR = high-temperature gas-cooled reactor, HWR = heavy-water reactor, LMR = liquid metal-cooled reactor, LWR = light-water reactor, MSR = molten salt reactor, NPPs = nuclear power plants, SCWR = supercritical water-cooled reactor, SMR = small modular reactor.

Source: International Atomic Energy Agency (2017).

11.2.3. Options for hydrogen production

As discussed in Chapter 4, H_2 is expected to play an important role in decarbonisation as a crucial energy carrier. It can be used flexibly in fuel cells, synthetic fuel production, or even direct combustion. As a secondary energy source – like electricity – its contribution depends on the scale and method of production. Nuclear reactors can facilitate large-scale H_2 production through various processes. The first is traditional water electrolysis under normal conditions, requiring approximately 50–55 MWh of electricity to produce 1 tonne of H_2. In this case, nuclear power functions similarly to other carbon-free electricity. The second process involves high-temperature steam electrolysis, which combines electricity and thermal energy. Producing 1 tonne of H_2 requires about 35 MWh of electricity and 11 MWh of thermal energy13F. Taking thermal efficiency into account, the total energy requirement equates to around 40 MWh of electricity. The most efficient process is the thermochemical iodine-sulphur process, which uses very high temperatures provided by HTGRs. This method can reduce energy consumption to less than 35 MWh of electricity per tonne of H_2 (Jin Iwatsuki, et al., 2014). Consequently, HTGRs are the most efficient technology for H_2 production, although other nuclear technologies can also contribute.

11.3. Recommendations for Strategic Implementation

Although nuclear technologies hold large potential for supporting a decarbonised society – and a variety of candidate technologies are available – Viet Nam must adopt a long-term, periodic strategic implementation plan. This plan should address technical, financial, social, and regulatory challenges, whilst leveraging its existing strengths and international partnerships to enable effective nuclear deployment. By learning from global experiences and leveraging its existing nuclear infrastructure, Viet Nam can integrate nuclear energy responsibly into its energy mix without repeating past setbacks. The following recommendations are likely to be beneficial.

11.3.1. Develop a long-term nuclear energy vision

A long-term vision for nuclear energy is critical to ensure economic viability, technological sustainability, energy security, and public trust. Such a vision transforms nuclear energy from a speculative project into a national legacy. Nuclear energy projects span decades – from planning and construction to operation and decommissioning – and require consistent policy frameworks, financial commitments, and broad societal support. Without a long-term vision, nuclear ambitions risk becoming fragmented, unaffordable, or obsolete.

This vision should align with national strategic goals such as energy security, climate commitments, and economic growth. Periodic targets must be determined to improve business predictability and encourage private investment. A clear technology road map should be designed to cover the nuclear energy lifecycle, from front-end fuel supply to back-end waste management. Especially, a plan must include a robust solution for radioactive waste disposal.

11.3.2. Develop social infrastructure

Viet Nam should follow the IAEA's 19 infrastructure milestones for new nuclear power programmes, which include site selection, environmental assessments, and emergency preparedness (IAEA, 2015).1 Legal and regulatory frameworks must be strengthened by updating the Atomic Energy Law and establishing comprehensive legislation covering safety, security, liability, waste management, and decommissioning, in alignment with IAEA standards. Regulatory bodies, such as the Vietnam Agency for Radiation and Nuclear Safety, must be granted independence and the technical capacity to enforce regulations and oversee future projects effectively.

Building public acceptance and trust is essential. This can be achieved by launching communication campaigns that demystify nuclear energy, address safety concerns, and highlight its benefits. Engagement with local communities, non-governmental organisations, and academic institutions in the decision-making process will foster trust and address social concerns. It is also important to showcase global examples of safe nuclear operations and highlight Viet Nam's experience with the Da Lat research reactor.

Financing for nuclear projects should be secured through a combination of approaches. These include attracting private investors through build–operate–transfer models, similar to those used in coal and LNG projects, and seeking low-interest loans or grants from institutions such as the IAEA, the World Bank, or the Asian Development Bank.

International partnerships with countries that possess advanced nuclear capabilities are important for facilitating technology transfer, training, and joint ventures.

11.3.3. Develop human resources

Human resource development (HRD) is one of the most important components of social infrastructure, as emphasised by the IAEA. Its guidelines identify key personnel, such as operators, engineers, and regulators, required across various organisations within the nuclear energy sector (Figure 11.3).

Figure 11.3. Organisations in the Nuclear Field Requiring Human Resources

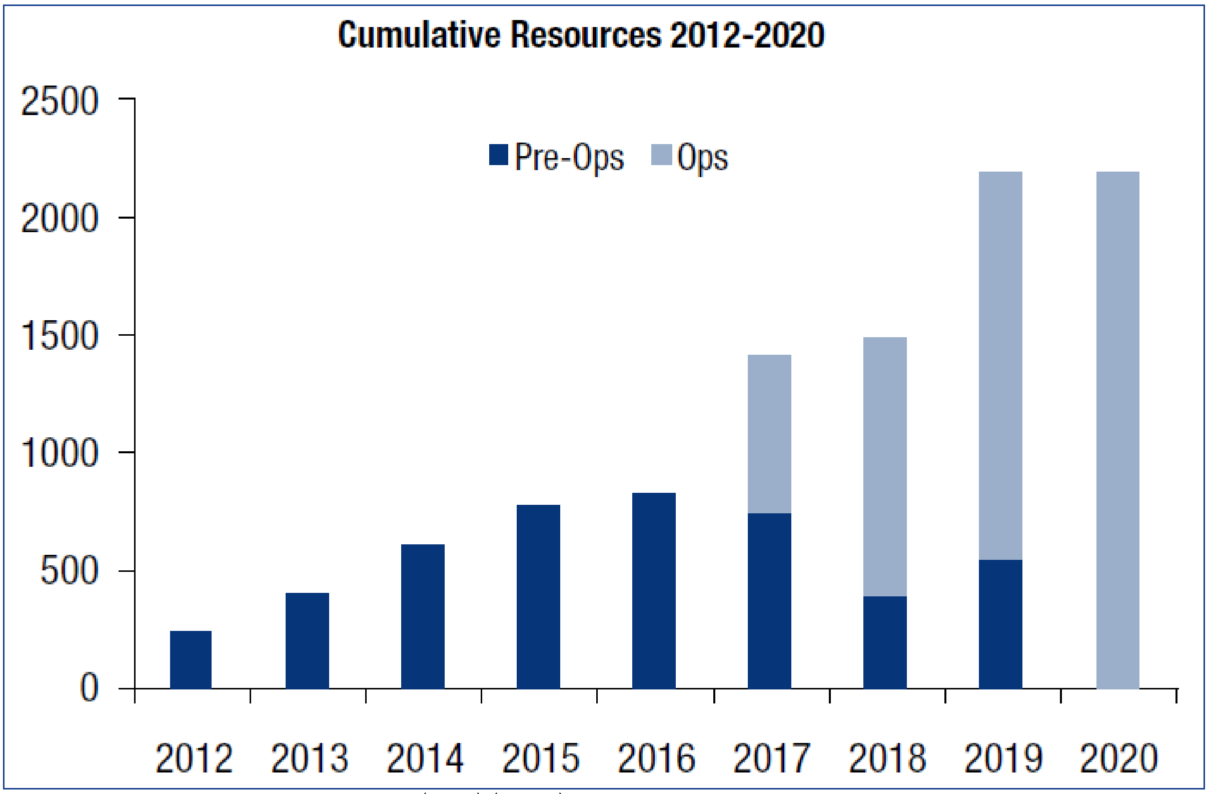
NPPs = nuclear power plants, R&D = research and development.
Source: International Atomic Energy Agency (2009).

The first step in HRD is to define the scope based on the size of the nuclear programme and the contractual arrangements. According to joint assessments by the OECD Nuclear Energy Agency and the IAEA, a typical nuclear power plant with a single LWR requires about 600 personnel annually for administration, O&M, and permanent contracts. An additional 80 personnel are required for nuclear waste management.

The recent experience of the UAE provides a useful reference. With a nuclear power programme similar in scale to Viet Nam's announced plan – four reactors in two sites – the UAE commenced construction of its four-reactor power plant in 2012. The Emirates Nuclear Energy Corporation estimated that 900–1,000 staff would be required immediately before the first reactor became operational (Figure 11.4). Following this, a combined workforce of about 1,400 personnel was needed, with a permanent operational staff of about 2,200 required once all four reactors were online. Based on this precedent, Viet Nam would likely need 2,200–2,400 on-site professionals to realise its nuclear ambitions.

This estimate excludes off-site personnel involved in regulation, R&D, and education. In advanced nuclear countries, the off-site workforce typically accounts for 15%–20% of the total nuclear personnel. This implies that an additional 330–480 highly educated professionals would be required to support the sustainable use of nuclear energy in Viet Nam.

Figure 11.4. Estimated Human Resources for the United Arab Emirates' Nuclear Power Programme



Source: Banks, Massy, and Ebinger (eds.) (2012).

The next step in HRD is to assess the current status. A survey conducted by the Ministry of Science and Technology in 2012 indicated that Viet Nam had approximately 300 personnel in the nuclear power workforce (Nguyen Thi Yen Ninh, 2014), of whom only 100 were specialised in nuclear reactor technology, safety, and installations. Under the National Human Resources Development Scheme to Support the Nuclear Power Program, a cumulative total of around 400 individuals were sent to Russia, nearly 100 to Japan, and another 100 to various other countries for education and training. However, following the suspension of the nuclear power programme in 2016, most trained personnel switched to other fields. A small number were hired by Rosatom to work on a project in Bangladesh, whilst others returned to work at the Vietnam Atomic Energy Institute (VAEI). Over the past 10 years, the VAEI has also sent nearly 100 individuals to study abroad. As a result, Viet Nam has an accumulated human resource base of approximately 1,000 individuals, many of whom have since retired (VAEI, 2024). The younger, trained cohort working in other fields will require retraining.

Comparing this with the estimated requirement of 2,530–2,880 personnel, only a few hundreds are currently available, mostly off-site professionals with high educational qualifications. This is encouraging, as this category of workforce typically requires long lead times to develop. The immediate priority, however, is to train the on-site workforce. Fortunately, 65%–80% of the required on-site personnel do not need graduate-level education. These roles can be supported through training by reactor vendors, either at foreign facilities or research institutes. Nevertheless, establishing a domestic training centre equipped with simulators and other necessary tools is essential for the ongoing development of HRD, particularly in the context of a larger future nuclear programme. The Da Lat Nuclear Research Institute could be expanded to serve this purpose.

The remaining 20%–35% of the workforce will require graduate-level education in science, technology, engineering, and mathematics, with about 5% needing a background in nuclear engineering. This segment represents the most challenging aspect of HRD and should be supported through both domestic initiatives and international collaboration. Strengthening nuclear engineering education in key institutions, such as Hanoi University of Science and Technology and Vietnam National University, should be prioritised. In parallel, partnership with leading institutions, including the IAEA, Massachusetts Institute of Technology in the US, University of Tokyo in Japan, and Korea Advanced Institute of Science & Technology in Korea, will be essential for curriculum development and faculty training. In addition to government-led initiatives, collaboration between academia and industry can enhance the relevance and quality of training programmes by aligning them with real-world industry needs.

11.3.4. Select foreign reactor technologies based on comprehensive examination

Viet Nam's choice of reactor technology must strike a balance between immediate energy needs and long-term technological sovereignty. A comprehensive evaluation of several key factors is required to ensure the safety, cost-effectiveness, and sustainability.

Technology maturity and deployment readiness are essential for enabling a quick project start and reducing the risks of construction delays and operational failures. Reactor designs with multiple operational units worldwide, such as the AP1000, APR1400, EPR, HPR1000, and VVER-1200, are preferable for initial projects to secure early success and build public and institutional confidence (Table 11.1).

Nuclear projects involve high upfront capital investments, often accounting for more than 70% of total expenditure across a 30-year payback period. These capital costs largely determine the LCOE, which directly influences affordability. Therefore, a detailed evaluation of overnight construction costs is necessary. Based on previous experience (Table 11.4) and existing studies (MIT CANES, 2024), large reactors tend to offer better economic performance per kilowatt and lower LCOE (Chapter 5). However, their substantial capital requirements introduce heightened risk of cost overruns in the event of construction delays. Accordingly, they require financing support, such as export credit guarantees, concessional loans, or public–private partnerships, to mitigate these risks.

The Russian VVER1200, for instance, has demonstrated bundled financing models based on state-backed investments in Türkiye and Bangladesh, making it a strong candidate amongst large LWRs. Similarly, the Korean APR1400 may be considered, given its successful deployment in the UAE through a fixed-price contract and partial vendor financing. Conversely, SMRs require significantly lower upfront investment, despite having theoretically higher overnight construction costs. Their modular, factory-fabricated components offer economic advantages by minimising construction delays and reducing cost overruns. Given past collaborations with GE Hitachi and potential future cooperation in North America, the BWRX300 from GE Hitachi and the VOYGR from NuScale are viable options amongst the more mature SMLWR designs summarised in Table 11.2.

As uranium is a strategic material tied to national security, ensuring a stable and long-term supply must be a key consideration. Additionally, until Viet Nam establishes its own fuel cycle capabilities, vendor arrangements regarding spent fuel management and waste disposal will have significant implications for long-term liabilities. In this context, Russian technology stands out, as Rosatom offers comprehensive packages, including long-term fuel supply and take-back programmes for spent fuel.

Technology transfer and localisation potential are also determining factors for the sustainability and resilience of Viet Nam's nuclear programme. Building domestic expertise not only ensures long-term reliability but also reduces costs and boosts the local industrial base. The APR1400's deployment in the UAE, with strong local workforce training, and the AP1000 construction in China, featuring high levels of domestic component manufacturing, serve as valuable examples.

Whilst immediate projects must prioritise proven technologies, Viet Nam should also consider future candidates. SMLWRs such as the BWRX300 and VOYGR are better suited to local grid conditions and offer superior load-following capabilities, which are crucial for integrating large-scale renewable energy. Moreover, they are ideal for replacing coal-fired power plants due to their scalability and siting flexibility. As previously mentioned, SMRs, including both SMLWRs and advanced technologies, can reliably power data centres, another cornerstone of the digital economy. Co-locating SMRs with data centres or on sites of retired coal plants could simplify emergency preparedness and create synergies between two forms of strategic infrastructure. Advanced reactor designs, especially HTGRs, offer promising applications in industrial heat supply and H_2 production. To ensure the long-term sustainability of nuclear power, the ultimate objective should be the development of IFRs, which close the fuel cycle and minimise long-lived radioactive waste.

11.3.5. Adopt a periodic domestic implementation plan

First, building on Viet Nam's historical cooperation with Russia, Japan, and Korea, and referencing successful international experiences in Bangladesh and UAE, and emerging opportunities in North America, select a mature commercial reactor technology, such as the VVER1200 or APR1400, or an SMLWR, such as the BWRX-300 or VOYGR to start construction at the designated Ninh Thuan site.

Second, analyse the site conditions of existing coal-fired plants to evaluate the feasibility of coal-to-nuclear transition. Carry it out in parallel with the exploration of advanced and flexible technologies, especially SMRs, for future deployment.

Third, evaluate the national demand for H_2 in alignment with long-term energy and climate goals. Pay close attention to the development of HTGRs, with particular interest in the JAEA's high-temperature engineering test reactor, the only reactor design that has achieved 950°C outlet temperature, suitable for efficient H_2 production.

Fourth, beyond the importation of reactor technologies, expand Viet Nam's peaceful nuclear applications beyond electricity generation to strengthen technical capacity, promote innovation, and build public acceptance. Efforts should include enhanced R&D and innovation through domestic institutional reinforcement and sustained international collaborations.

Finally, advance IFR development through both national efforts and participation in international collaboration, such as trilateral research programmes between the US, Japan, and Korea, to ensure the long-term sustainability of nuclear energy.

11.3.6. Collaborate with other ASEAN countries for collective nuclear security

A major challenge in importing foreign nuclear technologies lies in managing the trade-off between cost and diversity. Historical precedents in France, Russia, Korea, and China show that standardising around a single reactor design yields cost efficiencies and project streamlining. Even the US shifted from promoting multiple industrial competitors to a strategy of 'select one and build more'. However, international nuclear cooperation often results in long-term diplomatic and economic dependencies that can extend for nearly a century, from construction to decommissioning, introducing geopolitical risks.

One viable response to this challenge is enhanced regional collaboration. Several ASEAN countries are actively exploring or preparing for the deployment of nuclear energy. Indonesia, through BATAN and the RDE research reactor, has a long-standing nuclear research programme. In partnership with Rosatom (Russia), NuScale (US), and ThorCon (US–Indonesia), it aims to deploy its first commercial SMR by 2039 and achieve 4.8 GW of nuclear capacity by 2045. The Philippines is exploring the possibility of reviving the Bataan Nuclear Power Plant, built in the 1980s but never operated, and is conducting feasibility studies with NuScale, KEPCO (Korea), and Rosatom. Thailand targets 5% nuclear power in its generation mix by 2035, supported by bilateral agreements with China and Russia. Malaysia operates the TRIGA PUSPATI research reactor for technological development and is monitoring SMR advancements. Myanmar has expressed interest in nuclear energy and has partnered with Russia for technology research. Cambodia is exploring a research reactor development and workforce training through an agreement with Rosatom. Singapore is investigating microreactors and advanced technologies to bolster long-term energy security.

The ASEAN Power Grid, an initiative of ASEAN Vision 2020, provides an opportunity to link these diverse nuclear programmes, potentially coordinated through different technology vendors, into a framework of collective nuclear security. Viet Nam could play a key role in this alliance by strengthening the ASEAN Network of Regulatory Bodies on Atomic Energy, and by sharing its project development experiences through established platforms such as the Forum for Nuclear Cooperation in Asia. Strengthening ties between Viet Nam's national research institutions and regional educational programmes would facilitate collective human resource development. Should Viet Nam successfully commission its first commercial nuclear reactor by the early 2030s, it would set a precedent for the region and provide a skilled workforce and technical expertise to support neighbouring countries in their own nuclear journeys.

References

Part 1: Carbon Neutral Scenario Analysis

Asian Development Bank (2015), Renewable Energy Developments and Potential in the Greater Mekong Subregion. https://www.adb.org/sites/default/files/publication/161898/renewable-energy-developments-gms.pdf (accessed 7 March 2025).

Asian Development Bank (2017), Pathways to Low-Carbon Development for Viet Nam. https://www.adb.org/sites/default/files/publication/389826/pathways-low-carbon-devt-viet-nam.pdf (accessed 7 March 2025).

Cole, W. and A. W. Frazier (2020), *Cost Projections for Utility-scale Battery Storage: 2020 Update*. Golden, CO: National Renewable Energy Laboratory.

Data Center Map (2025), https://www.datacentermap.com/datacenters/ (accessed 7 March 2025).

Economic Research Institute for ASEAN and East Asia (forthcoming), *Energy Outlook and Energy Saving Potential in East Asia 2025*. Jakarta: ERIA.

Institute of Energy, Energy Analyses and the Danish Energy Agency (2023), Viet Nam Technology Catalogue for Power Generation. https://ens.dk/en/global-coorporation/energy-partnerships/vietnam (accessed 7 March 2025).

Fasihi, M., O. Efimova, and C. Breyer (2019), 'Techno-economic assessment of CO_2 direct air capture plants', *Journal of cleaner production*, *224*, 957–980.

Global Cement and Concrete Association (2019), GCCA Getting the Numbers Right Project Report. https://gccassociation.org/sustainability-innovation/gnr-gcca-in-numbers/ (accessed 28 June 2024).

Government of Viet Nam (2022), https://datafiles.chinhphu.vn/cpp/files/vbpq/2022/07/896-ttg.signed.pdf. (accessed 7 March 2025).

Government of Viet Nam (2023), Decision No. 500/QD-TTg of the Prime Minister: Approval of the National Power Development Plan for the 2021-2030 period, with a vision to 2050. https://xaydungchinhsach.chinhphu.vn/toan-van-quy-hoach-phat-trien-dien-luc-quoc-gia-119230516163152 44.htm (accessed 7 March 2025).

International Energy Agency (2021), *Carbon capture, utilisation and storage: the opportunity in Southeast Asia*. Paris: IEA.

International Energy Agency (2023a), *Energy Technology Perspectives*. Paris: IEA.

International Energy Agency (2023b), *World Energy Outlook 2023*. Paris: IEA.

International Energy Agency (2024), Achieving a Net Zero Electricity Sector in Viet Nam. https://www.iea.org/reports/achieving-a-net-zero-electricity-sector-in-viet-nam (accessed 7 March 2025).

Japan Ship Technology Research Association (2024), Survey of Offshore Wind Power Trends in Vietnam, the Philippines, and Australia. https://www.jstra.jp/PDF/report9_2023.pdf (accessed 7 March 2025).

Japan Science and Technology Agency (2022), Impact of Progress of Information Society on Energy Consumption (Vol. 4): Feasibility Study of Technologies for Decreasing Energy Consumption of Data Centers, LCS-FY2021-SR-01. https://www.jst.go.jp/lcs/en/proposals/fy2021-pp-01.html (accessed 7 March 2025).

Le, Doan Phac (2011), Vietnam's Nuclear Power Development Plan Challenges and Preparation Work for the First Nuclear Power Projects. https://nucleus.iaea.org/sites/INPRO/df3/Session%202/20.LeDoanPhac-Vietnam.pdf (accessed 7 March 2025).

Ministerial Council on Renewable Energy, Hydrogen and Related Issues (2023), Basic Hydrogen Strategy. https://www.meti.go.jp/shingikai/enecho/shoene_shinene/suiso_seisaku/pdf/20230606_5.pdf (accessed 28 June 2024).

Ministry of Natural Resources and Environment (2020), Report on National GHG Inventory for 2016.

National Power Transmission Corporation (2025), https://www.npt.com.vn/en-US (accessed 7 March 2025).

Otsuki, T., H. Obane, Y. Kawakami, K. Shimogori, Y. Mizuno, S. Morimoto, and Y. Matsuo (2022), 'Energy Mix for Net Zero CO_2 Emissions by 2050 in Japan, An Analysis Considering Siting Constraints on Variable Renewable Energy', *Electrical Engineering Japan*, 215(4).

Otsuki, T., R. Komiyama, and Y. Fujii (2019), 'Techno-economic Assessment of Hydrogen Energy in the Electricity and Transport Sectors Using a Spatially disaggregated Global Energy System Model', *Journal of the Japan Institute of Energy*, 98(4), pp.62–72.

Pfenninger, Stefan and I. Staffell, Renewables.ninja. https://www.renewables.ninja/ (accessed 7 March 2025).

United Nations (2024), World Population Prospects 2024. New York: UN.

Vietnam Briefing (2018), Opportunities in the Waste-to-Energy Sector in Vietnam. https://www.vietnam-briefing.com/news/opportunities-waste-energy-sector-vietnam.html/ (accessed 7 March 2025).

Vietnam Electricity (2019), Overview of hydropower in Vietnam. https://en.evn.com.vn/d6/news/Overview-of-hydropower-in-Vietnam-66-163-1514.aspx (accessed 7 March 2025).

Vietnam Electricity (2020), https://en.evn.com.vn/d6/news/Development-of-500-kV-transmission-network-in-the-future-a-questionable-issue-66-163-2065.aspx. (accessed 7 March 2025).

World Bank (2025),https://carbonpricingdashboard.worldbank.org/. (accessed 7 March 2025).

World Steel Association (2019), *Steel Statistical Yearbook 2019*, Concise Version. Brussels.

Part 2: Potential Utilisation of Nuclear Power in Viet Nam

Banks, John, K. Massy, and C. Ebinger (ed.) (2012), *Human Resource Development in New Nuclear Energy States: Case Studies from the Middle East.* Washington, D.C.: The Brookings Institution

Center for Advanced Nuclear Energy Studies (2024), *Total Cost Projection of Next AP1000.* Massachusetts: MIT CANES.

Chang, Yoon Il (2011), *Plentiful Energy*. CreateSpace

Da Lat Nuclear Research Institute (2024), *Celebrating the 40th Anniversary of Operation and Utilization of the Da Lat Nuclear Reactor – A Historical Journey.* Da Lat: Da Lat Nuclear Research Institute

GE Hitachi Nuclear Energy (2015), *GE Hitachi Continues to Support the Building of Vietnam's Nuclear Power Infrastructure.* Hanoi: GE Hitachi Nuclear Energy.

Government of Vietnam (2024), Decision 262/QD-TTg.

International Atomic Energy Agency (2009), *Managing Human Resources in the Field of Nuclear Energy.* Vienna: IAEA.

International Atomic Energy Agency (2015), *Milestones in the Development of a National Infrastructure for Nuclear Power, Nuclear Energy Series No. NG-G-3.1 (Rev. 1).* Vienna: IAEA.

International Atomic Energy Agency (2017), *Opportunities for Cogeneration with Nuclear Energy.* Vienna: IAEA

Idaho National Laboratory (2011), *Integration of High Temperature Gas-Cooled Reactors into Selected Industrial Process Applications.* Idaho: INL

Idaho National Laboratory (2022), *Investigating Benefits and Challenges of Converting Retiring Coal Plants into Nuclear Plants.* Idaho: INL

International Energy Agency (2014), *World Energy Outlook 2014.* Paris: IEA.

International Energy Agency (2019), *Nuclear Power in a Clean Energy System.* Paris: IEA.

International Energy Agency (2019), *World Energy Outlook 2019.* Paris: IEA.

International Energy Agency (2022), *World Energy Outlook 2022.* Paris: IEA.

International Energy Agency (2023), *Global Gas Security Review 2023.* Paris: IEA.

International Energy Agency (2024), *World Energy Outlook 2024.* Paris: IEA.

International Energy Agency (2025), *The Path to a New Era for Nuclear Energy*. Paris: IEA.

Iwatsuki, J., S. Kasahara, S. Kubo, Y. Inagaki, K. Kunitomi, M. Ogawa, M., and Japan Atomic Energy Agency, Tokai, Ibaraki (Japan) (2014), Economic evaluation of HTGR IS process hydrogen production system. Ibaraki: JAEA

Kairos Power (2024), 'Google and Kairos Power Partner to Deploy 500MW of Clean Electricity Generation'. California: Kairos Power

McMillan, Colin, R. Boardman, M. McKellar, P. Sabharwall, M. Ruth, and S. Bragg-Sitton (2016), *Generation and Use of Thermal Energy in the US Industrial Sector and Opportunities to Reduce its Carbon Emissions*. Colorado: The Joint Institute for Strategic Energy Analysis

Schlömer, S. (ed.) (2014), 'Technology-specific Cost and Performance Parameters, Annex III of Climate Change 2014: Mitigation of Climate Change', *Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.

Thi Yen Ninh, Nguyen (2014), *Human Resources Development for Nuclear Power Program in Vietnam.* Fukui: Fukui International Meeting on Human Resources Development for Nuclear Energy in Asia

Vietnam Atomic Energy Institute (2024), *Nuclear Energy Projects Need to Focus on Human Resource Training*. Hanoi: VAEI

World Nuclear News (2024), *Chinese industrial nuclear steam project commissioned.* London: WNN

World Nuclear Association (2024), *Carbon Dioxide Emissions from Electricity.* London: WNA

X-Energy (2024), *Amazon Invests in X-energy to Support Advanced Small Modular Nuclear*

Reactors and Expand Carbon-Free Power. Rockville: X-Energy,

Appendix

Summary Tables of Results from the Carbon-neutral Scenario Analysis Sector Energy-related CO_2 Emissions

Table A.1. Sector Energy-related Carbon Dioxide Emissions (Baseline scenario, $MtCO_2$)

	2019	2030	2040	2050
Electricity	154	351	567	770
Industry	74	156	239	313
Transport	44	81	96	92
Other end use	15	34	43	46
Other transformation including DACCS	0	13	27	36
Energy-related CO_2 emissions	287	634	972	1257

CO_2 = carbon dioxide, DACCS = direct air carbon capture and storage, $MtCO_2$ = metric tonnes of carbon dioxide.
Source: Author.

Table A.2. Sector Energy-related Carbon Dioxide Emissions (Carbon-neutral Scenario, $MtCO_2$)

	2019	2030	2040	2050
Electricity	154	189	64	-27
Industry	74	93	92	33
Transport	44	81	87	76
Other end use	15	24	30	30
Other transformation including DACCS	0	13	25	-24
Energy-related CO_2 emissions	287	401	297	89

CO_2 = carbon dioxide, DACCS = direct air carbon capture and storage, $MtCO_2$ = metric tonnes of carbon dioxide.
Source: Author.

Table A.3. Sector Energy-related Carbon Dioxide Emissions (CN_HighGDP Scenario, $MtCO_2$)

	2019	2030	2040	2050
Electricity	154	180	48	-23
Industry	74	87	50	27
Transport	44	89	114	102
Other end use	15	27	44	47
Other transformation including DACCS	0	18	41	-64
Energy-related CO_2 emissions	287	401	297	89

CN = carbon neutral, CN_HighGDP = carbon-neutral with high economic growth, = CO_2 = carbon dioxide, DACCS = direct air carbon capture and storage, $MtCO_2$ = metric tonnes of carbon dioxide.
Source: Author.

Final Energy Consumption by Source

Table A.4. Final Energy Consumption (Baseline Scenario, Mtoe)

	2019	2030	2040	2050
Coal	17	45	68	88
Oil	21	29	34	31
Oil (non-energy)	1	0	0	0
Natural gas	1	2	2	2
Natural gas (non-energy)	1	27	37	44
Electricity	18	36	57	81
Hydrogen and ammonia	0	0	0	0
Biomass	7	4	4	4
Total	66	143	202	250

$MtCO_2$ = metric tonnes of carbon dioxide, Mtoe = million tonnes of oil equivalent.
Source: Author.

Table A.5. Final Energy Consumption (Carbon-neutral Scenario, Mtoe)

	2019	2030	2040	2050
Coal	17	11	14	15
Oil	21	29	31	26
Oil (non-energy)	1	0	0	0
Natural gas	1	30	34	11
Natural gas (non-energy)	1	27	37	44
Electricity	18	36	62	87
Hydrogen and ammonia	0	0	0	35
Biomass	7	8	8	8
Total	66	141	186	226

$MtCO_2$ = metric tonnes of carbon dioxide, Mtoe = million tonnes of oil equivalent.
Source: Author.

Table A.6. Final Energy Consumption (CN_HighGDP Scenario, Mtoe)

	2019	2030	2040	2050
Coal	17	6	15	19
Oil	21	32	42	36
Oil (non-energy)	1	0	0	0
Natural gas	1	37	28	21
Natural gas (non-energy)	1	29	47	58
Electricity	18	39	87	130
Hydrogen and ammonia	0	0	24	51
Biomass	7	8	8	8
Total	66	152	252	323

CN = carbon neutral, CN_HighGDP = carbon-neutral with high economic growth, $MtCO_2$ = metric tonnes of carbon dioxide, Mtoe = million tonnes of oil equivalent.
Source: Author.

Power Generation by Technology

Table A.7. Power Generation by Technology (Baseline Scenario, TWh)

	2019	2030	2040	2050
Nuclear	0	0	0	0
Coal	119	369	629	861
Coal CCUS	0	0	0	0
Coal-ammonia	0	0	0	0
Coal-biomass	0	0	0	0
Nat. gas	43	21	28	65
Nat. gas CCUS	0	0	0	0
Nat. gas-hydrogen	0	0	0	0
Nat. gas-ammonia	0	0	0	0
Oil	2	0	0	0
Hydro	66	67	64	58
Geothermal	0	0	0	0
Solar PV	5	7	16	50
Onshore wind	1	1	1	0
Offshore wind	0	0	0	0
Biomass	2	0	0	0
Ammonia	0	0	0	0
Net imports	1	1	1	9
Total	238	465	738	1042

CCUS = carbon capture, utilisation, and storage; PV = photovoltaic; TWh = terawatt-hour.
Source: Author.

Table A.8. Power Generation by Technology (Carbon-neutral Scenario, TWh)

	2019	2030	2040	2050
Nuclear	0	0	0	0
Coal	119	114	0	0
Coal CCUS	0	0	100	92
Coal-ammonia	0	0	0	16
Coal-biomass	0	15	19	0
Nat. gas	43	155	173	2
Nat. gas CCUS	0	0	5	4
Nat. gas-hydrogen	0	0	0	1
Nat. gas-ammonia	0	0	0	149
Oil	2	0	0	0
Hydro	66	65	127	129
Geothermal	0	0	10	10
Solar PV	5	81	227	340
Onshore wind	1	1	1	0
Offshore wind	0	32	157	420
Biomass	2	0	10	34
Ammonia	0	0	0	114
Net imports	1	3	21	4
Total	238	465	848	1314

CCUS = carbon capture, utilisation, and storage; PV = photovoltaic; TWh = terawatt-hour.
Source: Author.

Table A.9. Power Generation by Technology (CN_HighGDP Scenario, TWh)

	2019	2030	2040	2050
Nuclear	0	8	33	81
Coal	119	108	0	0
Coal CCUS	0	0	57	61
Coal-ammonia	0	0	48	48
Coal-biomass	0	21	14	0
Nat. gas	43	146	147	4
Nat. gas CCUS	0	0	174	179
Nat. gas-hydrogen	0	0	0	4
Nat. gas-ammonia	0	0	0	92
Oil	2	0	0	0
Hydro	66	64	128	129
Geothermal	0	0	10	10
Solar PV	5	99	297	340
Onshore wind	1	1	1	0
Offshore wind	0	58	269	838
Biomass	2	0	16	34
Ammonia	0	0	0	182
Net imports	1	3	10	-4
Total	238	509	1203	1997

CCUS = carbon capture, utilisation, and storage; CN_HighGDP = carbon-neutral with high economic growth; PV = photovoltaic; TWh = terawatt-hour.
Source: Author.

Primary Energy Supply by Source

Table A.10. Primary Energy Supply (Baseline Scenario, Mtoe)

	2019	2030	2040	2050
Nuclear	0	0	0	0
Coal	47	135	215	286
Natural gas	9	32	44	56
Oil	25	29	34	32
Hydro	6	6	6	5
Geothermal	0	0	0	0
Solar	0	1	1	4
Wind	0	0	0	0
Biomass	9	5	5	6
Hydrogen and Ammonia	0	0	0	0
Total	96	208	305	389

Mtoe =million tonnes of oil equivalent.
Source: Author.

Table A.11. Primary Energy Supply (Carbon-neutral Scenario, Mtoe)

	2019	2030	2040	2050
Nuclear	0	0	0	0
Coal	47	47	49	46
Natural gas	9	82	100	56
Oil	25	29	31	26
Hydro	6	6	11	11
Geothermal	0	0	8	8
Solar	0	7	19	29
Wind	0	3	14	36
Biomass	9	14	18	19
Hydrogen and Ammonia	0	0	0	78
Total	96	187	250	311

Mtoe = million tonnes of oil equivalent.
Source: Author.

Table A.12. Primary Energy Supply (CN_HighGDP Scenario, Mtoe)

	2019	2030	2040	2050
Nuclear	0	2	9	22
Coal	47	41	41	45
Natural gas	9	90	127	108
Oil	25	32	42	37
Hydro	6	6	11	11
Geothermal	0	0	8	8
Solar	0	9	26	29
Wind	0	5	23	72
Biomass	9	16	25	20
Hydrogen and Ammonia	0	0	41	104
Total	96	200	353	457

CN_HighGDP = carbon-neutral with high economic growth, Mtoe = million tonnes of oil equivalent.
Source: Author.