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Decarbonisation of ASEAN Energy Systems: Optimum Technology Selection Model Analysis up to 2060

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Preface

According to the East Asia Summit energy outlook being updated by the Economic Research Institute for ASEAN and East Asia (ERIA), the Association of Southeast Asian Nations (ASEAN) will continue to depend on fossil fuels, coal, and gas for power generation and oil for transport. Their ratio to total primary energy supply in 2050 is 87% in a business-as-usual scenario and 82% in an alternative policy scenario, resulting from aggressive energy efficiency and conservation promotion and renewable energy deployment policies. Many countries, including in ASEAN, that participated in the 2021 United Nations Climate Change Conference (COP26) in Glasgow, United Kingdom, 31 October–13 November 2021, announced their carbon-neutral scenarios until 2050 or 2060. ASEAN countries, however, might not easily achieve carbon neutrality because (i) they will continuously increase energy consumption to catch up economically with Organisation for Economic Co-operation and Development countries, and (ii) variable renewable energy such as solar and/or wind is not suitable because the ASEAN region has only two seasons – dry and rainy – and few areas where wind speed is stable. Variable renewable energy will not, ultimately, achieve carbon neutrality in the region.

ERIA, in collaboration with the Institute for Energy Economics, Japan, must, therefore, seek carbon-neutral pathways for ASEAN countries by applying an optimisation approach, which is a linear programming model, to choose low- or zero-emission technologies under a carbon dioxide (CO_2) emission constraint and cost minimum objective function. Innovative energy technologies, including hydrogen, ammonia, carbon capture utilisation and storage, and direct air capture and biomass energy with CO_2 capture and storage, will be added to conventional low-emission energy technologies, which include energy efficiency and conservation, hydropower, geothermal, nuclear power, and biomass, in the transition period. ASEAN countries vary in economic development, energy resource potential, land and population size, and such diversity must be respected. Each ASEAN country will pursue its own carbon-neutral pathway.

The model represents a long-term energy transition from 2020 to 2050 or 2060 and analyses the relationship between energy consumption and CO_2 emissions (energy technology cost or marginal abatement cost). The cost of energy technology will be extremely high for ASEAN countries, which will need to resort to international financing mechanisms such as Asia

Energy Transition Finance promoted by the Ministry of Economic, Trade and Industry, Japan.

I hope this report will help ASEAN countries forge their own carbon-neutral pathways.

Professor Hidetoshi Nishimura
President
Economic Research Institute for ASEAN and East Asia

Acknowledgement

The publication was developed by a working team comprising two energy institutes: (i) the Economic Research Institute for ASEAN's East Asia Energy Unit, whose researchers are familiar with the energy situation of Association of Southeast Asian Nations (ASEAN) countries; and (ii) the Institute for Energy Economics, Japan, whose researchers have expertise on optimisation approaches and energy technologies. A working group consisting of energy policymakers of all ASEAN countries was formed to comment on the carbon-neutral scenarios produced by the working team, using the optimisation model.

We thank the working group members for their great contributions to the ASEAN carbon-neutral scenarios towards 2050 or 2060 produced by the working team. We appreciate the strong support from Takeshi Soda, director of the Oil and Gas Division, Agency of Natural Resources and Energy, Ministry of Economic, Trade and Industry, Japan.

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List of Abbreviations and Acronyms

ASEAN	Association of Southeast Asian Nations
BECCS	bioenergy with carbon capture and storage
CO_2	carbon dioxide
CCS	CO_2 capture and storage
DAC	direct air capture
DACCS	direct air capture with carbon storage
ERIA	Economic Research Institute for ASEAN and East Asia
GDP	gross domestic product
GHG	greenhouse gas
GIS	geographic information system
H_2	hydrogen
IEA	International Energy Agency
IEEJ	Institute of Energy Economics, Japan
IEEJ-NE	IEEJ-New Earth
LULUCF	land use, land-use change, and forestry
MAC	marginal CO_2 abatement cost
$MtCO_2$	million tonnes of carbon dioxide
Mtoe	million tonnes of oil equivalent
NH_3	ammonia
Nm^3	normal cubic meter
PV	photovoltaic
VRE	variable renewable energy

Glossary

Baseline	A case with no CO_2 emission target
CCSInov	A case of technological innovation, which considers cost reduction of direct air capture and larger CO_2 storage capacity (Table 3.2)
CN2050/2060	A case of net-zero CO_2 emissions in 2050 or 2060, which considers carbon sinks
CN2050/2060_Innovation	Five cases describing the impacts of technological innovation (Table 3.2)
CN2050/2060_Stringent2030	A case where emission constraints are tightened in 2030 in CN2050/2060
CN2050/2060_w/oCarbonSink	A case of net-zero CO_2 emissions by 2050 or 2060, which does not consider carbon sinks
Combo	A case of technological innovation, which considers all assumptions mentioned in Table 3.2
DemInov	A case of technological innovation, which considers cost reduction of advanced end-use technologies (Table 3.2)
H_2Inov	A case of technological innovation, which considers cost reduction of technologies related to supply and demand of H_2 (Table 3.2)
PowerInov	A case of technological innovation, which considers cost reduction of lithium-ion battery and expansion of international power grid (Table 3.2)

Chapter 1
Background

The goal of the Paris Agreement (United Nations [UN], 205) is 'holding the increase in the global average temperature to well below 2°C above pre-industrial levels, and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels'. It aims to reach the global peak of greenhouse gas (GHG) emissions as soon as possible and 'achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century' (UN, 2015). Many countries have announced highly ambitious medium- to long-term GHG emission reduction targets. The Intergovernmental Panel on Climate Change (2021) warned that unless CO_2 and other GHG emissions are drastically reduced in the coming decades, global warming will exceed 1.5°C and 2°C during the 21st century. The decarbonisation movement is expected to spread across not only developed countries but also many other countries, including in Association of Southeast Asian Nations (ASEAN), which have presented or are expected to present ambitious GHG emission reduction targets, including carbon-neutral declarations.

Such large-scale GHG emission reductions require the fundamental transformation of energy systems: the almost complete decarbonisation of the power sector, followed by electrification or decarbonisation of energy consumption other than electricity, and offsetting of remaining CO_2 emissions using negative-emission technologies. However, the availability of power systems or low-carbon energy and the possibility of using alternative energy vary significantly across countries and regions, and energy transition cannot be accomplished uniformly. Asian countries are still highly dependent on fossil fuels and, unlike Europe, not blessed with abundant wind resources. Accelerating decarbonisation whilst maintaining economic growth is not straightforward.

The study

(i) aims to quantitatively describe the energy transition pathway necessary to realise carbon neutrality in ASEAN countries through model analysis;

(ii) provides information to formulate energy policies in each country and seek support from developed countries; and

(iii) suggests how to minimise the additional costs of transforming the energy supply–demand structure by using a cost-optimal technology selection model, which evaluates combinations of energy technologies.

The study uses a single model covering the 10 ASEAN countries. In analysing the model, we discussed energy policies and actual situations with the ASEAN countries and, on that basis, considered assumptions for the analysis and priorities of technologies to be introduced. The study is merely a second opinion to support ASEAN countries as they develop their own road maps for energy transition towards carbon neutrality. We will review our assumptions and reflect the latest data in the model analysis when the expected cost reduction of each technology is updated by international organisations and research institutes.

Chapter 2
Methodology

1. IEEJ–NE Model

We conducted an analysis using an optimum technology selection model (the Institute of Energy Economics, Japan [IEEJ]–<New Earth> [NE] model) developed by Otsuki et al. (2019) and encompassing the entire energy system. The analysis covers the 10 ASEAN countries from 2017 to 2060,[1] with representative years 2017, 2030, 2040, 2050, and 2060. We consider energy-related CO_2.

The IEEJ-NE model is formulated as a linear programming model. Like the market allocation (MARKAL) model developed by the Energy Technology Systems Analysis Program (ESTAP) of the International Energy Agency (IEA), the IEEJ-NE model takes the cost and performance of each energy technology as input values and yields a single combination of the scale and operational patterns of individual energy technologies to be introduced. Doing so minimises the total cost of the energy system when various constraints such as CO_2 emissions and power supply–demand balance are given. The model covers the energy conversion and end-use sectors (industry, transport, households, and commercial), and incorporates more than 350 technologies into them. The model evaluates combinations of the technologies by giving factors such as capital costs, fuel costs, and CO_2 emissions to each technology. The model includes low-carbon technologies such as solar photovoltaic (PV) power generation, onshore and offshore wind power generation, hydrogen (H_2)-fired power generation, 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 2.1). The IEEJ-NE model shows the entire energy system, starting from energy imports, secondary energy conversion, intraregional energy trade, CO_2 capture and storage (CCS), and final consumption. The model assumes various types of energy to be consumed (Figure 2.1).

[1] Brunei Darussalam, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand, and Viet Nam.

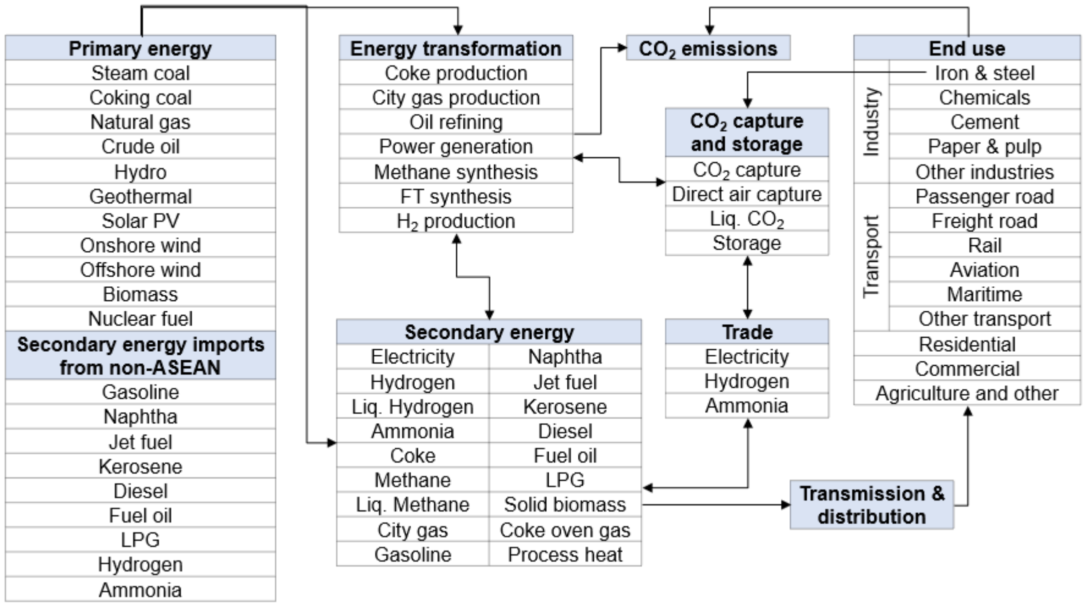
Modelling of the end-use sectors is based on data from the ERIA outlook, the IEA energy balance table, and the IEEJ outlook. However, some sectors are not simulated because data were unavailable (Figure 2.2).

Table 2.1. Selected Low-carbon Technologies in the Model

Renewables	Solar photovoltaic, onshore wind, offshore wind, hydro, geothermal, biomass
Nuclear	Light water reactor
CO_2 capture, utilisation, and storage	CO_2 capture: Chemical absorption, physical absorption, direct air capture CO_2 utilisation: Methane synthesis, FT liquid fuel synthesis CO_2 storage: Geological storage
H_2	Supply: Electrolysis, coal gasification, methane reforming, H_2 separation from NH_3, H_2 trade amongst Association of Southeast Asian Nations (ASEAN) countries, H_2 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, 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 (bioenergy with carbon capture and storage)

CCS = CO_2 capture and storage, CO_2 = carbon dioxide, FT = Fischer-Tropsch, H_2 = hydrogen, NH_3 = ammonia.
Source: Author.

Figure 2.1. Modelled Energy System



CO_2 = carbon dioxide, H2 = hydrogen, FT = Fischer-Tropsch, liq. = liquid, LPG = liquefied petroleum gas, PV = photovoltaic.
Source: Author.

Figure 2.2 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, KHM = Cambodia, IDN = Indonesia, LAO = Lao People's Democratic Republic, LDV = light-duty vehicle, MYS = Malaysia, MMR = Myanmar, PHL = Philippines, SGP = Singapore, THA = Thailand, VNM = Viet Nam.
Note: The manufacturing processes of iron and steel for each country are based on World Steel Association (2019). The assumptions on cement, such as efficiency for each country, are based on Global Cement and Concrete Association (2019).
Source: Author.

In the model, the total cost expressed as the sum of fixed costs, fuel costs, and variable costs, such as operation and maintenance (O&M) cost for technologies, is minimised using an objective function indicated in equation (1).

$$\boldsymbol{min\,TotalCost} = \sum_{y}\sum_{r}\sum_{i}\left(\boldsymbol{Fix}_{y,r,i} + \boldsymbol{Fuel}_{y,r,i} + \boldsymbol{Variable}_{y,r,i}\right)\cdot \boldsymbol{r} \qquad (\mathbf{1})$$

Fix: fixed cost (sum of the capital cost and the fixed O&M cost); ***Fuel***: fuel cost; ***Variable***: O&M cost; ***r***: discount coefficient (discount rate is 8%); Subscript *y*, *r,* and *i* stand for year, region (country), and technology.

Typical constraints include CO_2 emissions in representative years, power supply–demand balance at each time slice, upper limit on the introducible amount of each power source, and load following (see Otsuki et al. [2019]). To balance supply and demand of electricity even when solar PV and wind power plants are not operating, electricity must be discharged from storage batteries and H_2- and NH_3-fired power generation or other thermal power generation operated with CCS.

In the model, the power supply–demand is divided by time to express the fluctuation of renewable energy and the system integration cost. One year for power supply–demand is split into 2,190 time slices (4-hour resolution). The model explicitly simulates co-firing thermal power generation at existing and new power plants, that is, co-firing coal and NH_3 and co-firing gas and H_2. The modelled technologies are as follows: coal-fired power generation; co-firing coal and NH_3 (20%); integrated coal gasification combined cycle (IGCC); gas-fired power generation; gas combined (cycle power generation); co-firing gas and H_2 (H_2: 20%, 40%, 60%, 80%); hydropower; geothermal; solar PV; onshore and offshore wind power; biomass-fired; nuclear power; H_2-fired; NH_3-fired; pumped hydropower; lithium-ion battery; and H_2 tank.

For supply–demand of H_2 and NH_3, the model simulates production of H_2 and NH_3 in ASEAN countries and imports from outside ASEAN. Some countries consider domestic production of H_2. The model assumes that H_2 can be used for power generation, fuel synthesis, industry, and transport, whilst NH_3 is used only for power generation.

Table 2.2. Supply and Demand of Hydrogen and Ammonia

H_2 supply	Coal gasification, methane reforming, water electrolysis, H_2 trade amongst ASEAN countries, H_2 imports from outside ASEAN, H_2 separation from NH_3
H_2 consumption	Gas–H_2 co-firing, H_2-fired, methane synthesis, Fischer-Tropsch synthesis, NH_3 synthesis, H_2-based direct reduced iron–electric arc furnace, H_2 heat (industry), FCEV (light-duty vehicle), FCEV (bus and truck), H_2 ship, H_2 aviation
NH_3 supply	NH_3 synthesis, NH_3 trade amongst ASEAN, NH_3 imports from outside ASEAN
NH_3 consumption	Coal–NH_3 co-firing, NH_3-fired

FCEV = fuel cell electric vehicle, H2 = hydrogen, NH3 = ammonia.
Note: H_2 heat is assumed in iron and steel and chemical industries.
Source: Author.

The model considers DACCS and BECCS negative-emission technologies. Direct air capture (DAC) enables capturing CO_2 directly from the atmosphere, and the captured CO_2 is either permanently stored in deep geological formation (negative emission) or used to manufacture synthetic fuels by combining it with H_2 (carbon recycle). Fifteen DAC plants are operating all over the world and capturing more than 9,000 tons of CO_2 per year (IEA, 2020). However, DAC requires a large amount of energy, and the cost is extremely high at US$600 per tonnes of carbon dioxide (tCO_2). With high carbon prices aiming to achieve carbon neutrality, however, DAC may be cost-competitive. The cost assumptions for DAC in the model are in Table 2.3.

Table 2.3. Cost Assumptions for Direct Air Pressure in 2050

Item	Value	Unit
Capital cost	694	US$/($tCO_2$/year)
O&M cost	35	US$/$tCO_2$
Electricity consumption	1.5	MWh/tCO_2
Capturing cost	253	US$/$tCO_2$

MWh = megawatt-hour, O&M = operation and maintenance, tCO_2 = tonne of carbon dioxide.
Note: Electricity price is assumed to be US$0.1 per killowatt-hour for capturing cost.
Source: Author.

2. Preconditions

2.1. Case Settings

The Paris Agreement sets the goal of 'holding the increase in the global average temperature to well below 2°C above pre-industrial levels, and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels' (UN, 2015). The IEA states that to achieve the 1.5°C target, global carbon neutrality must be achieved by 2050. The IEA estimates that even under the scenario of achieving net-zero emissions for the entire world in 2050, some CO_2 emissions from developing countries will remain.

Based on those global circumstances, this study analyses five cases:

(i) Baseline does not set any CO_2 emissions target.

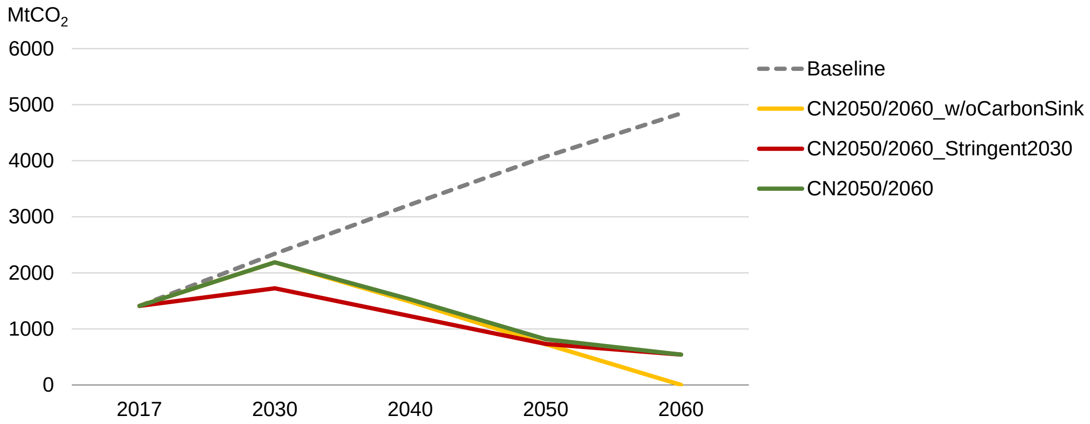
(ii) CN2050/2060 reflects nationally declared carbon-neutral target years and considers carbon sinks in Indonesia, Malaysia, Myanmar, Thailand, and Viet Nam based on discussions with each country.

(iii) CN2050/2060_Innovation cases, where five cases describe the impacts of technological innovation as sensitivity analysis of (ii).

(iv) CN2050/2060_Stringent2030 tightens emission constraints in 2030 of CN2050/2060 to the same level as the IEA sustainable development scenario. Case (iv) shows the results as sensitivity analysis of case (ii).

(v) CN2050/2060_w/oCarbonSink assumes that energy-related CO_2 emissions become net zero by 2060 and does not consider carbon sinks. The case assumes that the year net-zero emissions are achieved in ASEAN varies by country, based on the World Bank's classification by income level. Brunei Darussalam and Singapore are assumed to achieve net-zero emissions by 2050 and other countries by 2060. We initially assumed CN2050/2060_w/oCarbonSink, discussed it with ASEAN countries based on the initial results, and developed CN2050/2060 to reflect each country's comments.

Figure 2.3. Energy-related Carbon Dioxide Emissions in ASEAN



$MtCO_2$ = million tonnes of carbon dioxide.
Source: Author.

2.2. Key Assumptions

(a) Grid Connections amongst ASEAN Countries

ASEAN countries launched the ASEAN Power Grid in 2007, and since then, interconnectors amongst them have been constructed and operated. As of 2021, total transmission capacity was 5.7 gigawatts (GW). Countries are planning to continue to expand the international power grids. The study imposes a constraint of 55 GW in total based on the planned capacity and comments from each country.

(b) Hydrogen and Ammonia Imports from non-ASEAN Countries

The maximum amounts of H_2 and NH_3 imports from outside ASEAN are assumed to be up to 203 million tonnes of oil equivalent (Mtoe) per year in 2040, 540 Mtoe in 2050, and 638 Mtoe in 2060. An upper limit on imports after 2050 is equivalent to 30% of the total Baseline primary energy supply. H_2 prices are assumed at US$0.30 per normal cubic meter (Nm^3)–H_2

in 2030, US$0.20 in 2050, and US$0.175 in 2060, based on the Government of Japan's long-term H_2 supply chain target[2]. NH_3 prices are assumed to be US$0.18 per Nm^3–H_2 in 2030 and US$0.16 in 2050 and 2060, based on IEA (2020).

The study does not specify the production method of imported H_2, either green H_2 using electrolysers with electricity from renewable energy, or blue H_2 from fossil fuels tied with CCS. Specific H_2-exporting countries are not identified either. However, given the geographical transport distances and the potential for clean H_2 production, Australia, India, and Middle Eastern countries are regarded as candidates.

(c) Annual CO_2 Storage Capacity

In the study, the annual CO_2 storage potential is estimated at up to 687 million tonnes of carbon dioxide ($MtCO_2$) per year in 2040, 1,138 $MtCO_2$ per year in 2050, and 1,610 $MtCO_2$ per year in 2060. This potential for 2050 is equivalent to 25% of CO_2 emissions in Baseline and 30% in 2060. It is difficult to accurately estimate CO_2 storage potential. However, even if only relatively feasible options such as storage in depleted oil fields or gas fields and enhanced oil recovery in mature oil fields are considered, the potential of ASEAN countries is high (Global CCS Institute, 2016).[3]

(d) Supply Potential of Biofuels for Vehicles

As transport decarbonises, the model considers expanding the use of biofuels as well as electrifying automobiles. Biofuel supply potential in the study is assumed to increase in proportion to demand for road transport.

(e) Levelised Cost of Electricity

Power generation costs are estimated by IEEJ based on publicly available reports such as Danish Energy Agency (2021) for Indonesia and information obtained by ASEAN countries. Figure 2.4 shows the power generation costs in 2050 in Indonesia. The capacity factor of each power generation and the required storage capacity of batteries are endogenously determined.

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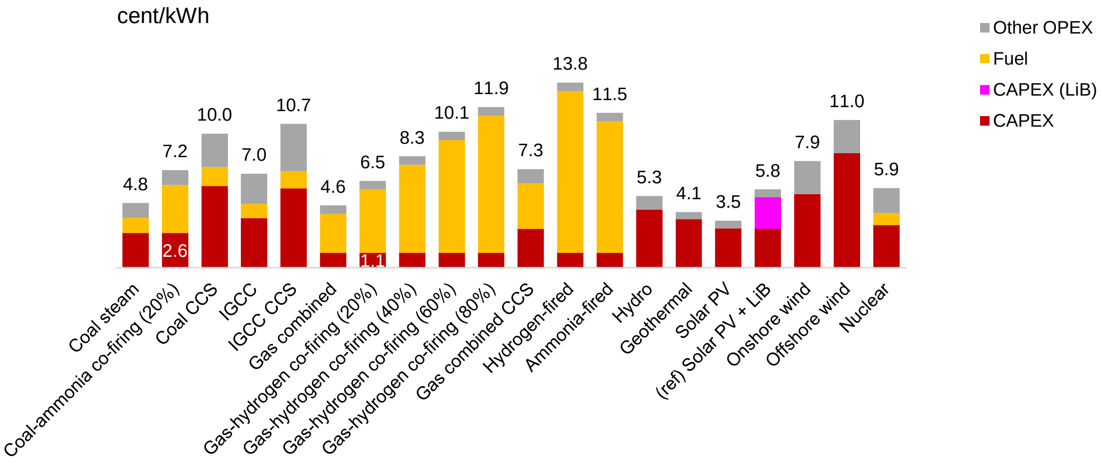
[2] These prices are for blue or green hydrogen, covering transport cost.
[3] The cumulative potential of five countries combined (Indonesia, Malaysia, Philippines, Thailand, and Viet Nam) is estimated to be 75 $GtCO_2$ according to GCCSI (2016).

Figure 2.4. Power Generation Cost in 2050 (Indonesia)



CAPEX = capital expenditure, CCS = carbon dioxide capture and storage H_2 = hydrogen, IGCC = integrated coal gasification combined cycle, LiB = lithium-ion battery, Nm^3 = normal cubic meter, OPEX = operating expenditure, PV = photovoltaic, ref = reference.

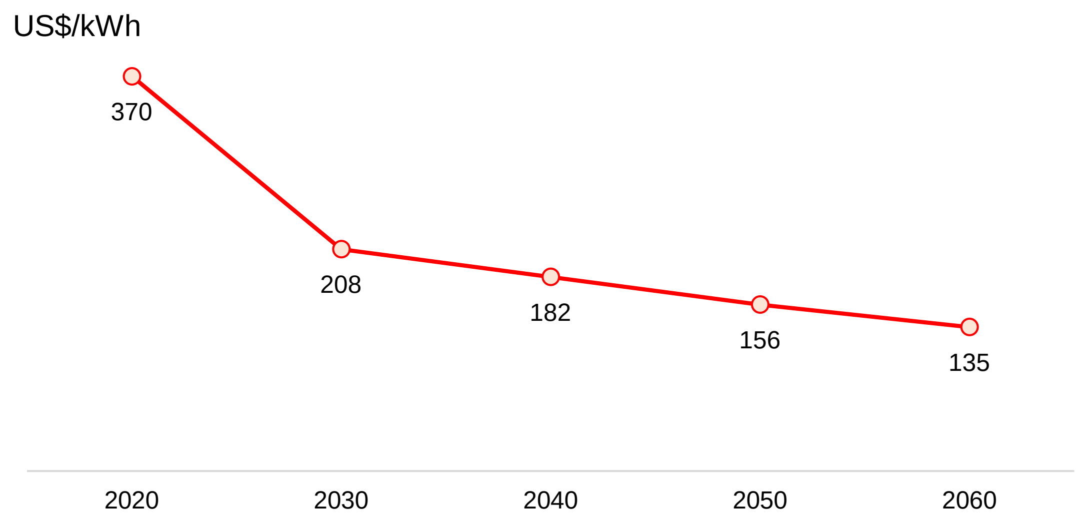
Note: H_2 price: US\$0.20/Nm^3–H_2; ammonia price: US\$0.16/Nm^3–H_2; capacity factor: 40% for hydro, 80% for geothermal, 15% for solar PV, 20% for onshore wind, 30% for offshore wind, 80% for nuclear, 60% for the rest of the technologies.

Source: Estimated by the Institute of Energy Economics, Japan, based on Danish Energy Agency (2021) and information provided by Indonesia.

(f) Energy Storage Technologies

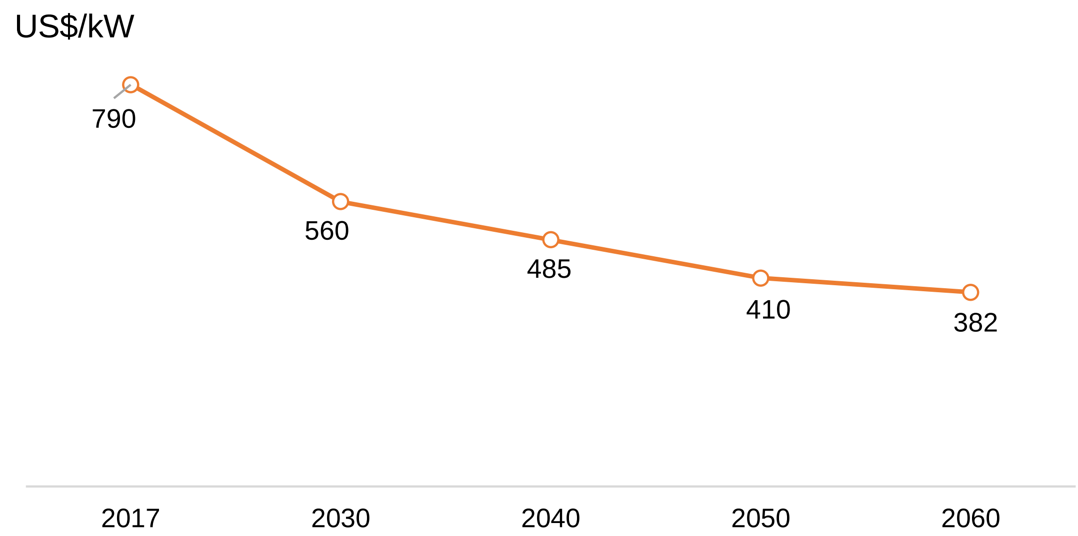
The model simulates pumped hydro storage, lithium-ion batteries, and compressed H_2 tanks as energy storage technologies. The required amounts for lithium-ion batteries and compressed H_2 tanks are endogenously determined. The production cost of lithium-ion batteries is expected to substantially decline. Future cost reduction in the study is based on a cost forecast by the National Renewable Energy Laboratory of the United States.

Figure 2.5. Assumed Lithium-ion Battery Cost



kWh = kilowatt-hour.
Note: 2019 US$.
Source: National Renewable Energy Laboratory (2020).

Figure 2.6. Assumed Capital Cost of Solar Photovoltaic Generation

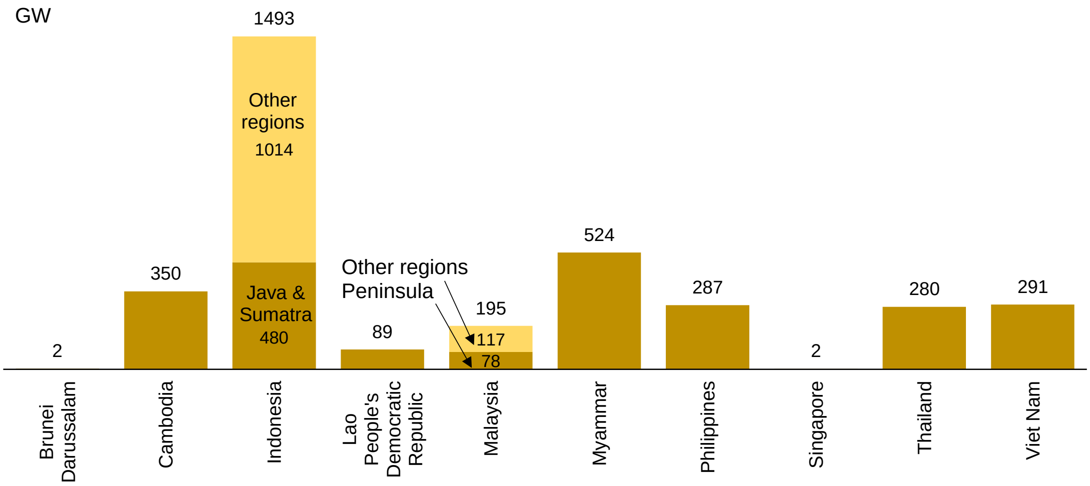


kW = kilowatt.
Note: 2019 US$.
Source: Estimated by the Institute of Energy Economics, Japan, based on Danish Energy Agency (2021).

(g) Solar Photovoltaic Potential

IEEJ estimates the potential of solar PV power generation based on geographic information system (GIS) data to be 3,513 GW for the entire ASEAN. The potential of solar PV power generation in Indonesia, an archipelago, is divided into 'Java and Sumatra' and 'other regions' given the regional imbalance between electricity demand and renewable energy sources. Solar PV power generation in 'other regions' is assumed to be used for H_2 production. The potential in Malaysia is divided into 'peninsula' and 'other regions' given its geographical characteristics.

Figure 2.7. Solar Photovoltaic Potential

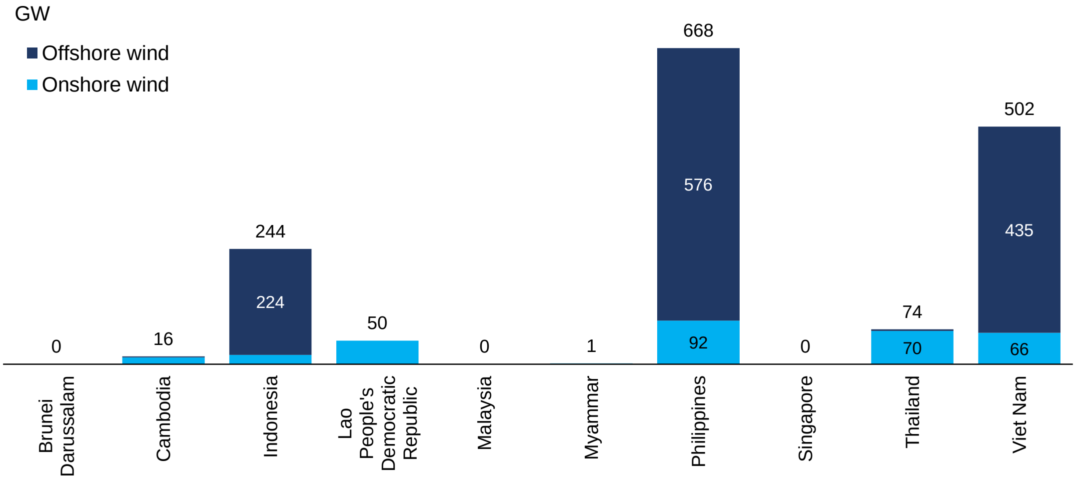


Source: Author.

(h) Wind Power Potential

The potential of wind power generation, which is divided into onshore and offshore, is estimated by IEEJ based on GIS data. The potential of onshore wind power generation in the entire ASEAN is assumed to be 313 GW and offshore 1,241 GW. The potential of onshore and offshore wind power generation in Indonesia is divided into 'Java and Sumatra' and 'other regions' to consider the regional imbalance between electricity demand and resources. Wind power generation in 'other regions' is assumed to be used for H_2 production.

Figure 2.8. Wind Power Potential

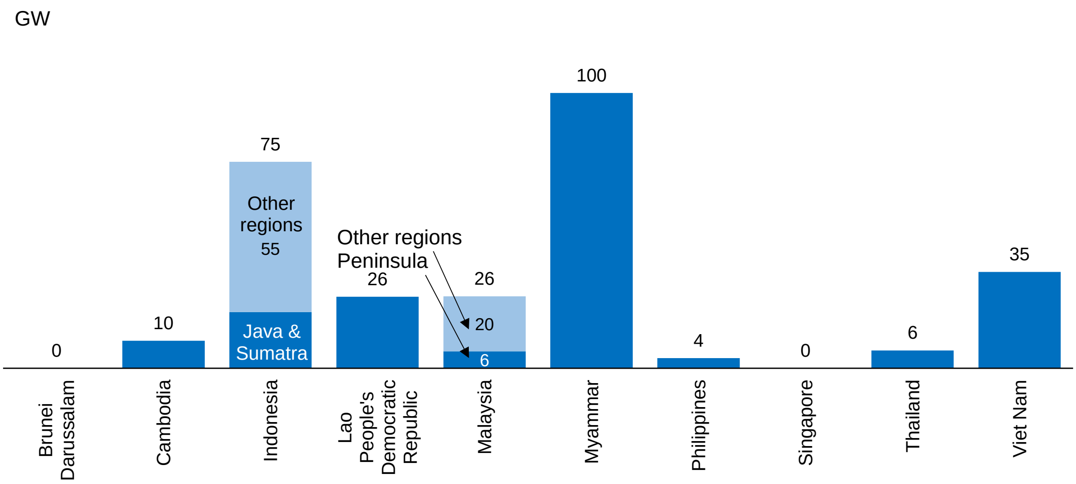


GW = gigawatt.
Source: Author.

(i) Hydropower Potential

The potential of hydropower generation is assumed to be 282 GW in the entire ASEAN based on data from sources such as PricewaterhouseCoopers (2018). The potential of hydropower generation in Indonesia is divided into 'Java and Sumatra' and 'other regions' given the regional imbalance between electricity demand and resources, and hydropower generation in 'other regions' is assumed to be for H_2 production. Potential in Malaysia is divided into 'peninsula' and 'other regions'.

Figure 2.9. Hydropower Potential



GW = gigawatt.
Source: Author.

Chapter 3
Results for ASEAN

1. Results for CN2050/2060

CN2050/2060 reflects nationally declared carbon-neutral target years and considers carbon sinks in Indonesia, Malaysia, Myanmar, Thailand, and Viet Nam based on discussions with each country.

Table 3.1. Target Year and Assumptions of Carbon Sink in CN2050/2060

Country	CN Target Year	Energy-related CO_2 Emission Reduction Target from 2017	Note
Brunei Darussalam	2050	100%	• Target year: No CN target. Set to 2050, considering income level • Sink: Not considered
Cambodia	2050	100%	• Target year: 2050 CN declaration (CAA member country) • Sink: Not considered
Indonesia	2060	50%	• Target year: 2060 CN declaration • Sink: 2050 value of the LCCP scenario in the LTS. Although original target is calculated to be 39%, set to 50% as the minimum requirement
Lao PDR	2050	100%	• Target year: 2050 CN declaration (CAA member country)

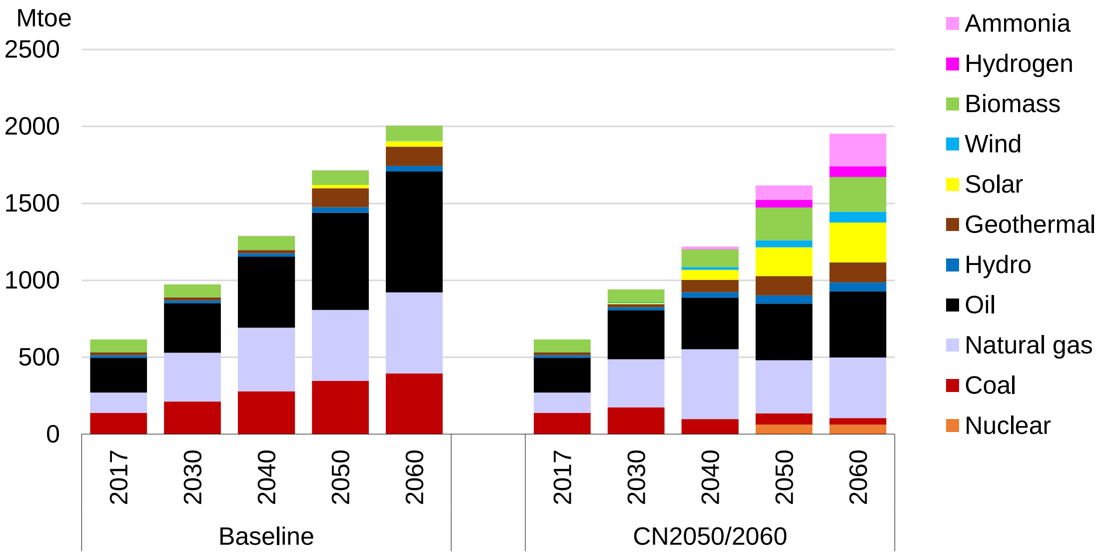
			• Sink: Not considered
Malaysia	2050	50%	• Target year: Referred to 2050 CN by Prime Minister • Sink: 2016 value of the inventory. Although original target is calculated to be -14%, set to 50% as the minimum requirement
Myanmar	2060	60%	• Target year: 2060 CN (requested by Myanmar) • Sink: 2030 target of the unconditional NDC
Philippines	2060	100%	• Target year: No CN target. Set to 2060 • Sink: Not considered
Singapore	2050	100%	• Target year: No CN target. Set to 2050, considering income level • Sink: Not considered
Thailand	2050	50%	• Target year: 2050 CN (requested by Thailand) • Sink: Use values provided by Thailand
Viet Nam	2050	70%	• Target year: 2050 CN declaration • Sink: 2030 target of the unconditional NDC

CAA = climate ambition alliance, CN = carbon neutral, LTS = long-term strategy, LCCP = low-carbon scenario compatible with Paris Agreement target, NDC = nationally determined contribution.
Source: Author.

1.1. Primary Energy Supply

Figure shows the primary energy supply in Baseline and CN2050/2060. Primary energy supply in 2060 substantially increases to about 3.3 times the 2017 level in Baseline, and to about 3.2 times in CN2050/2060. In Baseline, primary energy supply from fossil fuels such as coal, natural gas, and oil continues to increase in 2060. However, promoting decarbonisation towards carbon neutrality requires a broad range of technologies, such as renewable energy, nuclear, CCS, and H_2 and NH_3 imports. In CN2050/2060, the share of these technologies goes up to 51% of primary energy supply in 2050 and 56% in 2060.

Figure 3.1. Primary Energy Supply in ASEAN (CN2050/2060)

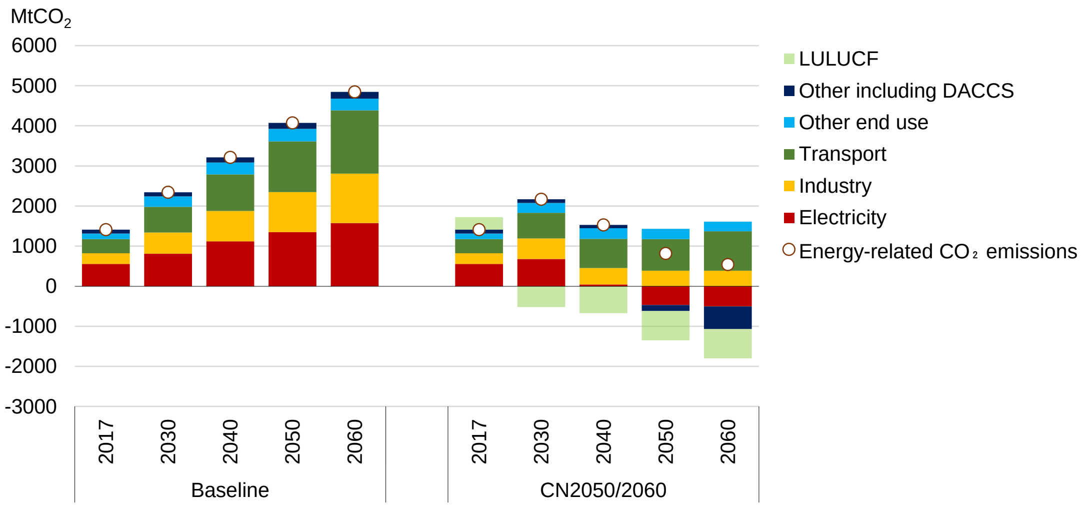


Mtoe = million tonnes of oil equivalent.
Source: Author.

1.2. Sector Carbon Dioxide Emissions

Figure 3.2 illustrates sector CO_2 emissions in Baseline and CN2050/2060. In Baseline, CO_2 emissions increase mainly in electricity and transport with the growth of final energy consumption. In CN2050/2060, CO_2 emissions from transport, particularly buses and trucks, remain whilst the power sector is fully decarbonised by 2050 because the costs of alternative vehicles, specifically battery electric vehicles and fuel cell vehicles, are high. End-use CO_2 emissions are offset through not only decarbonisation of power but also a combination of negative-emission technologies such as BECCS and DACCS. Integrating negative-emission technologies with end-use emission reduction is estimated to be a cost-effective strategy to achieve carbon neutrality.

Figure 3.2. Sector Energy-related Carbon Dioxide Emissions in ASEAN (CN2050/2060)

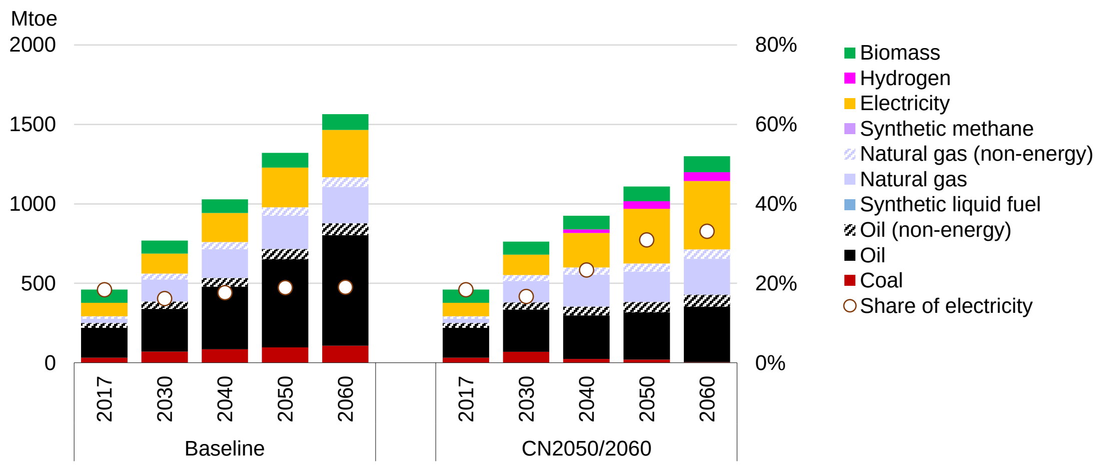


CO_2 = carbon dioxide; DACCS = direct air capture with carbon storage; LULUCF = land use, land-use change, and forestry; $MtCO_2$ = million tonnes of carbon dioxide.
Source: Author.

1.3. Final Energy Consumption

Figure 3.3 shows final energy consumption in Baseline and CN2050/2060. In CN2050/2060, final energy consumption in 2060 decreases by 17% compared with Baseline. In CN2050/2060, the share of electricity increases to 33% by 2060. The changes suggest that advancing energy efficiency and electrification is a core strategy to decarbonise end-use sectors.

Figure 3.3. Final Energy Consumption in ASEAN (CN2050/2060)

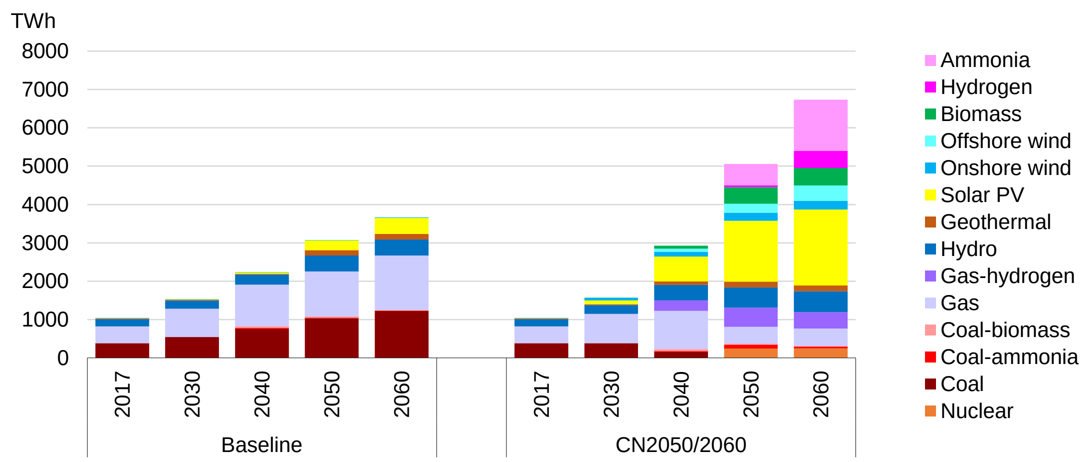


Mtoe = million tonnes of oil equivalent.
Source: Author.

1.4. Power Generation

Figure 3.4 describes the power generation in Baseline and CN2050/2060. In Baseline, coal-fired power generation and natural gas-fired power generation account for most of the electricity mix even in 2060. In CN2050/2060, renewable energy is a major power source, accounting for 56% in 2060. H_2- and NH_3-fired power generation follow renewables, accounting for 26%. The share of solar PV power generation is 53% of electricity generation from renewables.

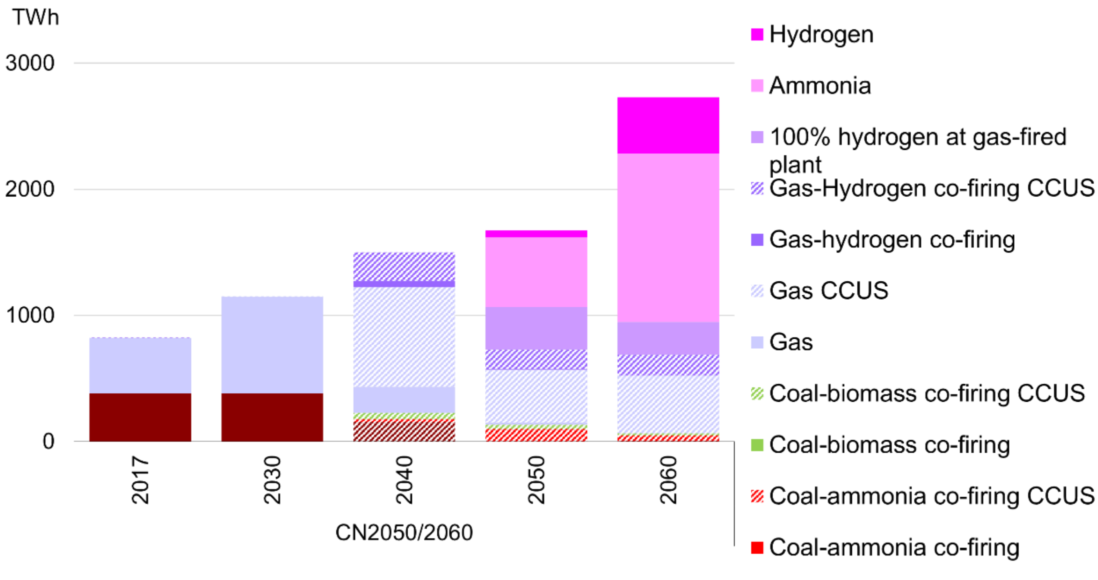
Figure 3.4. Power Generation in ASEAN (CN2050/2060)



PV = photovoltaic, TWh = terawatt-hour.
Source: Author.

Figure 3.4 shows that H_2 and NH_3, including co-firing, play roles in the electricity mix in CN2050/2060. Figure 3.5 shows the transition of thermal power generation (coal, natural gas, NH_3, H_2) in total electricity generation. In the near term, for example, up to 2030, highly efficient gas-fired power generation is estimated to contribute to curbing CO_2 emissions from power generation. In the medium to long term, gas-fired power generation with CO_2 capture, utilisation, and storage (CCUS), co-firing with NH_3 or H_2, and 100% NH_3- or H_2-fired power generation are the candidates. From 2040 to 2050, co-firing at existing coal- and gas-fired power stations, gas-fired power generation with CCUS, and 100% NH_3-fired power generation are expected to be pursued, and a major share of thermal power generation shifts to 100% NH_3-fired power generation by 2060.

Figure 3.5. Generated Electricity from Coal, Gas, Ammonia, and Hydrogen in ASEAN (CN2050/2060)

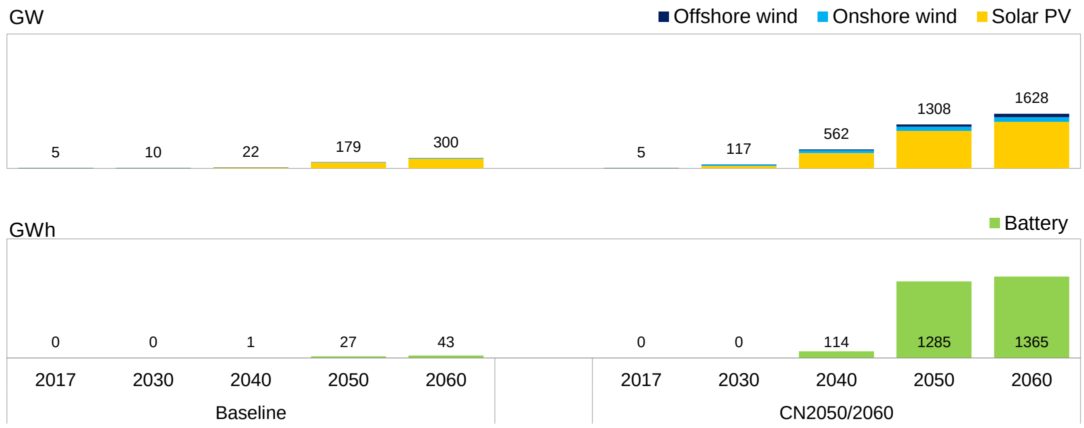


CCUS = carbon dioxide capture, utilisation, and storage; TWh = terawatt-hour.
Source: Author.

1.5. Variable Renewable Energy and Battery

In CN2050/2060, variable renewable energy (VRE), such as solar PV and wind power generation, is expected to be deployed. Installed capacity of solar PV power generation is estimated to account for a large share, and that of all VRE reaches about 1,628 GW by 2060 (Figure 3.6). The cost of batteries and VRE significantly decreases and the mass deployment of VRE is expected to accelerate after 2040 (Figure 2.5, Figure 2.6). The study considers sodium-sulphur, lithium-ion, and redox flow batteries as storage technologies.

Figure 3.6. Variable Renewable Energy and Battery Capacity in ASEAN (CN2050/2060)

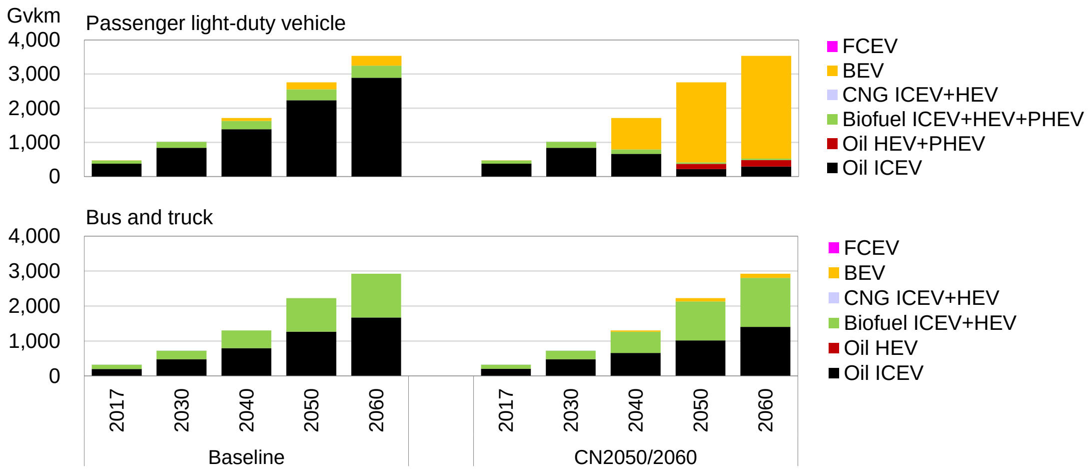


GW = gigawatt, GWh = gigawatt-hour, PV = photovoltaic.
Source: Author.

1.6. Road Transport

Transport contributes greatly to the growth of final energy consumption in Baseline. Figure 3.7 shows travel distance of passenger light-duty vehicles in the upper graph and that of buses and trucks in the lower graph and demonstrates that the use of oil persists in short- and long-distance transport in Baseline. By contrast, a major share of passenger vehicles are electrified by 2050 in CN2050/2060. However, long-distance alternative vehicle technologies, such as battery electric vehicles and fuel cell vehicles, are expensive and, therefore, oil consumption is expected to remain until 2060. The use of biofuels in internal combustion engines and hybrid vehicles is expected to expand.

Figure 3.7. Travel Distance by Vehicle Technology in ASEAN (CN2050/2060)

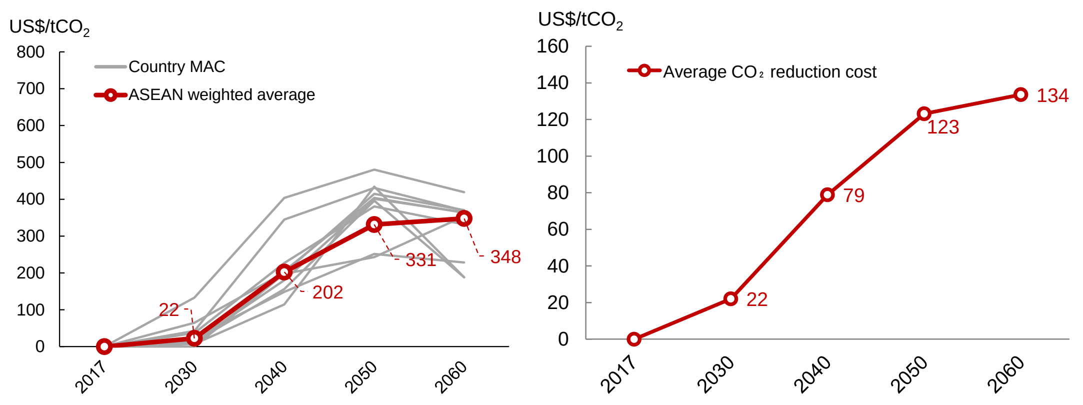


BEV = battery electric vehicle, CNG = compressed natural gas, FCEV = fuel cell electric vehicle, HEV = hybrid electric vehicle, ICEV = internal combustion engine vehicle, Gvkm = 10^9 vehicle-km, PHEV = plug-in hybrid electric vehicle.
Note: Biofuel includes bioethanol and biodiesel mixed with petroleum fuel.
Source: Author.

1.7. Costs for Reducing Carbon Dioxide and Energy Prices

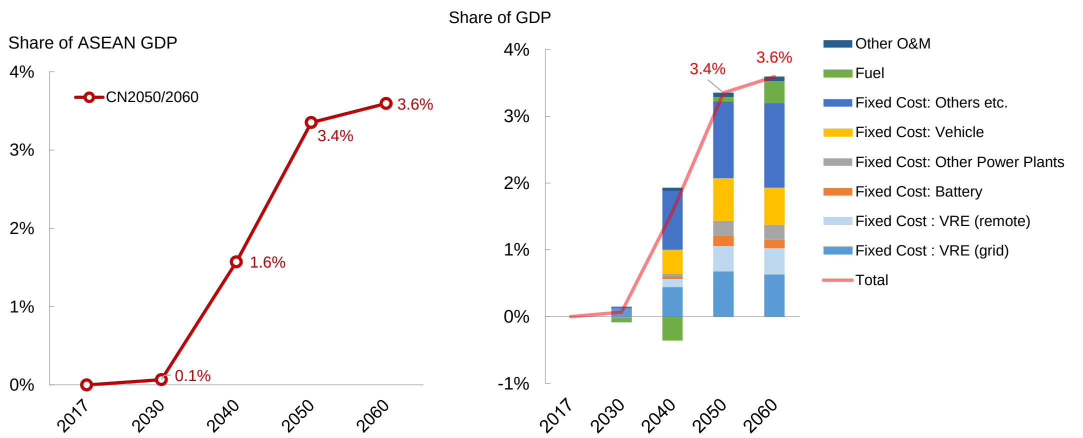
The marginal CO_2 abatement cost (MAC) is the cost required for the entire energy system to reduce marginally 1 ton of CO_2, as yielded by the model simulation (see Enkvist et al. [2007]). Figure 3.8 illustrates the weighted average of MAC in ASEAN. In CN2050/2060, the MAC rises to US$348/t$CO_2$ in 2060, implying an economic challenge to decarbonisation. In CN2050/2060, the MAC increases only slightly during 2050 and 2060 because CO_2 emissions constraints are moderate. The additional annual cost in CN2050/2060 compared with Baseline is estimated at about 3.6% (US$0.58 trillion) of ASEAN's gross domestic product (GDP) in 2060.

Figure 3.8. Marginal Carbon Dioxide Abatement Cost (Left), Average Carbon Dioxide Reduction Cost (Right) (CN2050/2060)



CO_2 = carbon dioxide, MAC = marginal CO_2 abatement cost, tCO_2 = tonne of carbon dioxide.
Source: Author.

Figure 3.9. Additional Annual Cost (Left), Composition of Additional Annual Cost (Right) (CN2050/2060)

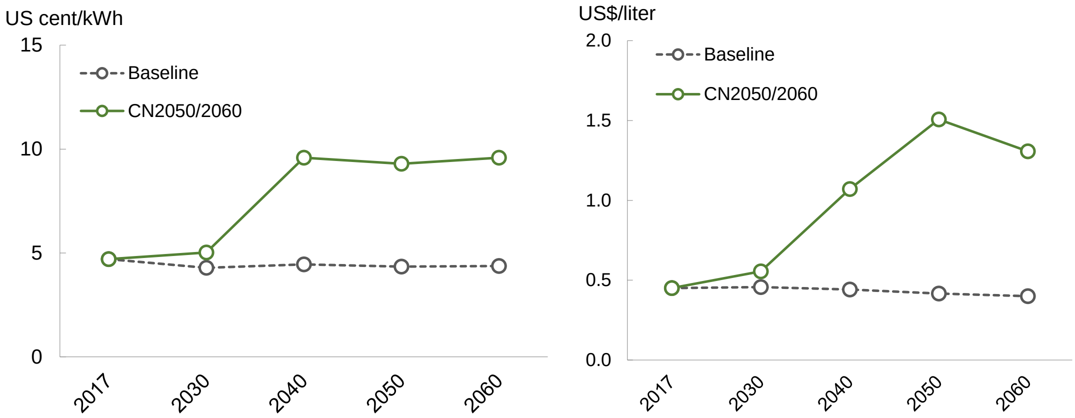


GDP = gross domestic product, O&M = operation and maintenance, VRE = variable renewable energy.
Source: Author.

The costs presented here do not include costs to enhance emission reductions in the land use, land-use change, and forestry (LULUCF) sector, such as afforestation. The Intergovernmental Panel on Climate Change (2018) estimates the cost of afforestation and reforestation at US$5–US$50/tCO_2. In addition to the cost assessment and setting of certain assumptions for baseline LULUCF sector emissions,[4] additional annual costs are estimated at 0.2%–0.7% of ASEAN GDP in 2030 and 0.1%–0.3% in 2060. However, the marginal abatement costs of LULUCF and setting of the baseline are subject to large uncertainties.

Electricity and diesel prices are estimated to rise two- to four-fold in CN2050/2060. Whilst the rise of energy prices is considered inevitable to achieve carbon neutrality, policymakers must minimise the economic impact of decarbonisation on end users. The diesel end-use price increases because a carbon price is imposed in the future.

Figure 3.10. Electricity Price (Left), Diesel End-use Price (Right) (CN2050/2060)



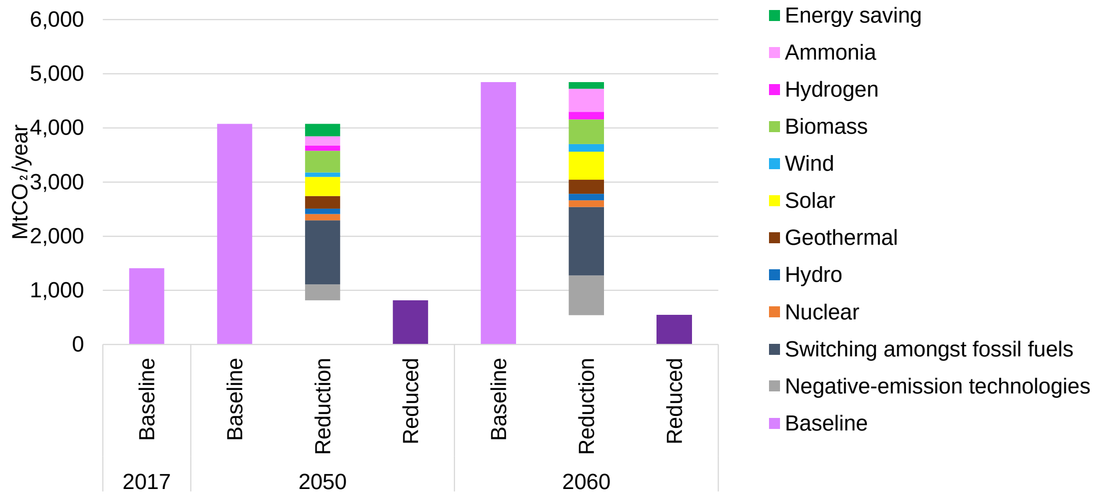
kWh = kilowatt-hour.
Source: Author.

1.8. Contribution of Mitigation Measures

Figure 3.11 shows the contributions of technologies to reducing energy-related CO_2 emissions in CN2050/2060. Carbon neutrality cannot be achieved solely by VRE but by combinations of reduction technologies. In addition to energy efficiency, imported H_2 and NH_3, and negative-emission technologies, switching amongst fossil fuels can play important roles in the ASEAN region.

[4] The MAC was set at US$25 and US$50 per ton-CO_2. Baseline emissions in the LULUCF sector were assumed to remain unchanged. However, since Indonesia's current emissions are positive, a case with a linear decrease towards zero in 2050 was also considered.

Figure 3.11. Contribution of Mitigation Measures (CN2050/2060)



$MtCO_2$ = million tonnes of carbon dioxide.
Source: Author.

1.9. Sensitivity Analysis 1: Technological Innovation

In the first sensitivity analysis, five cases of technological innovation were set to analyse the impact of the innovation on energy mix and mitigation costs (MAC and additional annual cost). 3.2 shows the assumptions of the cases.

Table 3.2. Key Technology Assumptions for Technological Innovation Cases

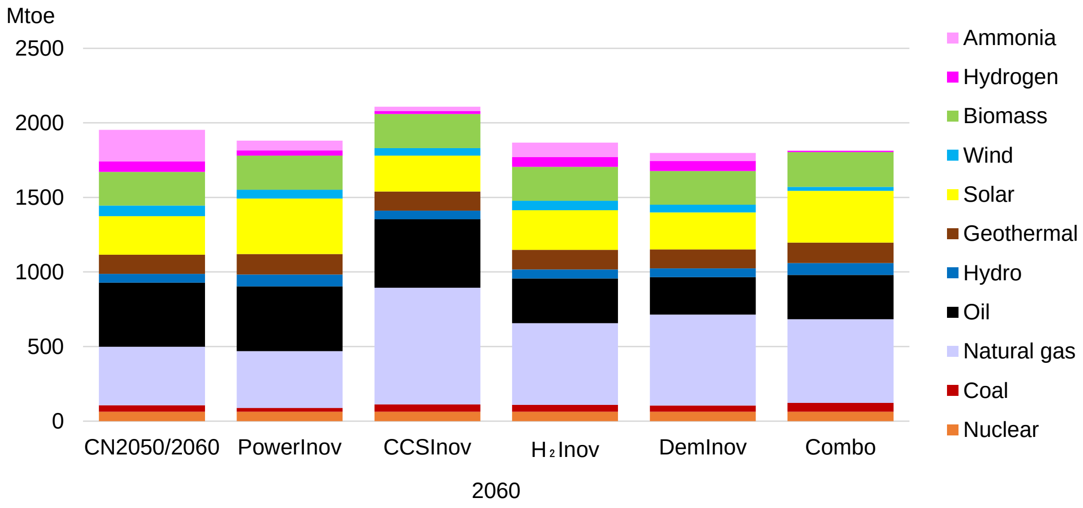
Case	Net-zero Year	Key Technology Assumptions
CN2050/2060	2060	Reference technology cost International power grid extension constrained by planned ASEAN power grid capacity CO_2 storage up to 1.6 $GtCO_2$/year in 2060
PowerInov	2060	Cost reduction of lithium-ion battery (-25% in 2040 and -50% after 2050, from the reference level) and international grid extension No upper limit for international power grid extension Large-scale electricity exports from Myanmar to Thailand

CCSInov	2060	Cost reduction of direct air capture (-25% in 2040 and -50% after 2050) CO_2 storage up to 2.7 $GtCO_2$/year in 2060
H_2Inov	2060	Cost reduction of coal gasification and methane reforming (-25% in 2040 and -50% after 2050), electrolyser (-22% in 2040 and 2050, -35% in 2060) Cost reduction of H_2 consumption: H_2 based DRI-EAF and fuel cell ship (-25% in 2040 and -50% after 2050), FCEV (comparable to hybrid electric vehicle price in 2060)
DemInov	2060	Cost reduction of advanced end-use technologies (-50% in and after 2040)
Combo	2060	Combined the assumptions of four innovation cases mentioned above

CO_2 = carbon dioxide, DRI-EAF = direct reduced iron–electric arc furnace, FCEV = fuel cell electric vehicle, $GtCO_2$ = gigatonnes of carbon dioxide, H_2 = hydrogen.
Source: Author.

Figure 3.12 shows the primary energy supply for each case in 2060. The overall energy mix seems not to differ significantly from case to case. In CCSInov, more natural gas and oil supplies remain than in other cases in 2060 because of large CO_2 storage capacity and large negative-emission potential (e.g. DACCS).

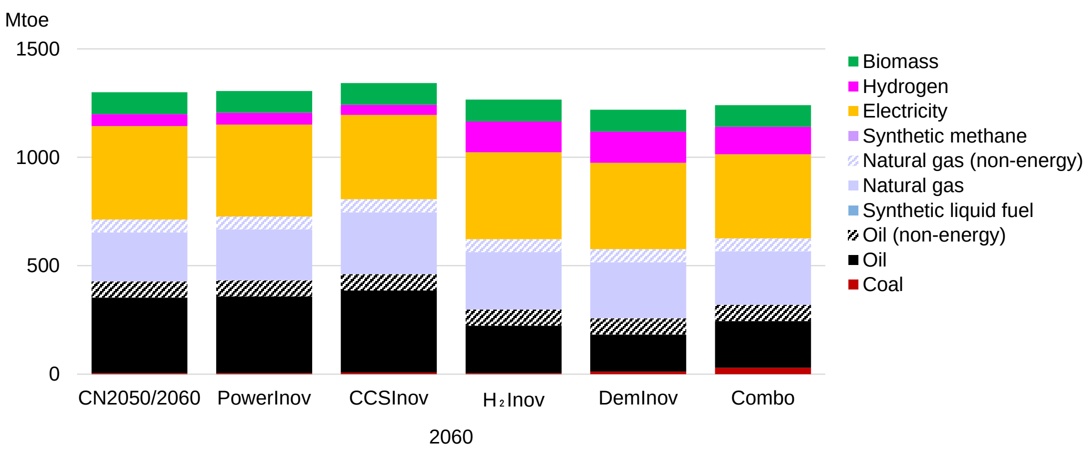
Figure 3.12. Primary Energy Supply in 2060 (Sensitivity Analysis 1)



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

Figure 3.13 shows final energy consumption for each case in 2060. In CCSInov, more fossil fuel consumption, such as oil and natural gas, remains than in other cases. In H2Inov and DemInov, fossil fuel and electricity consumption decrease due to growth of H_2 consumption. The increase in H_2 consumption in H2Inov and DemInov is caused mainly by demand for fuel cell buses and trucks. In both cases, 40%–45% of buses and trucks in ASEAN are expected to be fuel cell vehicles in 2060.

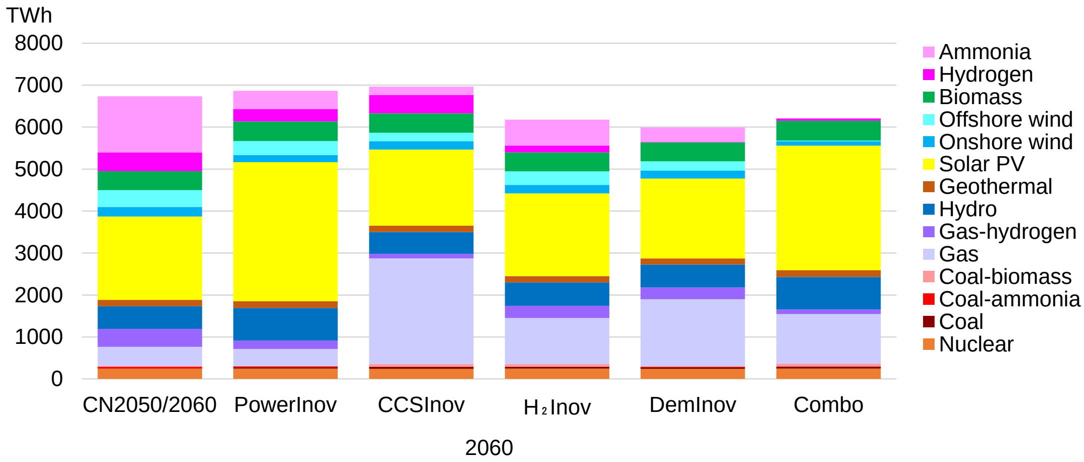
Figure 3.13. Final Energy Consumption in 2060 (Sensitivity Analysis 1)



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

Figure 3.14 shows the electricity mix for each case in 2060. PowerInov suggests that the ASEAN region enables the introduction of low-cost renewable energy sources by extending grid interconnections, for example, by introducing solar PV in place of offshore wind. Total electricity generation in H2Inov and DemInov is about 10% less than total electricity generation in CN2050/2060 since end-use electricity consumption declines.

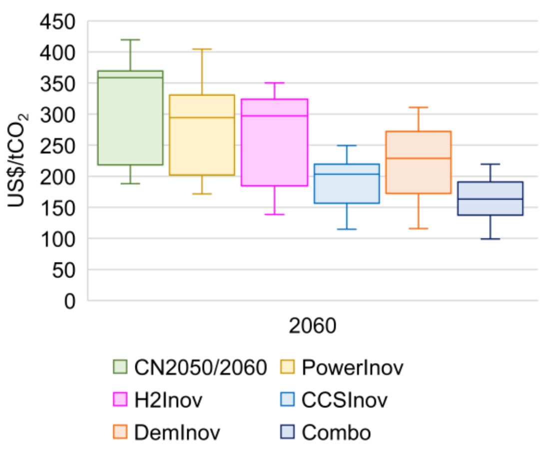
Figure 3.14. Generated Electricity in 2060 (Sensitivity Analysis 1)

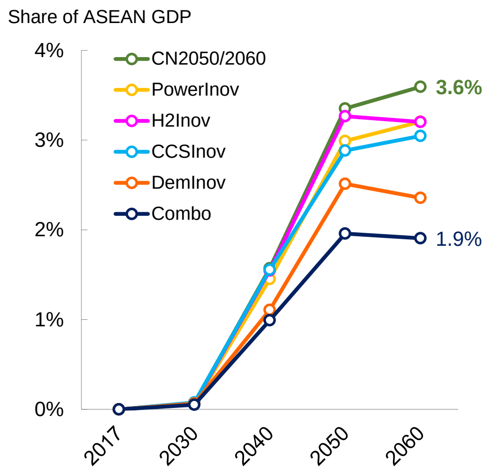


Mtoe = million tonnes of oil equivalent, PV = photovoltaic.
Source: Author.

Figure 3.15 illustrates the mitigation costs for each case in 2060. A comparison of CN2050/2060 with the technological innovation cases shows that energy cooperation in ASEAN, such as cost reduction of each technology through innovation and expansion of grid interconnections, substantially reduces mitigation costs. Mitigation costs as of 2060 in Combo are about half or less than that for CN2050/2060, indicating that research and development and international collaboration are essential to achieve carbon neutrality. Technological innovation is especially important because it not only lowers the cost of the carbon-neutral scenario but also leads to early carbon neutrality. Therefore, rather than promoting individual efforts, all countries should pursue international cooperation to accelerate innovation that leads to cost reduction.

Figure 3.15. Marginal Abatement Cost (Left), Additional Annual Cost (Right) (Sensitivity Analysis 1)





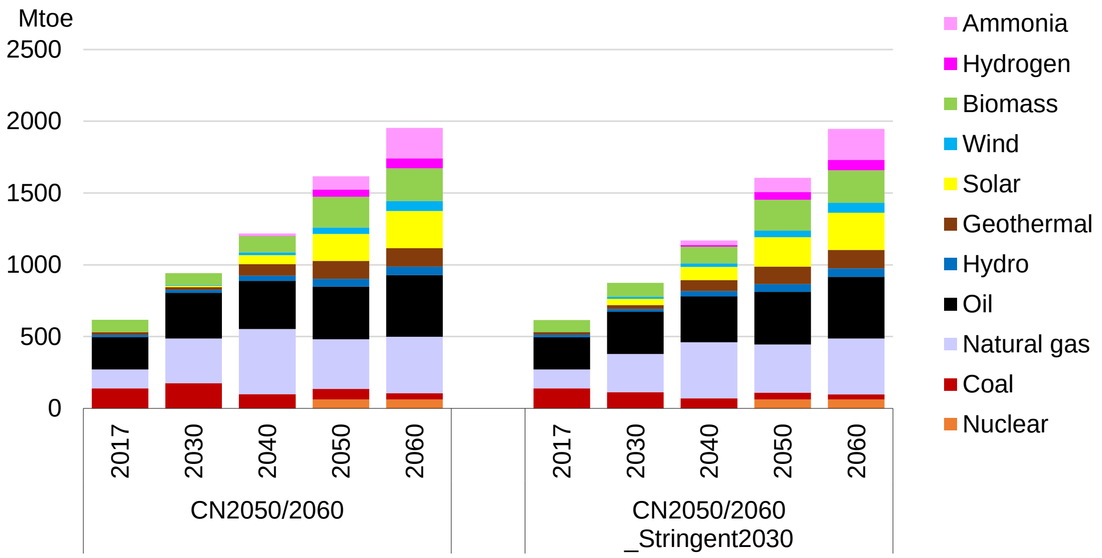
GDP = gross domestic product, tCO_2 = tonne of carbon dioxide.
Source: Author.

1.10. Sensitivity Analysis 2: Strengthen Carbon Dioxide Emission Constraints in 2030

The second sensitivity analysis presents the results of CN2050/2060_Stringent2030, which tightens emission constraints in 2030 in CN2050/2060 to the same level as the IEA Sustainable Development Scenario.

Figure 3.16 shows the primary energy supply in CN2050/2060 and CN2050/2060_Stringent2030. In CN2050/2060_Stringent2030, strengthened emission constraints reduce the share of fossil fuels and increase that of solar PV in 2030. The share of H_2 and NH_3 increases slightly from 1% to 4% in 2040 in CN2050/2060_Stringent2030.

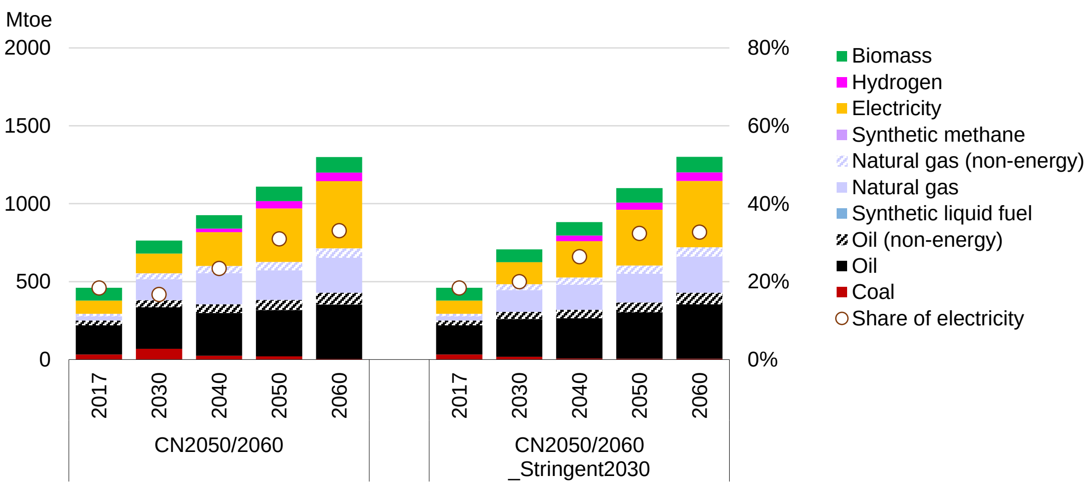
Figure 3.16. Primary Energy Supply (CN2050/2060_Stringent2030)



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

Figure 3.17 illustrates final energy consumption in CN2050/2060 and CN2050/2060_Stringent2030. Final energy consumption in 2060 is the same for both cases, but CN2050/2060_Stringent2030 lower than CN2050/2060 by 7% in 2030 and 5% in 2040. The share of electricity in CN2050/2060_Stringent2030 increases slightly in 2030 and 2040.

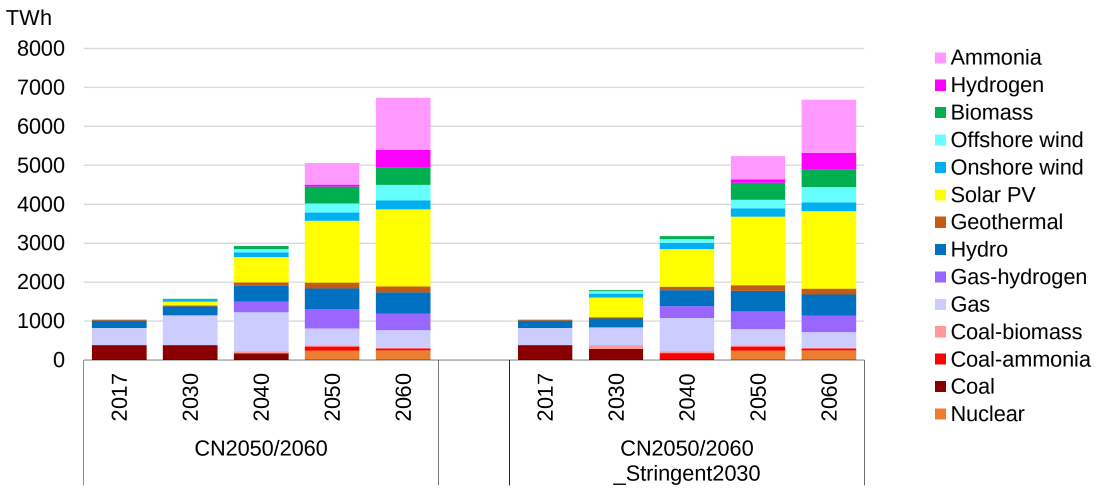
Figure 3.17. Final Energy Consumption (CN2050/2060_Stringent2030)



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

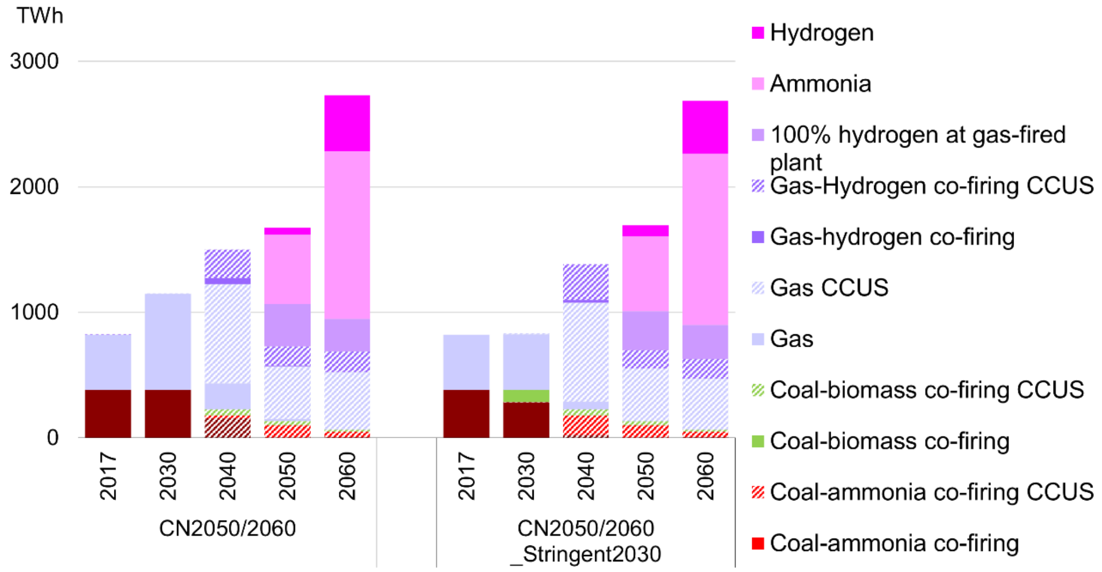
Figures 3.18–3.19 describe power generation in CN2050/2060 and CN2050/2060_Stringent2030. In CN2050/2060_Stringent2030, solar PV is introduced on a large scale from 2030. Looking at electricity generated by thermal power (coal, natural gas, NH_3, and H_2), gas-fired power generation decreases in 2030 whilst coal–biomass co-firing is introduced. There is no significant difference in transition in thermal power generation after 2040, but in CN2050/2060_Stringent2030, coal–NH_3 co-firing replaces coal-fired power generation in 2040.

Figure 3.18. Power Generation (CN2050/2060_Stringent2030)



PV = photovoltaic, TWh = terawatt-hour.
Source: Author.

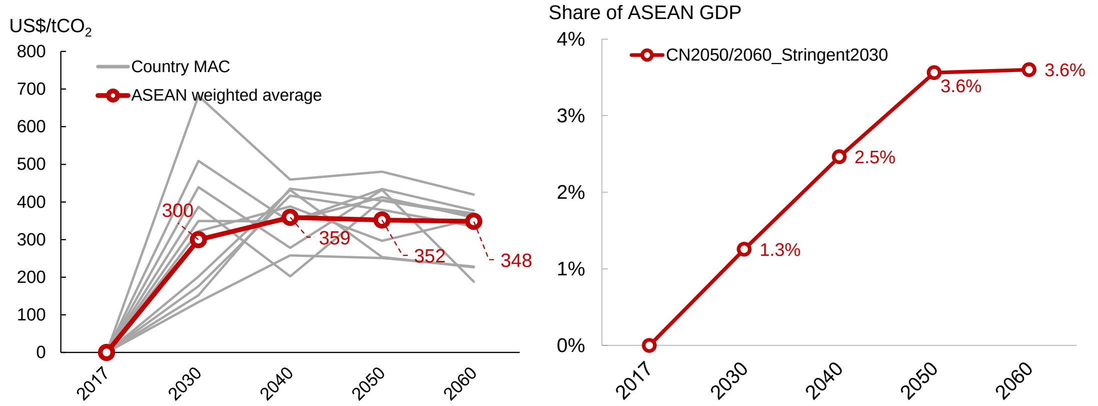
Figure 3.19. Generated Electricity from Coal, Gas, Ammonia, and Hydrogen in ASEAN (CN2050/2060_Stringent2030)



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

In CN2050/2060_Stringent2030, the MAC in 2030 increases significantly to US$300/t$CO_2$ due to enhanced CO_2 emission constraints. The MAC and additional annual cost for CN2050/2060_Stringent2030 are higher than that for CN2050/2060 in 2030 and 2040 but show no significant difference after 2040. The value of the objective function is larger in CN2050/2060_Stringent2030 than in CN2050/2060.

Figure 3.20. Marginal Carbon Dioxide Abatement Cost (Left), Additional Annual Cost (Right) (CN2050/2060_Stringent2030)



GDP = gross domestic product, MAC = marginal carbon dioxide abatement cost, tCO_2 = tonne of carbon dioxide.
Source: Author.

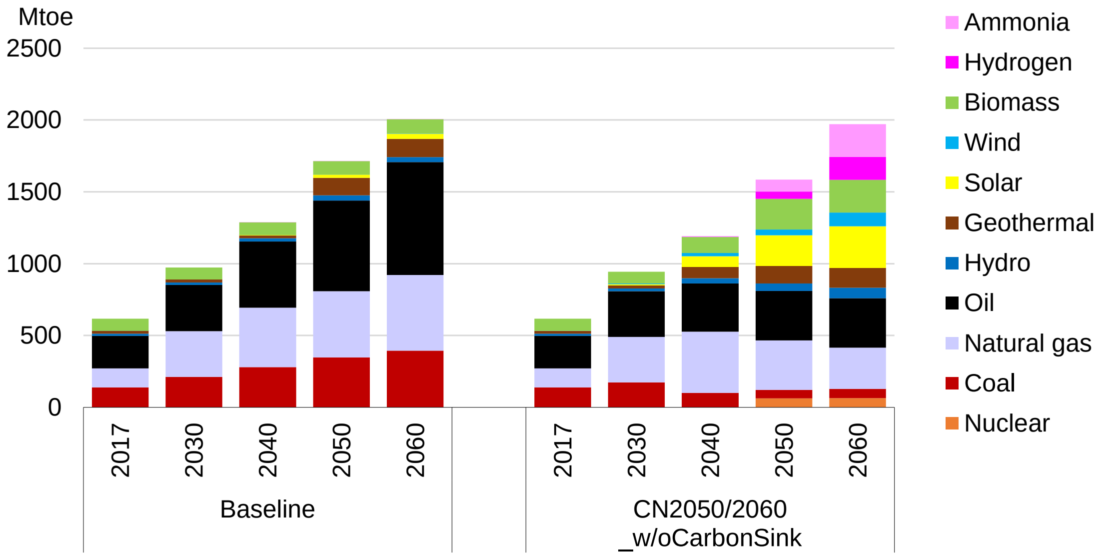
2. Results of CN2050/2060_w/oCarbonSink

CN2050/2060_w/oCarbonSink assumes that energy-related CO_2 emissions become net zero by 2060 and does not consider carbon sinks (Figures 3.21–3.31).

2.1. Primary Energy Supply

Figure 3.21 shows the primary energy supply in Baseline and CN2050/2060_w/oCarbonSink. Primary energy supply in 2060 substantially increases by 3.2 times in CN2050/2060_w/oCarbonSink. The share of a broad range of technologies, e.g. renewable energy, nuclear, CCS, and H_2 and NH_3 imports, goes up to 65% of the primary energy supply in 2060.

Figure 3.21. Primary Energy Supply in ASEAN (CN2050/2060_w/oCarbonSink)

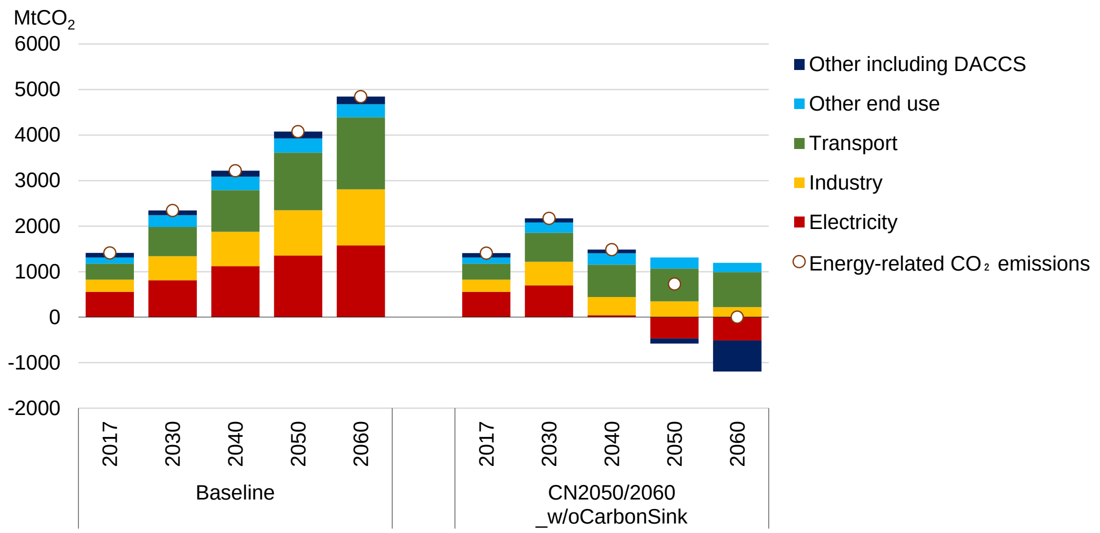


Mtoe = million tonnes of oil equivalent.
Source: Author.

2.2. Sector Carbon Dioxide Emissions

Figure 3.22 illustrates sector CO_2 emissions in Baseline and CN2050/2060_w/oCarbonSink. In CN2050/2060_w/oCarbonSink and CN2050/2060, CO_2 emissions from transport, particularly buses and trucks, remain whilst power is fully decarbonised by 2050. CN2050/2060_w/oCarbonSink does not consider carbon sinks; therefore, negative-emission technologies such as BECCS and DACCS contribute more than in CN2050/2060.

Figure 3.22. Sector Energy-related Carbon Dioxide Emissions in ASEAN (CN2050/2060_w/oCarbonSink)

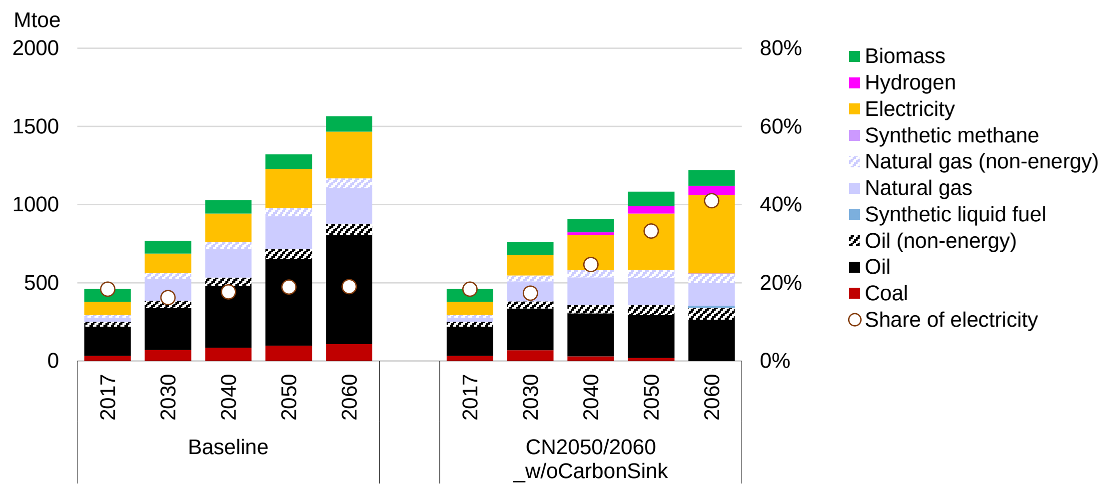


CO_2 = carbon dioxide, DACCS = direct air capture with carbon storage, MtCO2 = million tonnes of carbon dioxide.
Source: Author.

2.3. Final Energy Consumption

Figure 3.23 shows final energy consumption in Baseline and CN2050/2060_w/oCarbonSink. Final energy consumption in 2060 decreases by 22% in CN2050/2060_w/oCarbonSink, more than in other cases, such as CN2050/2060 and CN2050/2060_Stringent2030. In CN2050/2060_w/oCarbonSink, the share of electricity increases to 41% by 2060.

Figure 3.23. Final Energy Consumption in ASEAN (CN2050/2060_w/oCarbonSink)

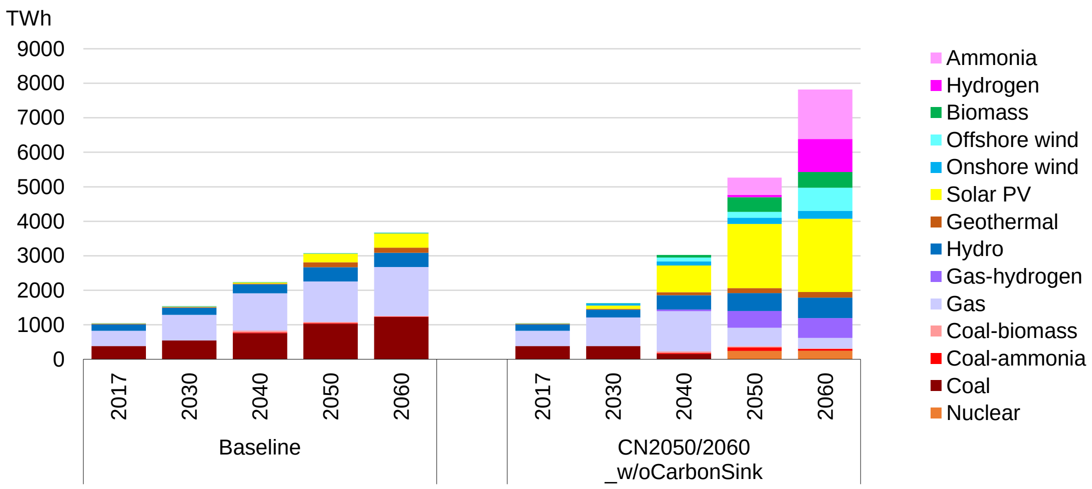


Mtoe = million tonnes of oil equivalent.
Source: Author.

2.4. Power Generation

Figure 3.24 illustrates power generation in Baseline and CN2050/2060_w/oCarbonSink. In CN2050/2060_w/oCarbonSink and other cases, renewable energy is a major power source, accounting for 54% in 2060. H_2- and NH_3-fired power generation account for 31%. The share of solar PV power generation is 50% of electricity generation from renewables.

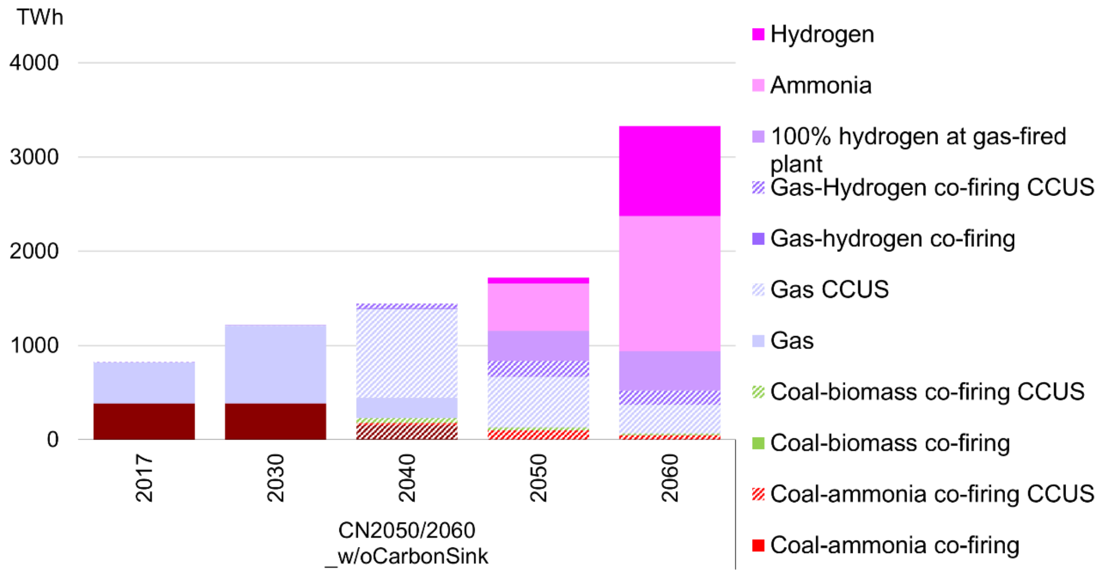
Figure 3.24. Power Generation in ASEAN (CN2050/2060_w/oCarbonSink)



PV = photovoltaic, TWh = terawatt-hour.
Source: Author.

H_2 and NH_3, including co-firing, play roles in the electricity mix in CN2050/2060_w/oCarbonSink. CN2050/2060 and CN2050/2060_w/oCarbonSink do not show significant differences in the transition of thermal power generation technologies after 2030. The amount of electricity by thermal power generation in 2060 increases 22% compared with CN2050/2060 and the introduction of H_2-fired power generation progresses.

Figure 3.25. Generated Electricity from Coal, Gas, Ammonia, and Hydrogen in ASEAN (CN2050/2060_w/oCarbonSink)

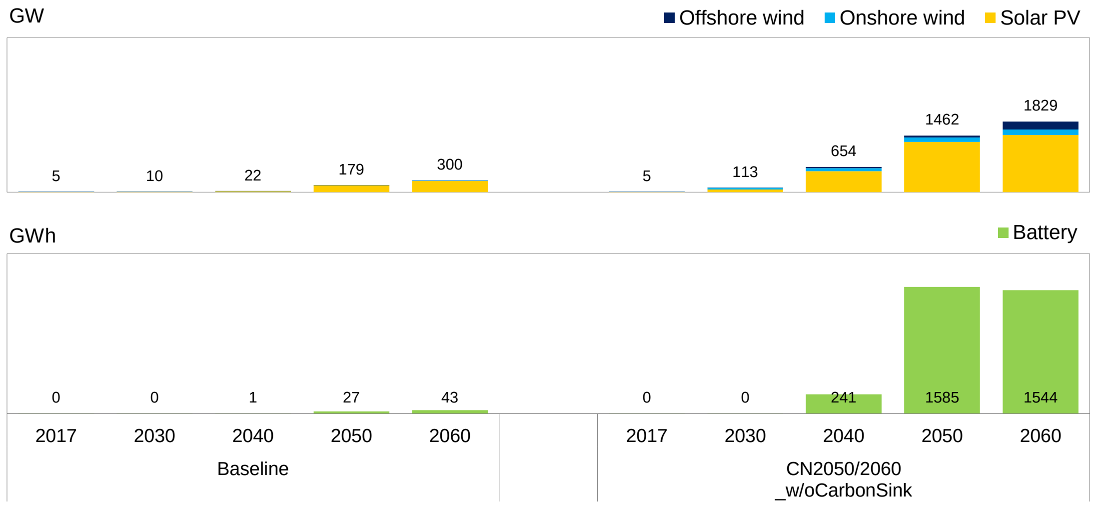


CCUS = carbon dioxide capture, utilisation, and storage; TWh = terawatt-hour.
Source: Author.

2.5. Variable Renewable Energy and Battery

Variable renewable energy (VRE), such as solar PV and wind power, is expected to be deployed in CN2050/2060_w/oCarbonSink. The installed capacity of solar PV power generation is estimated to account for a large share and that of all VRE is about 1,829 GW by 2060.

Figure 3.26. Variable Renewable Energy and Battery Capacity in ASEAN (CN2050/2060_w/oCarbonSink)

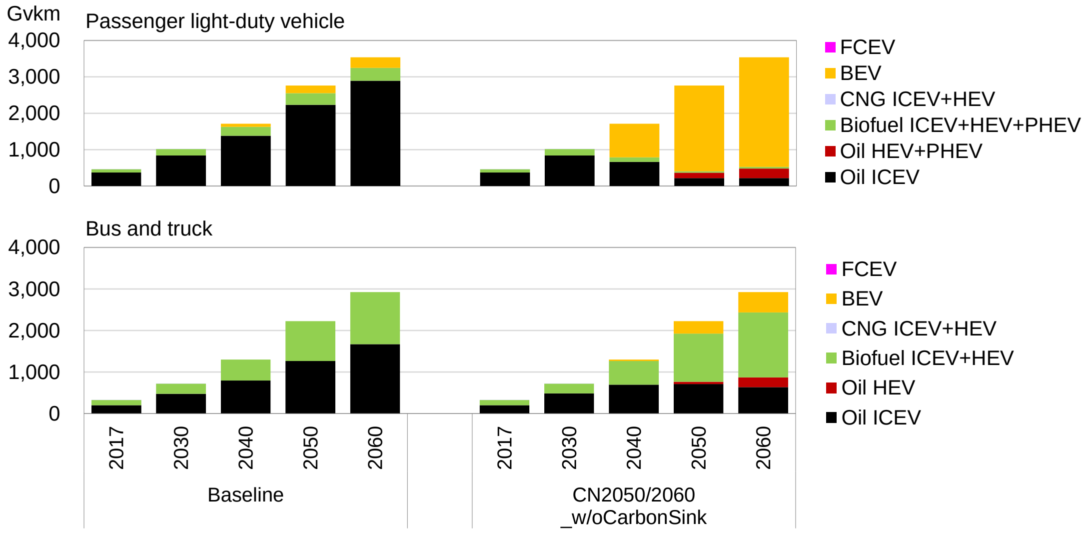


GW = gigawatt, GWh = gigawatt-hour, PV = photovoltaic.
Source: Author.

2.6. Road Transport

Figure 3.27 shows passenger light-duty vehicles in the upper graph, and buses and trucks in the lower graph. In CN2050/2060_w/oCarbonSink, a major share of passenger vehicles are electrified by 2050. Comparing CN2050/2060 and CN2050/2060_w/oCarbonSink, the share of battery electric vehicles increases and that of biofuels decreases in long-distance transport. Oil consumption is expected to remain until 2060 in buses and trucks.

Figure 3.27. Travel Distance by Vehicle Technology in ASEAN (CN2050/2060_w/oCarbonSink)



BEV = battery electric vehicle, CNG = compressed natural gas, FCEV = fuel cell electric vehicle, HEV = hybrid electric vehicle, ICEV = internal combustion engine vehicle, Gvkm = 10^9 vehicle-km, PHEV = plug-in hybrid electric vehicle.

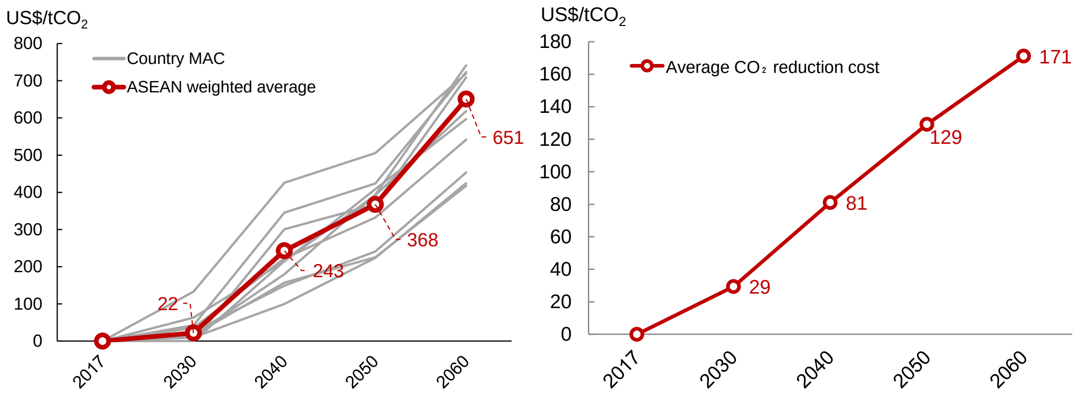
Note: Biofuel includes bioethanol and biodiesel mixed with petroleum fuel.

Source: Author.

2.7. Costs of Reducing Carbon Dioxide and Energy Prices

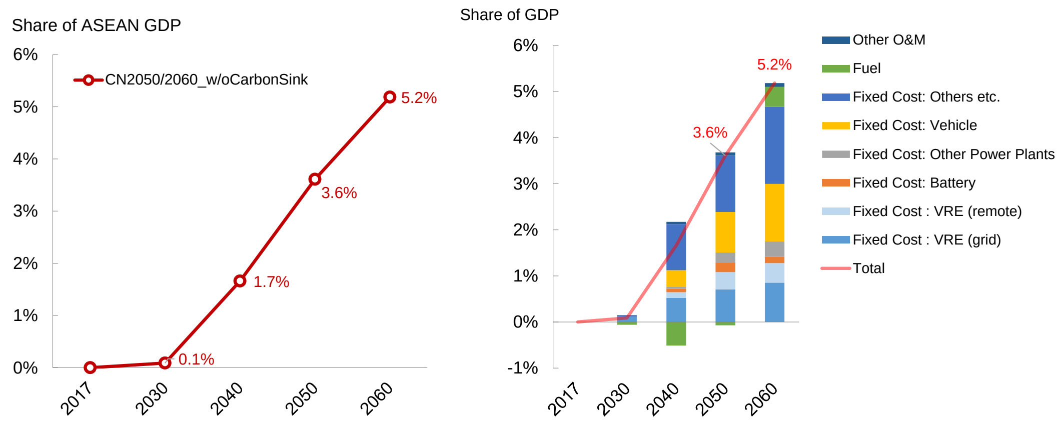
In CN2050/2060_w/oCarbonSink, the MAC rises sharply from 2050 to US$651/t$CO_2$ in 2060, implying a major economic challenge to decarbonisation. Increase in the MAC is derived from more stringent constraints on CO_2 emissions from 2050 to 2060. The additional annual cost in CN2050/2060_w/oCarbonSink compared with Baseline is estimated at about 5.2% (US$0.83 trillion) of ASEAN's GDP in 2060.

Figure 3.28. Marginal Carbon Dioxide Abatement Cost (Left), Average Carbon Dioxide Reduction Cost (Right) (CN2050/2060_w/oCarbonSink)



CO_2 = carbon dioxide, MAC = marginal carbon dioxide abatement cost, tCO_2 = tonne of carbon dioxide.
Source: Author.

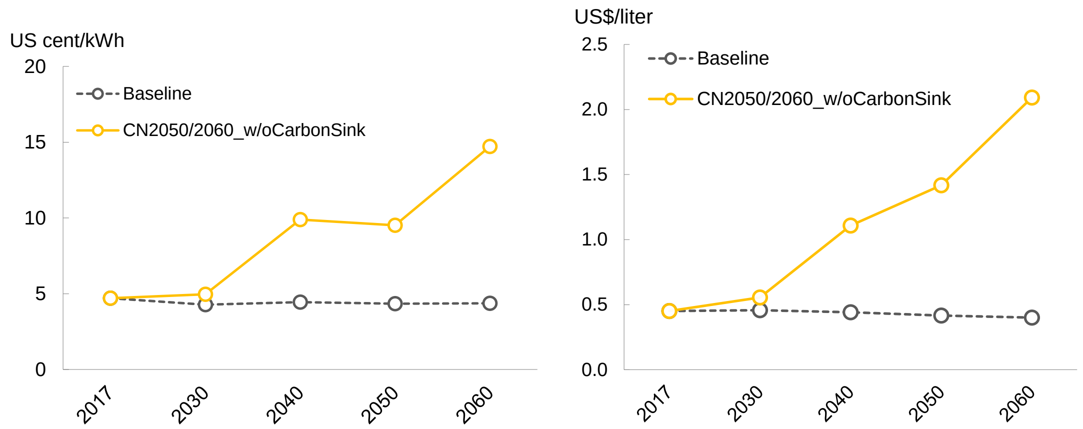
Figure 3.29. Additional Annual Cost (Left), Composition of Additional Annual Cost (Right) (CN2050/2060_w/oCarbonSink)



GDP = gross domestic product, O&M = operation and maintenance, VRE = variable renewable energy.
Source: Author.

Electricity and diesel prices are estimated to rise two- to five-fold in CN2050/2060_w/oCarbonSink.

Figure 3.30. Electricity Price (Left), Diesel End-use Price (Right) (CN2050/2060_w/oCarbonSink)

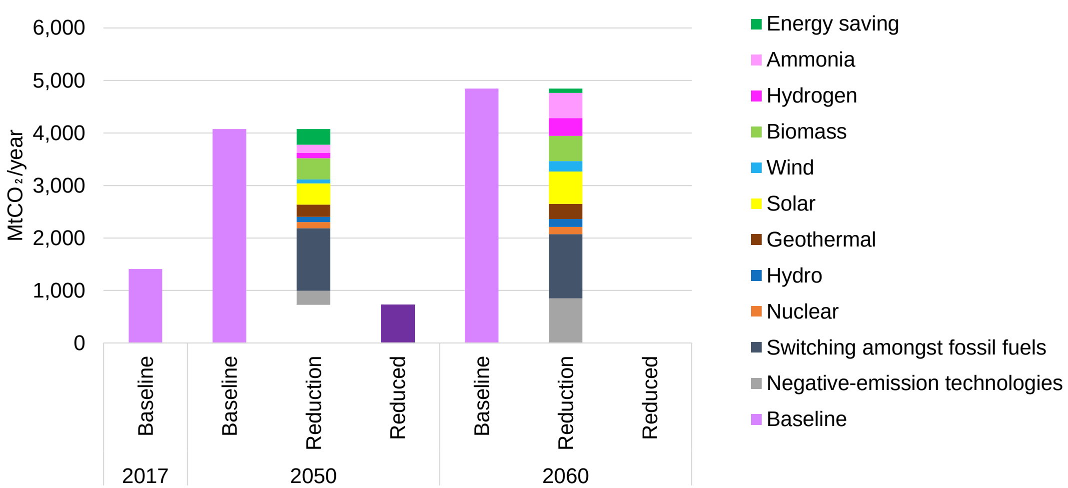


Source: Author.

2.8. Contribution of Mitigation Measures

Figure 3.31 shows the contribution of technology to the reduction of energy-related CO_2 emissions in CN2050/2060_w/oCarbonSink.

Figure 3.31. Contribution of Mitigation Measures (CN2050/2060_w/oCarbonSink)



$MtCO_2$ = million tonnes of carbon dioxide.
Source: Author.

Chapter 4
Conclusions

Using an optimal technology selection model, the study estimated the cost-optimal deployment of energy technologies to achieve carbon neutrality in ASEAN countries around 2060. The results of the analyses indicate the following:

First, energy efficiency and electrification in the end-use sector can be a core strategy to decarbonise ASEAN's energy systems when combined with 'decarbonised' power sources. Given VRE potential in the ASEAN region, the development of solar PV power generation plays a major role in the region's decarbonisation. Not only VRE but also other carbon-free technologies, such as hydro, geothermal, biomass, and nuclear power, however, contribute to carbon neutrality. Therefore, power sources should be decarbonised by combining multiple technologies. Whilst energy demand in the region is expected to steadily grow, progress in end-use energy efficiency and electrification is crucial for deeper decarbonisation. In addition to the supply of CO_2-free H_2, CCS and negative-emission technologies are essential to achieve carbon neutrality. Even if the technologies are still highly expensive, they will become widely used in the long term as technological innovation reduces their cost. Various decarbonisation technologies must be used in cooperation with developed countries. Solar PV potential that comes from GIS data is considered as the upper limit of deployment in the study. The study considers system integration costs such as the cost for a electricity storage system, curtailment of output, and grid interconnections, and the levelised cost of electricity. Therefore, expanding the capacity of storage batteries by halving their cost from the current level and developing grid interconnections will lead to breakthroughs. Research and development and international collaboration are key to accelerating the pace towards carbon neutrality (chapter 3).

Second, during the energy transition period, various *low-carbon* technologies can reduce CO_2 emissions. The analysis results showed that the transition from coal- to natural gas–fired power generation, introduction of more efficient turbines, co-firing with H_2 or NH_3, and fossil fuel–fired power generation with CCS can contribute to a deep decarbonisation pathway in the power sector. The ASEAN region has many old and new coal- and gas-fired power plants in operation. In the medium term, affordable low-carbon technologies will likely be introduced. Introducing low-carbon technologies and effectively utilising existing facilities make possible decarbonising whilst moderating the economic burden on end users. The final stage of achieving carbon neutrality requires introducing more expensive decarbonisation technologies. However, the effective use of low-carbon technologies during the transition period leads to steady reduction of CO_2 emissions.

Third, the study's analysis results suggest major economic challenges for decarbonisation. Mitigation costs and energy prices increase in CN2050/2060, CN2050/2060_Stringent2030, and CN2050/2060_w/oCarbonSink. Although costs of decarbonisation technologies are expected to be reduced, policymakers need to consider how to minimise the economic impacts of decarbonisation on end users.

Fourth, cost reduction and international cooperation are key to achieving carbon neutrality affordably. More expensive decarbonisation technologies must be introduced at the final stage. To develop and deploy still-expensive decarbonisation technologies, costs must be reduced through technological innovation and economies of scale. Regional cooperation, such as enhancing grid interconnections, contributes to more efficient deployment of low-carbon technologies, including VRE. Research and development on low-carbon technologies in cooperation with developed countries is important to achieve carbon neutrality in the long term.

The analysis simulates the cost-optimal deployment of energy technologies. However, the feasibility of energy technologies is uncertain. To achieve the ambitious goal of carbon neutrality, steadily reducing CO_2 emissions and efficiently utilising limited policy resources are pivotal. More cost-effective technologies must be supported after thoroughly examining multiple technology options instead of pursuing a particular technology. The efforts towards carbon neutrality in ASEAN have just begun. The analysis results will, it is hoped, serve as a reference for ASEAN countries in considering the direction of their energy transition.

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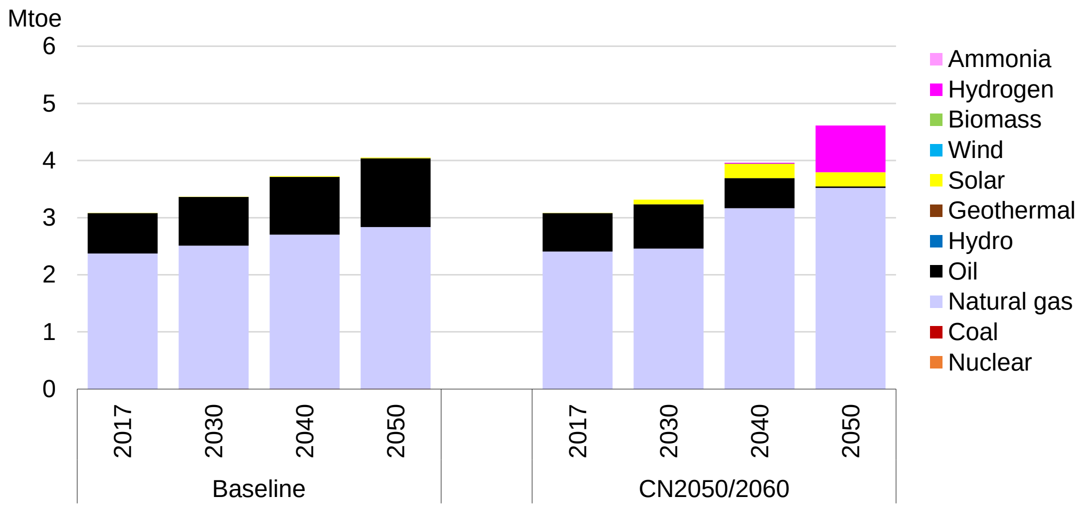
Appendix

1. Brunei Darussalam

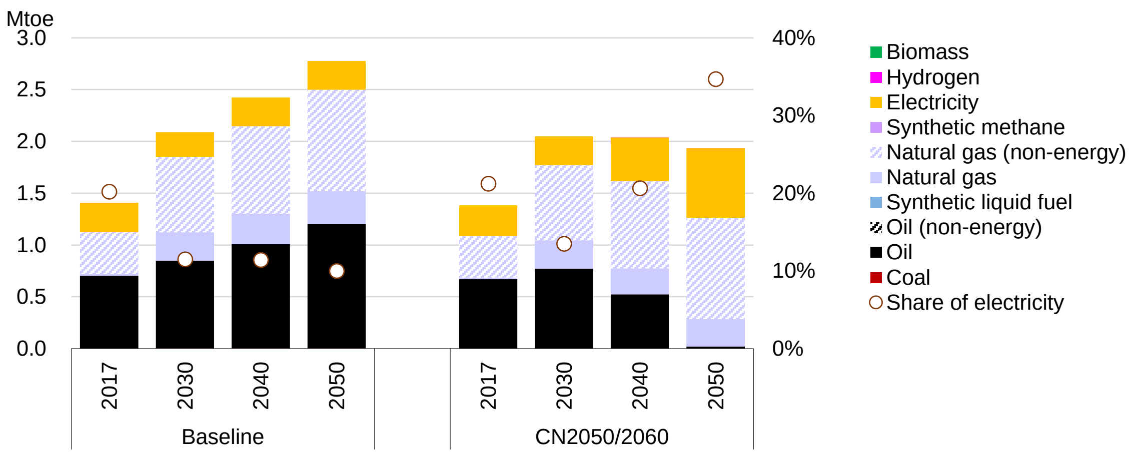
(a) CN2050/2060

Figure A.1. Primary Energy Supply (BRN-CN2050/2060)



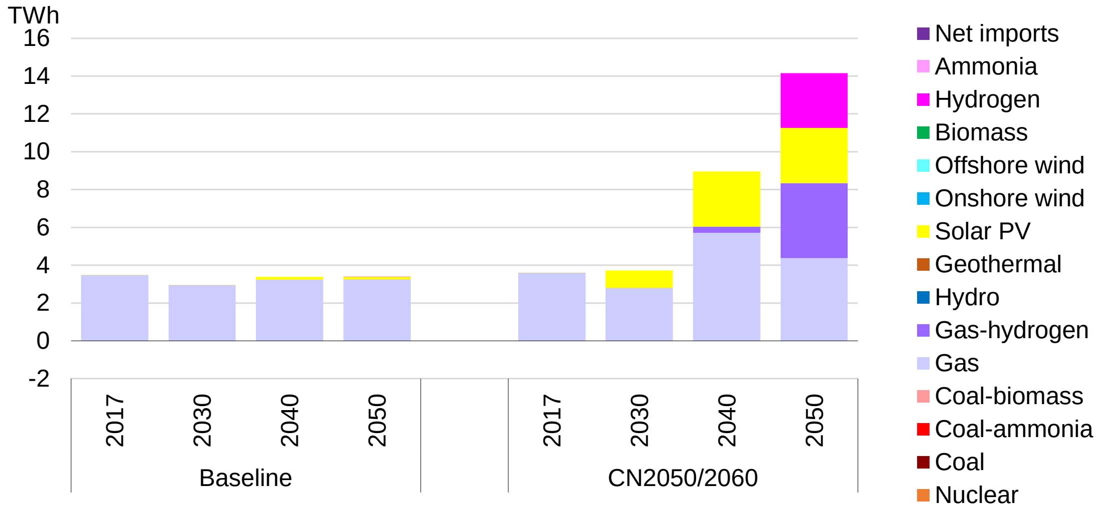
BRN = Brunei Darussalam, Mtoe = million tonnes of oil equivalent.
Source: Author.

Figure A.2. Final Energy Consumption (BRN-CN2050/2060)



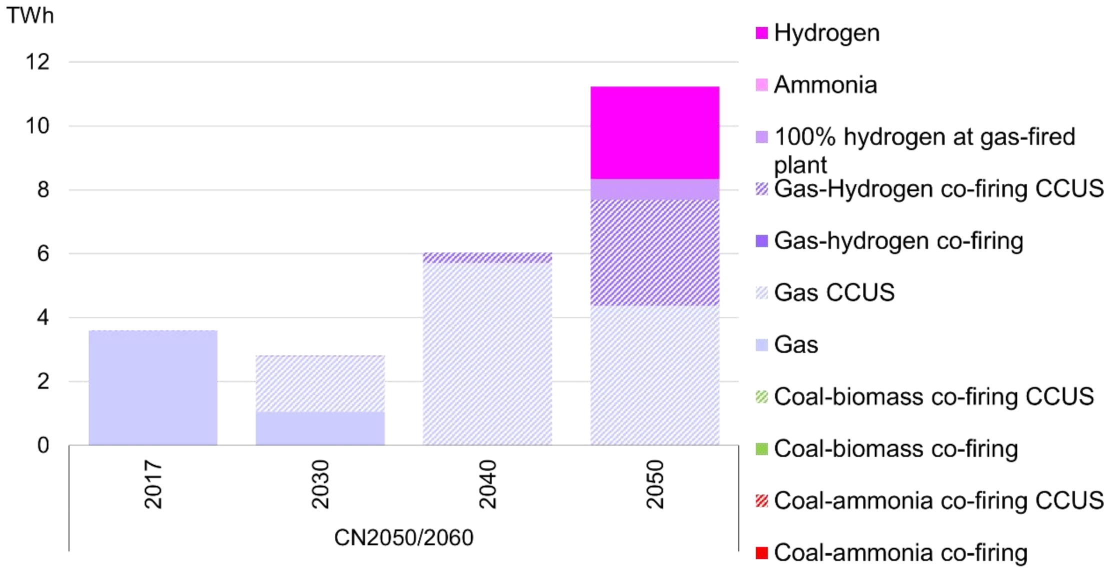
BRN = Brunei Darussalam, Mtoe = million tonnes of oil equivalent.
Source: Author.

Figure A.3. Power Generation (BRN-CN2050/2060)



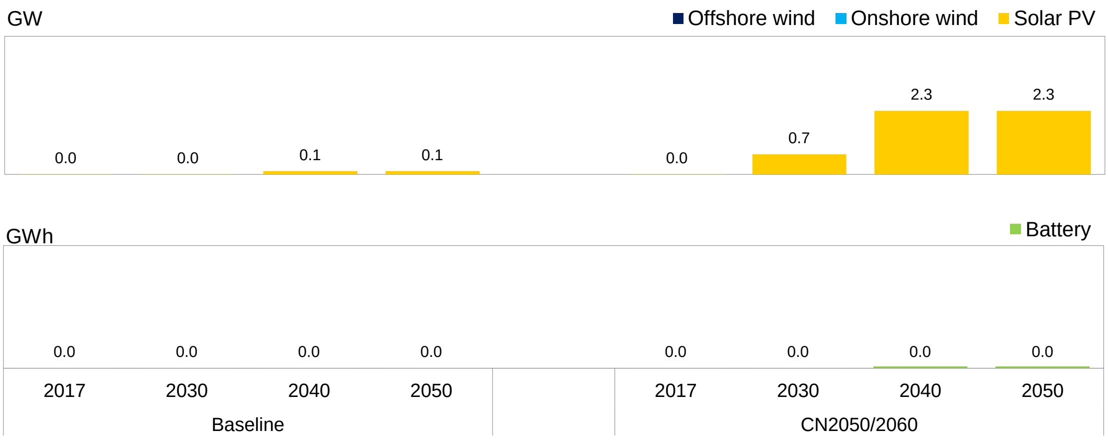
BRN = Brunei Darussalam, PV = photovoltaic, TWh = terawatt-hour.
Source: Author.

Figure A.4. Generated Electricity from Coal, Gas, Ammonia, and Hydrogen (BRN-CN2050/2060)



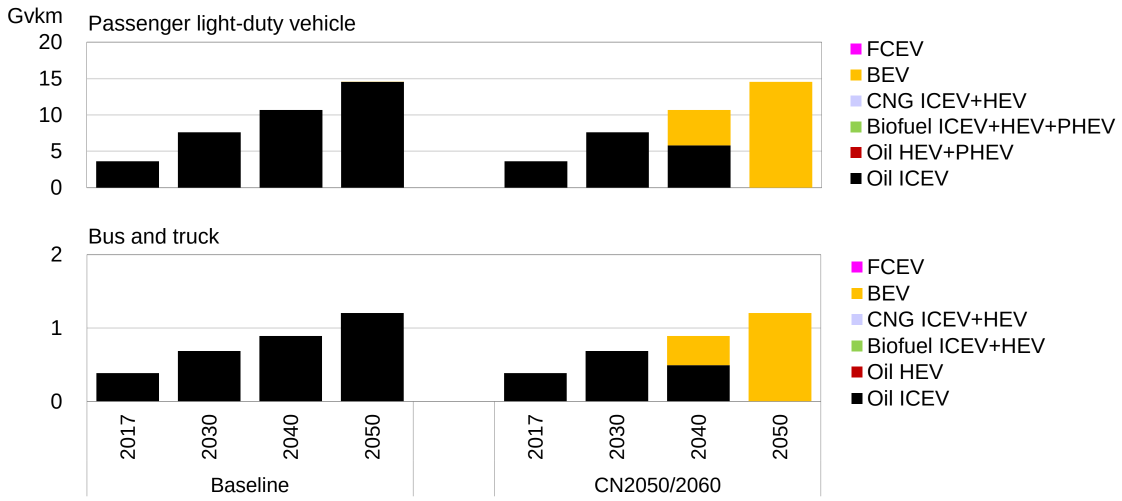
BRN = Brunei Darussalam; CCUS = carbon dioxide capture, utilisation, and storage; TWh = terawatt-hour.
Source: Author.

Figure A.5. Variable Renewable Energy and Battery (BRN-CN2050/2060)



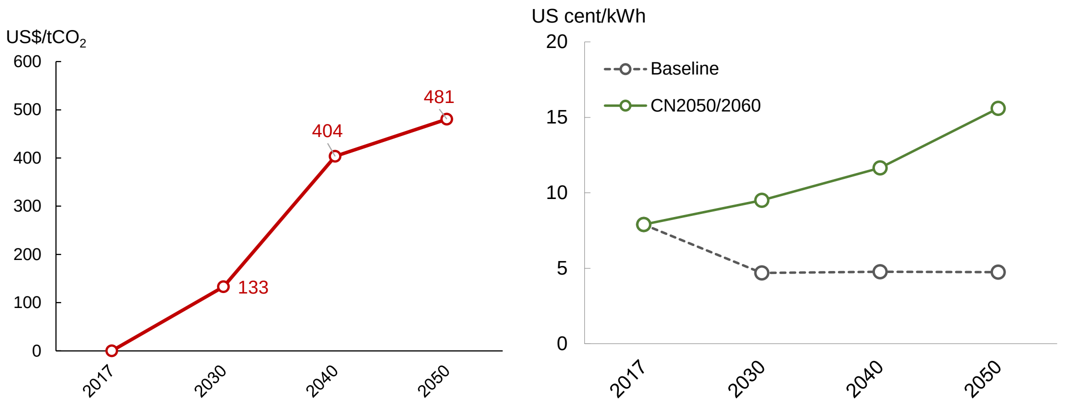
BRN = Brunei Darussalam, GW = gigawatt, GWh = gigawatt-hour, PV = photovoltaic.
Source: Author.

Figure A.6. Travel Distance by Vehicle Technology (BRN-CN2050/2060)



BEV = battery electric vehicle, BRN = Brunei Darussalam, CNG = compressed natural gas, FCEV = fuel cell electric vehicle, HEV = hybrid electric vehicle, ICEV = internal combustion engine vehicle, Gvkm = 10^9 vehicle-km, PHEV = plug-in hybrid electric vehicle.
Source: Author.

Figure A.7. Marginal Carbon Dioxide Abatement Cost (Left), Electricity Price (Right) (BRN-CN2050/2060)



BRN = Brunei Darussalam, kWh = kilowatt-hour, tCO_2 = tonne of carbon dioxide.
Source: Author.

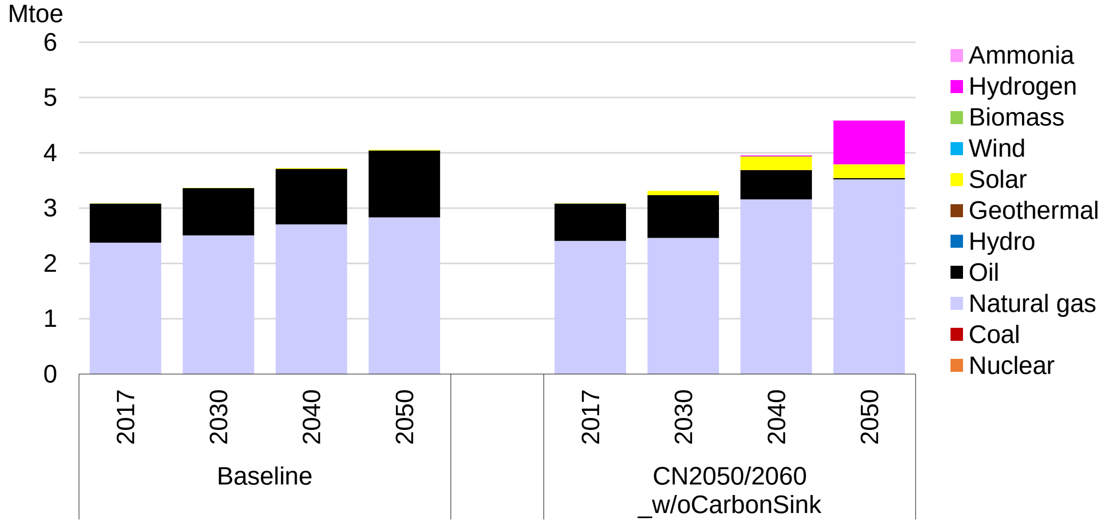
Table A.1. Carbon Dioxide Emission Baseline and with Carbon Sink Scenarios (BRN-CN2050/2060)

	Baseline ($MtCO_2$)					BRN-CN2050/2060 ($MtCO_2$)				
	2017	**2030**	**2040**	**2050**	**2060**	**2017**	**2030**	**2040**	**2050**	**2060**
Electricity	2.46	1.41	1.54	1.48	1.26	2.54	0.58	0.27	0.32	0.33
Industry	0.41	0.39	0.40	0.41	0.42	0.41	0.14	0.04	0.04	0.04
Transport	1.56	2.28	2.73	3.30	4.38	1.45	2.28	1.54	0.06	0.03
Other end use	0.17	0.50	0.55	0.59	0.66	0.17	0.50	0.55	0.58	0.64
Other including DACCS	2.14	2.14	2.14	2.14	2.14	2.14	2.14	0.42	-0.99	-1.04
LULUCF						0.00	0.00	0.00	0.00	0.00
Energy-related CO_2 emissions	6.73	6.72	7.37	7.93	8.85	6.71	5.64	2.82	0.00	0.00

BRN = Brunei Darussalam, $MtCO_2$ = Million tonne of carbon dioxide, DACCS = Direct Air Carbon Capture and Storage, LULUCF = land use, land-use change and forestry.
Source: Author.

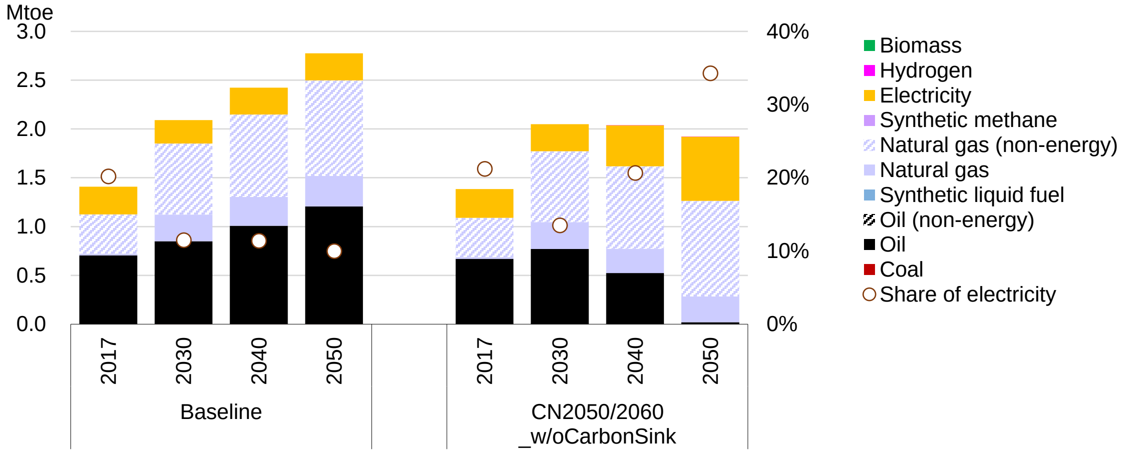
(b) CN2050/2060_w/oCarbonSink

Figure A.8. Primary Energy Supply (BRN-CN2050/2060_w/oCarbonSink)



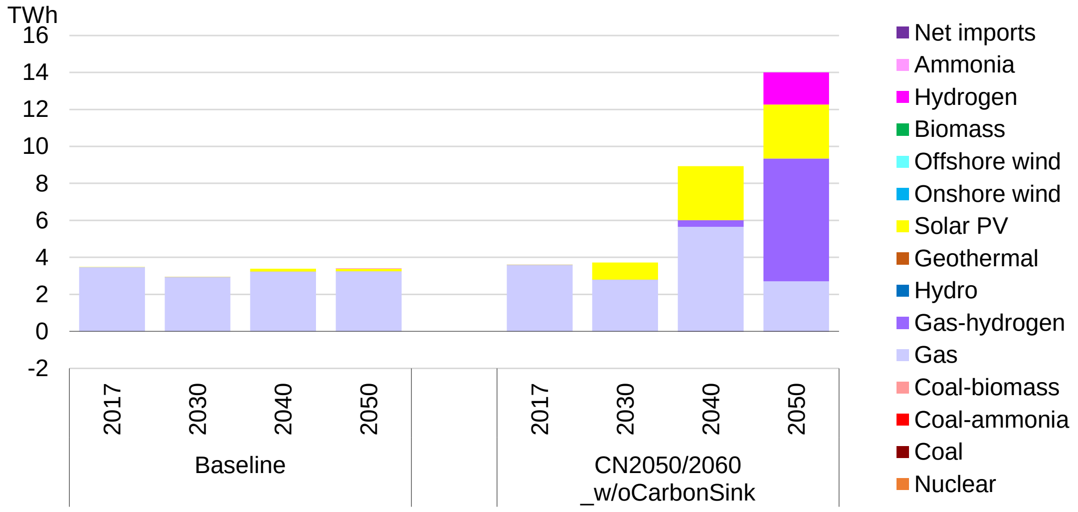
BRN = Brunei Darussalam, Mtoe = million tonnes of oil equivalent .
Source: Author.

Figure A.9. Final Energy Consumption (BRN-CN2050/2060_w/oCarbonSink)



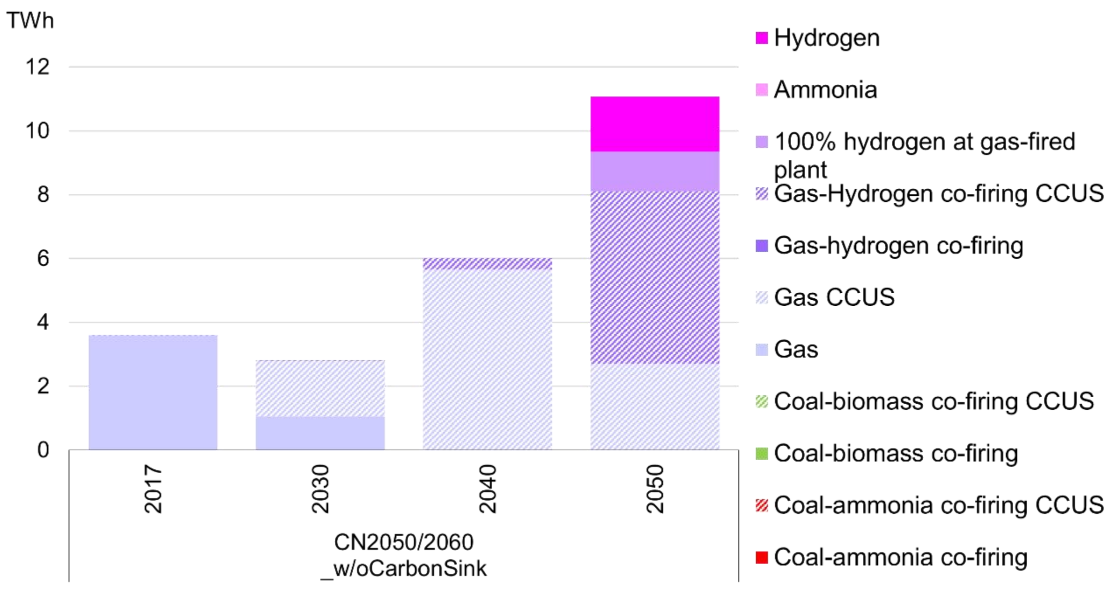
BRN = Brunei Darussalam, Mtoe = million tonnes of oil equivalent.
Source: Author.

Figure A.10. Power Generation (BRN-CN2050/2060_w/oCarbonSink)



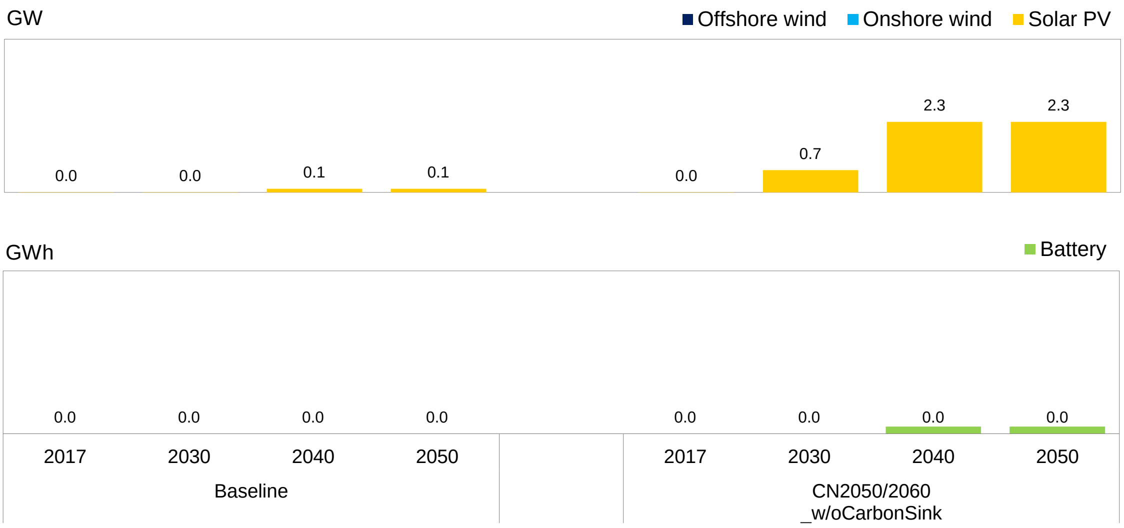
BRN = Brunei Darussalam, PV = photovoltaic, TWh = terawatt-hour.
Source: Author.

Figure A.11. Generated Electricity from Coal, Gas, Ammonia, and Hydrogen (BRN-CN2050/2060_w/oCarbonSink)



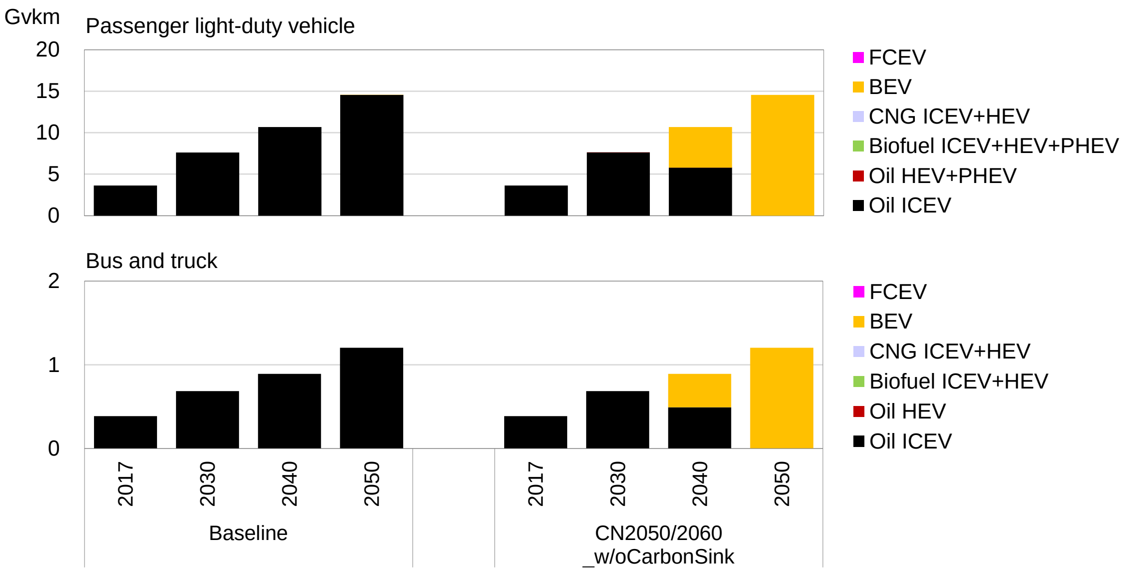
BRN = Brunei Darussalam; CCUS = carbon dioxide capture, utilisation, and storage; TWh = terawatt-hour.
Source: Author.

Figure A.12. Variable Renewable Energy and Battery (BRN-CN2050/2060_w/oCarbonSink)



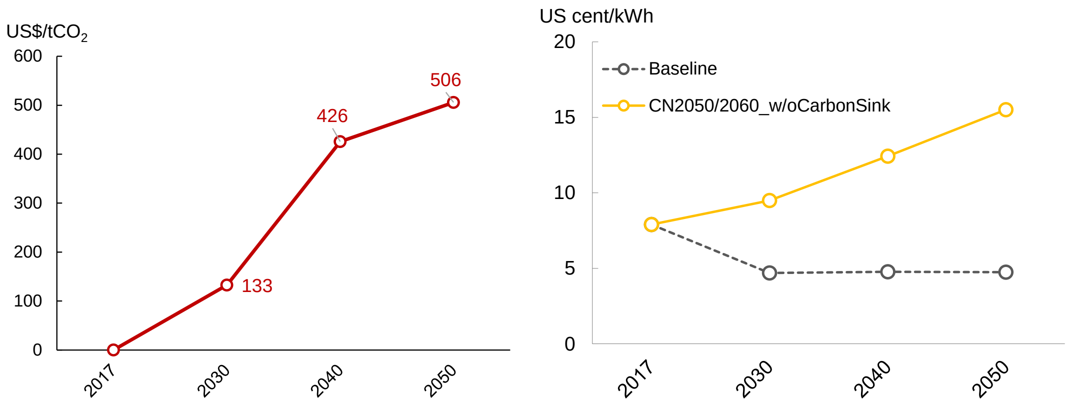
BRN = Brunei Darussalam, GW = gigawatt, GWh = gigawatt-hour, PV = photovoltaic.
Source: Author.

Figure A.13. Travel Distance by Vehicle Technology (BRN-CN2050/2060_w/oCarbonSink)



BEV = battery electric vehicle, BRN = Brunei Darussalam, CNG = compressed natural gas, FCEV = fuel cell electric vehicle, HEV = hybrid electric vehicle, ICEV = internal combustion engine vehicle, Gvkm = 10^9 vehicle-km, PHEV = plug-in hybrid electric vehicle.
Source: Author.

Figure A.14. Marginal Carbon Dioxide Abatement Cost (Left), Electricity Price (Right) (BRN-CN2050/2060_w/oCarbonSink)



BRN = Brunei Darussalam, KWh = kilowatt-hour, tCO_2 = tonne of carbon dioxide.
Source: Author.

Table A.2. Carbon Dioxide Emission Baseline and without Carbon Sink Scenarios (BRN-CN2050/2060_w/oCarbonSink)

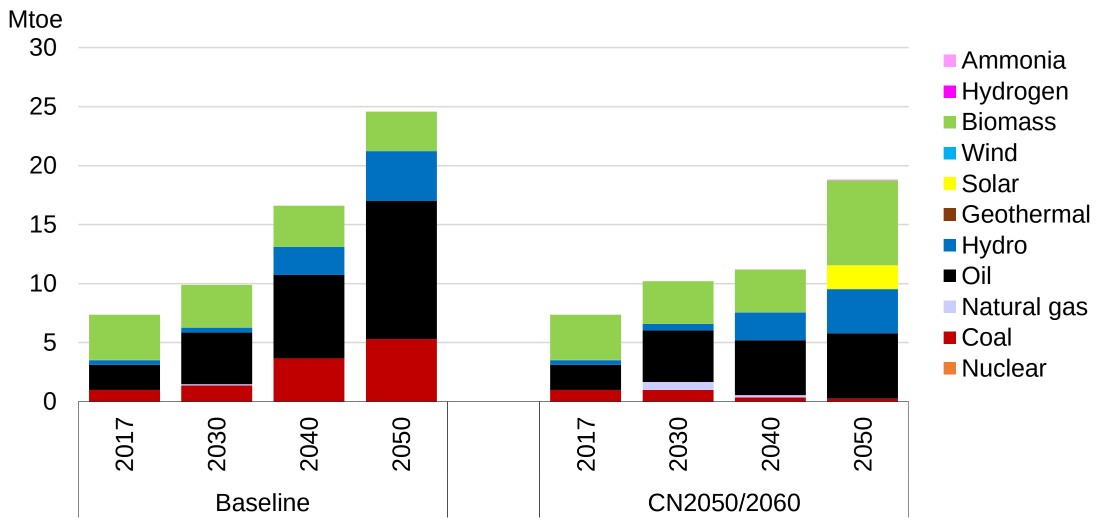
	Baseline ($MtCO_2$)					**BRN-CN2050/2060_w/oCarbonSink ($MtCO_2$)**				
	2017	**2030**	**2040**	**2050**	**2060**	**2017**	**2030**	**2040**	**2050**	**2060**
Electricity	2.46	1.41	1.54	1.48	1.26	2.54	0.58	0.27	0.32	0.24
Industry	0.41	0.39	0.40	0.41	0.42	0.41	0.14	0.04	0.04	0.08
Transport	1.56	2.28	2.73	3.30	4.38	1.45	2.28	1.54	0.06	0.03
Other end use	0.17	0.50	0.55	0.59	0.66	0.17	0.50	0.55	0.58	0.64
Other including DACCS	2.14	2.14	2.14	2.14	2.14	2.14	2.14	0.43	-0.99	-0.99
LULUCF										
Energy-related CO_2 emissions	6.73	6.72	7.37	7.93	8.85	6.71	5.64	2.82	0.00	0.00

BRN = Brunei Darussalam, $MtCO_2$ = Million tonne of carbon dioxide, DACCS = Direct Air Carbon Capture and Storage, LULUCF = land use, land-use change and forestry.
Source: Author.

2. Cambodia

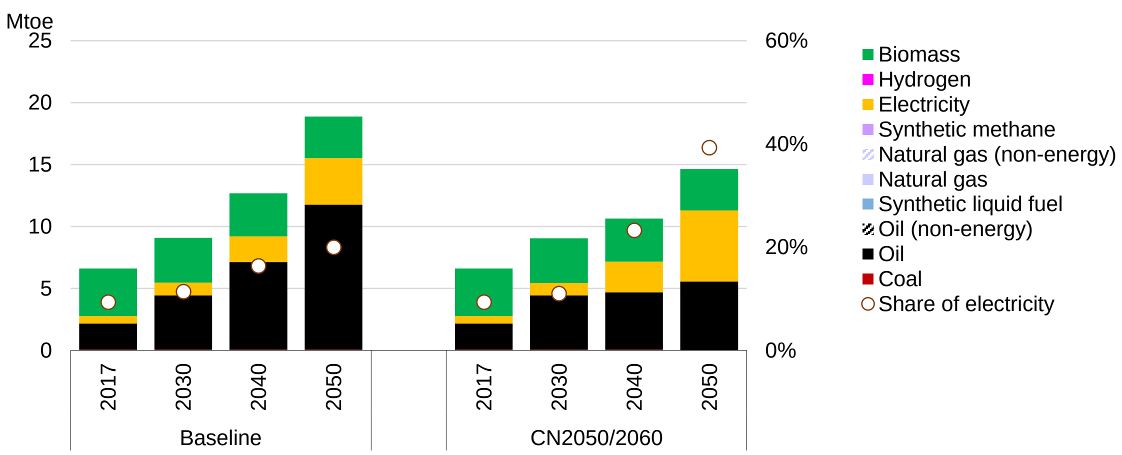
(a) CN2050/2060

Figure A.15. Primary energy supply (KHM-CN2050/2060)



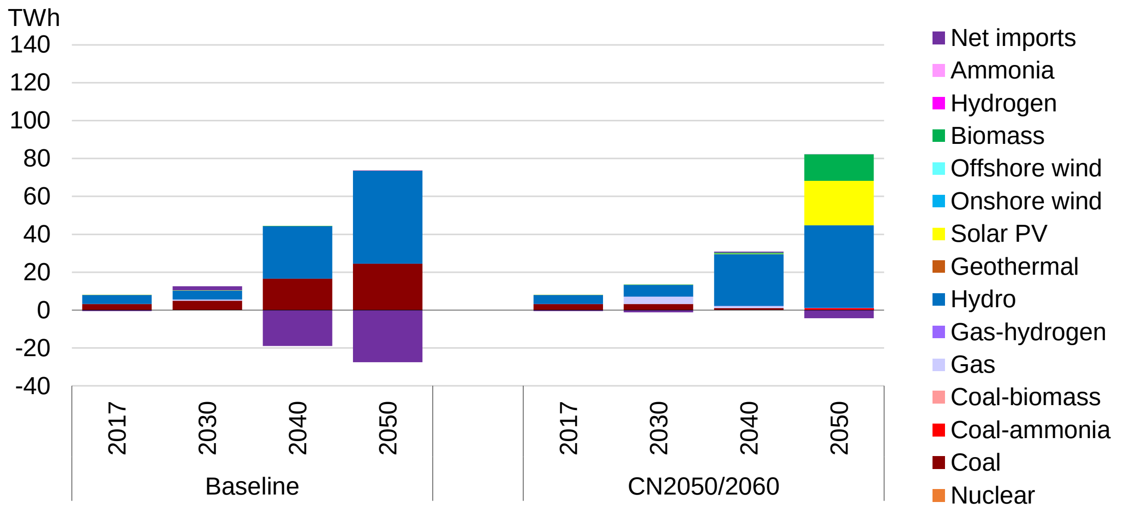
KHM = Cambodia.
Source: Author.

Figure A.16. Final Energy Consumption (KHM-CN2050/2060)



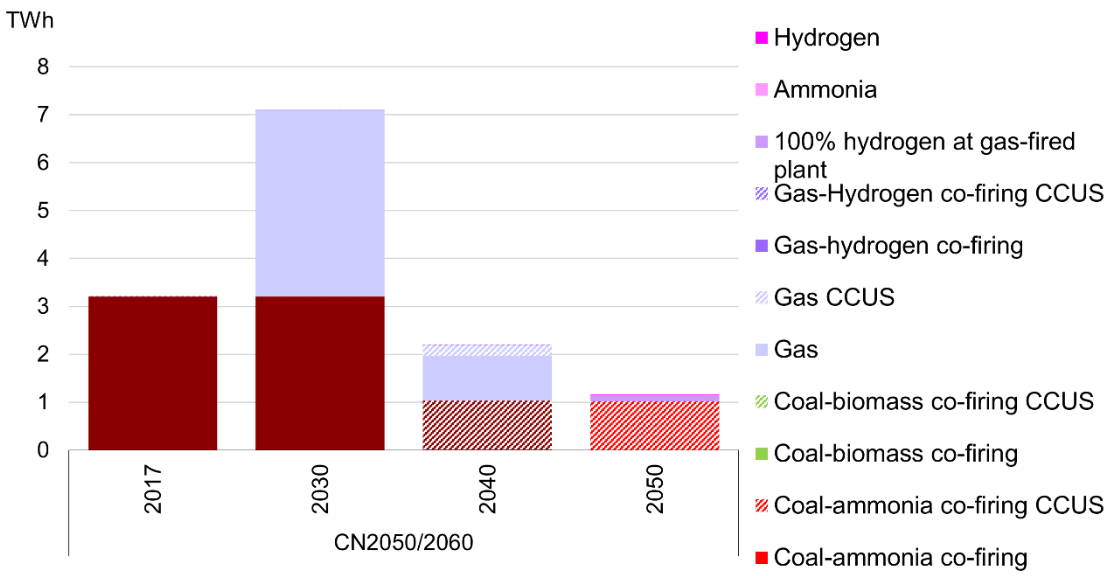
KHM = Cambodia, Mtoe = million tonnes of oil equivalent.
Source: Author.

Figure A.17. Power Generation (KHM-CN2050/2060)



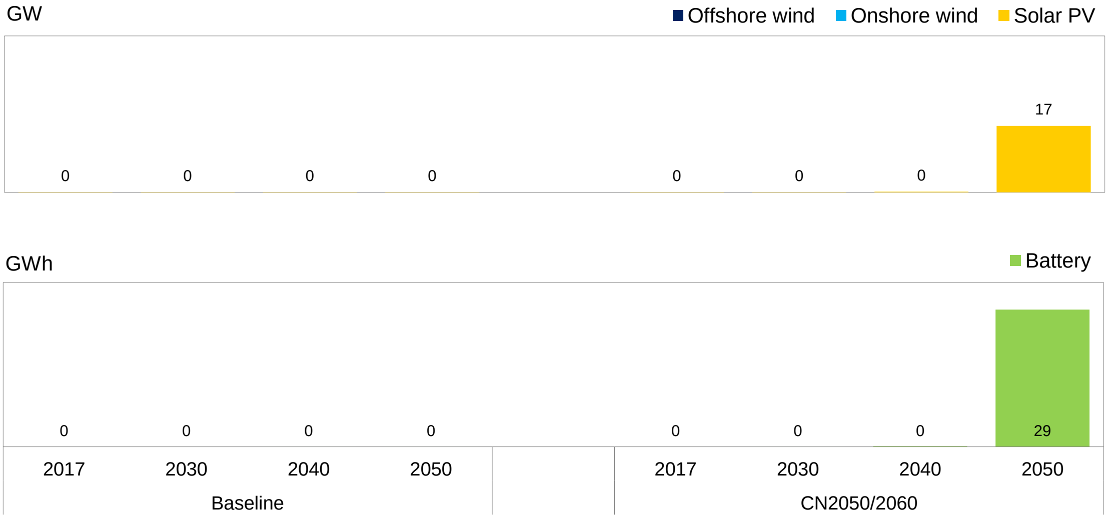
KHM = Cambodia, PV = photovoltaic, TWh = terawatt-hour.
Source: Author.

Figure A.18. Generated Electricity from Coal, Gas, Ammonia, and Hydrogen (KHM-CN2050/2060)



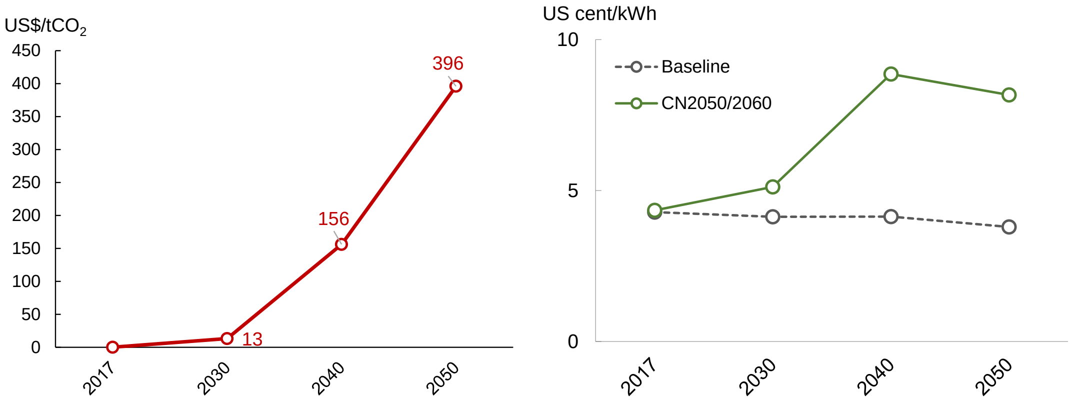
CCUS = carbon dioxide capture, utilisation, and storage; KHM = Cambodia; TWh = terawatt-hour.
Source: Author.

Figure A.19. Variable Renewable Energy and Battery (KHM-CN2050/2060)



GW = gigawatt, GWh = gigawatt-hour, KHM = Cambodia, PV = photovoltaic.
Source: Author.

Figure A.20. Marginal Carbon Dioxide Abatement Cost (Left), Electricity Price (Right) (KHM-CN2050/2060)



KHM = Cambodia, kWh = kilowatt-hour, tCO_2 = tonne of carbon dioxide.
Source: Author.

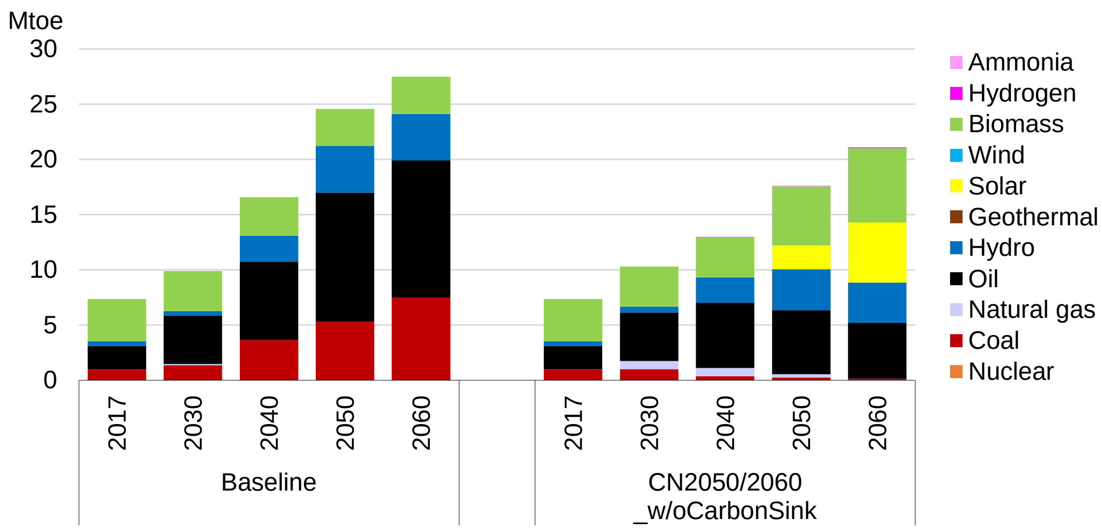
Table A.3. Carbon Dioxide Emission Baseline and with Carbon Sink Scenarios (KHM-CN2050/2060)

	Baseline ($MtCO_2$)					KHM-CN2050/2060 ($MtCO_2$)				
	2017	**2030**	**2040**	**2050**	**2060**	**2017**	**2030**	**2040**	**2050**	**2060**
Electricity	3.77	5.47	14.28	20.79	29.38	3.77	5.31	-0.15	-16.16	-15.99
Industry	0.62	4.02	10.10	21.48	25.15	0.62	3.99	1.84	4.22	5.23
Transport	5.42	8.09	9.25	10.47	8.43	5.42	8.09	9.25	10.39	8.43
Other end use	0.55	1.65	2.88	4.88	5.67	0.55	1.65	2.88	1.55	2.33
Other including DACCS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LULUCF						0.00	0.00	0.00	0.00	0.00
Energy-related CO_2 emissions	10.37	19.23	36.51	57.61	68.64	10.37	19.04	13.81	0.00	0.00

KHM = Cambodia, $MtCO_2$ = Million tonne of carbon dioxide, DACCS = Direct Air Carbon Capture and Storage, LULUCF = land use, land-use change and forestry.
Source: Author.

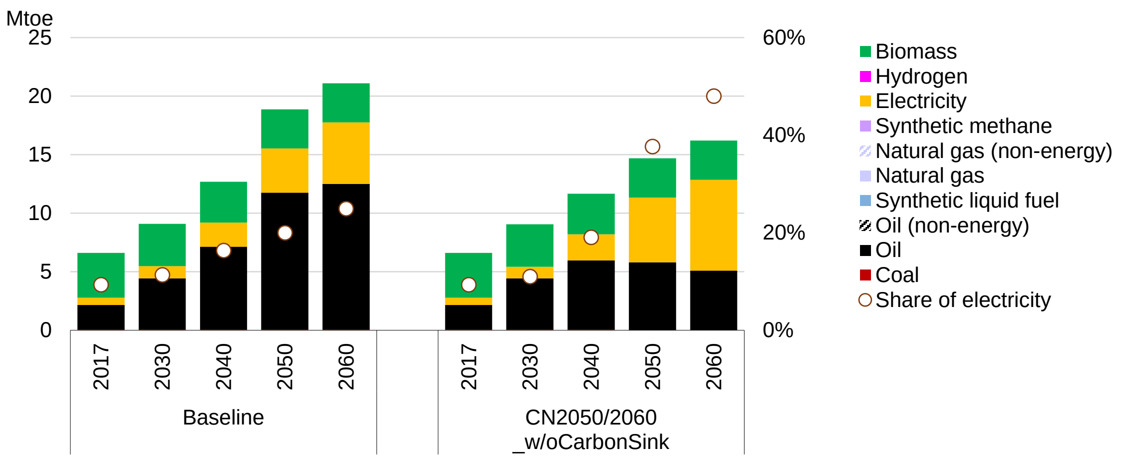
(b) CN2050/2060_w/oCarbonSink

Figure A.21. Primary Energy Supply (KHM-CN2050/2060_w/oCarbonSink)



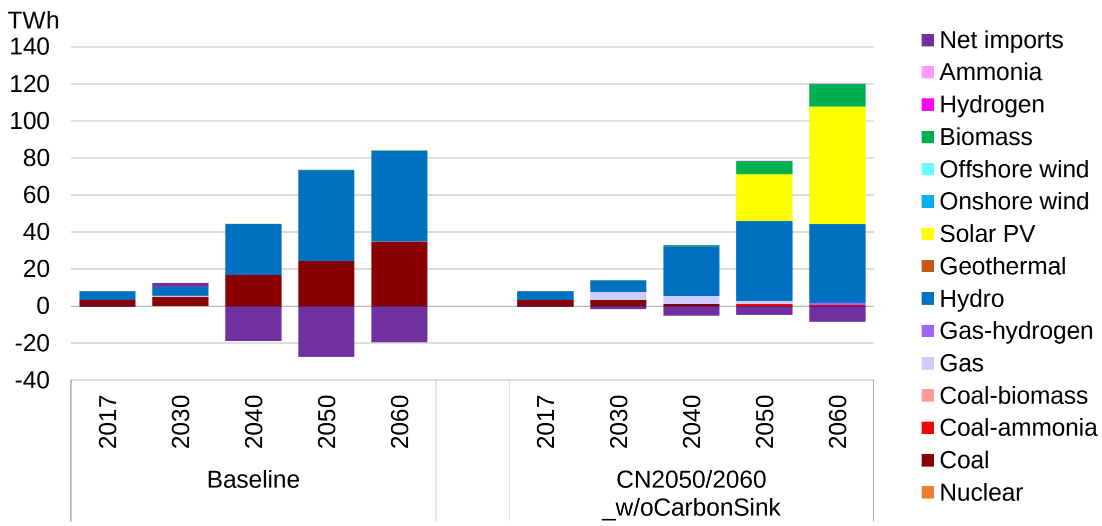
KHM = Cambodia, Mtoe = million tonnes of oil equivalent.
Source: Author.

Figure A.22. Final Energy Consumption (KHM-CN2050/2060_w/oCarbonSink)



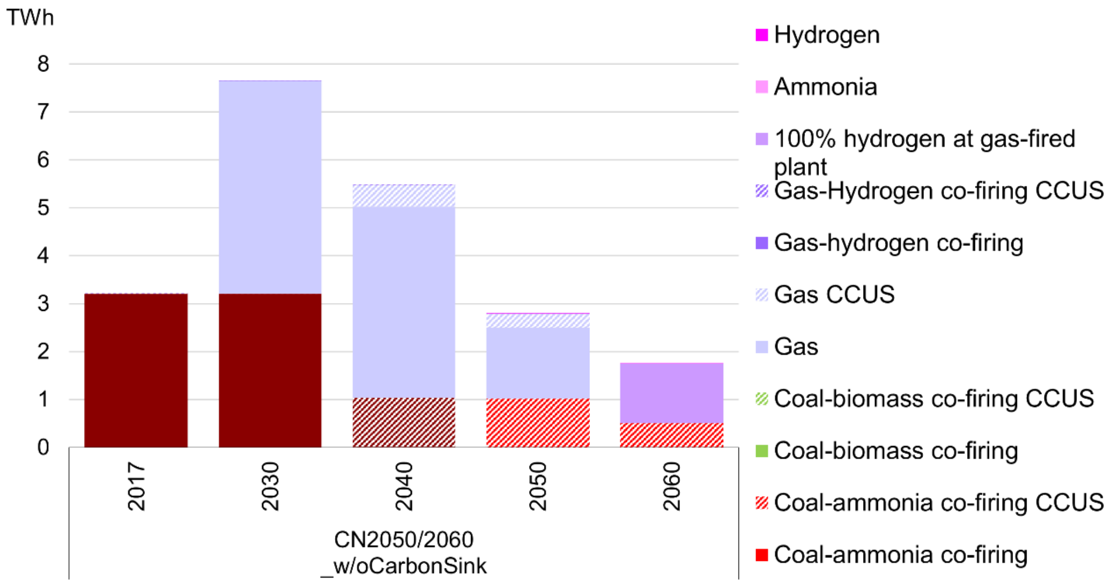
KHM = Cambodia, Mtoe = million tonnes of oil equivalent.
Source: Author.

Figure A.23. Power Generation (KHM-CN2050/2060_w/oCarbonSink)



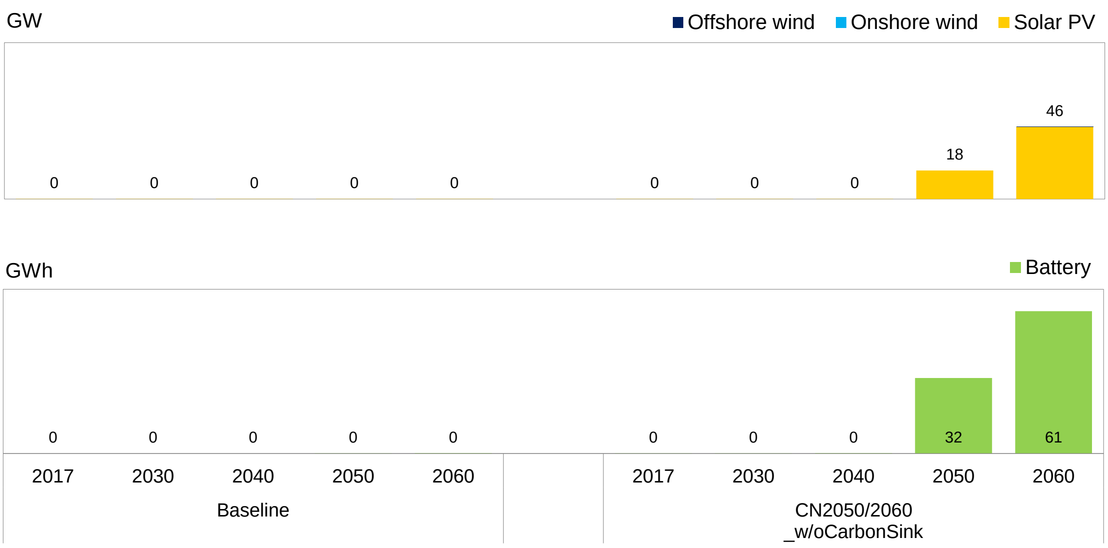
KHM = Cambodia, PV = photovoltaic, TWh = terawatt-hour.
Source: Author.

Figure A.24. Generated Electricity from Coal, Gas, Ammonia, and Hydrogen (KHM-CN2050/2060_w/oCarbonSink)



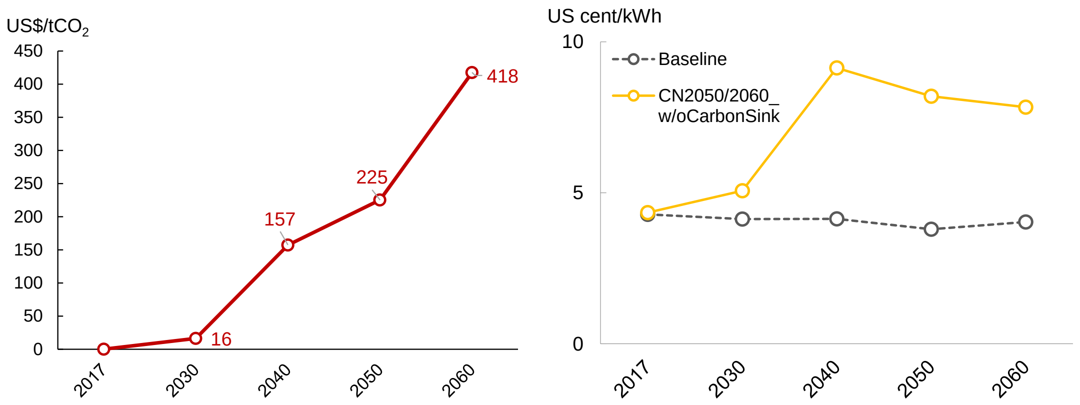
CCUS = carbon dioxide capture, utilisation, and storage; KHM = Cambodia; TWh = terawatt-hour.
Source: Author.

Figure A.25. Variable Renewable Energy and Battery (KHM-CN2050/2060_w/oCarbonSink)



GW = gigawatt, GWh = gigawatt-hour, KHM = Cambodia, PV = photovoltaic.
Source: Author.

Figure A.26. Marginal Carbon Dioxide Abatement Cost (Left), Electricity Price (Right) (KHM-CN2050/2060_w/oCarbonSink)



KHM = Cambodia, tCO_2 = tonne of carbon dioxide.
Source: Author.

Table A.4. Carbon Dioxide Emission Baseline and without Carbon Sink Scenarios (KHM-CN2050/2060_w/oCarbonSink)

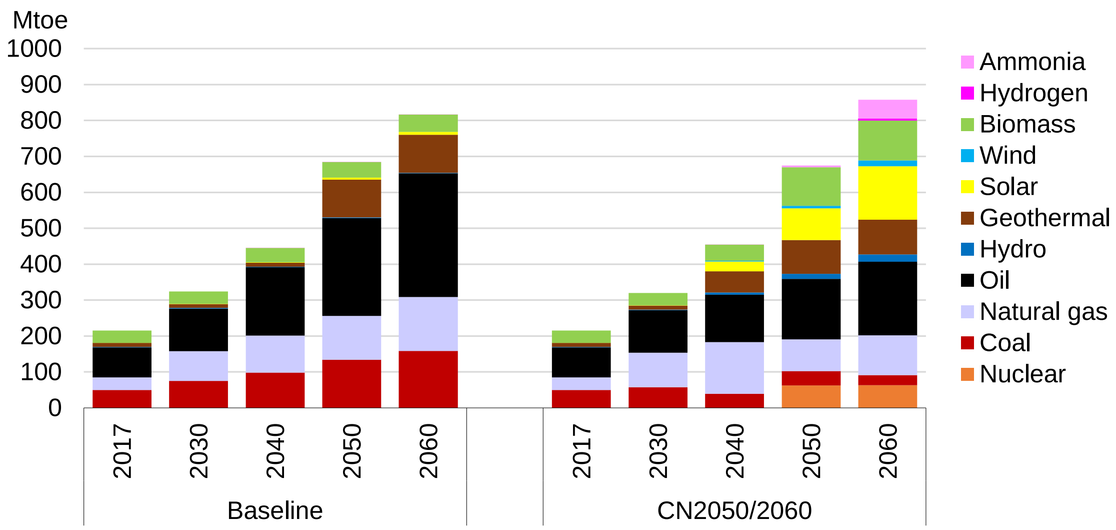
	Baseline ($MtCO_2$)					KHM-CN2050/2060_w/oCarbonSink ($MtCO_2$)				
	2017	**2030**	**2040**	**2050**	**2060**	**2017**	**2030**	**2040**	**2050**	**2060**
Electricity	3.77	5.47	14.28	20.79	29.38	3.77	5.52	1.07	-7.73	-14.12
Industry	0.62	4.02	10.10	21.48	25.15	0.62	3.77	5.21	4.22	5.22
Transport	5.42	8.09	9.25	10.47	8.43	5.42	8.09	9.25	10.47	7.89
Other end use	0.55	1.65	2.88	4.88	5.67	0.55	1.65	2.88	2.24	1.01
Other including DACCS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LULUCF										
Energy-related CO_2 emissions	10.37	19.23	36.51	57.61	68.64	10.37	19.04	18.41	9.20	0.00

KHM = Cambodia, $MtCO_2$ = Million tonne of carbon dioxide, DACCS = Direct Air Carbon Capture and Storage, LULUCF = land use, land-use change and forestry.
Source: Author.

3. Indonesia

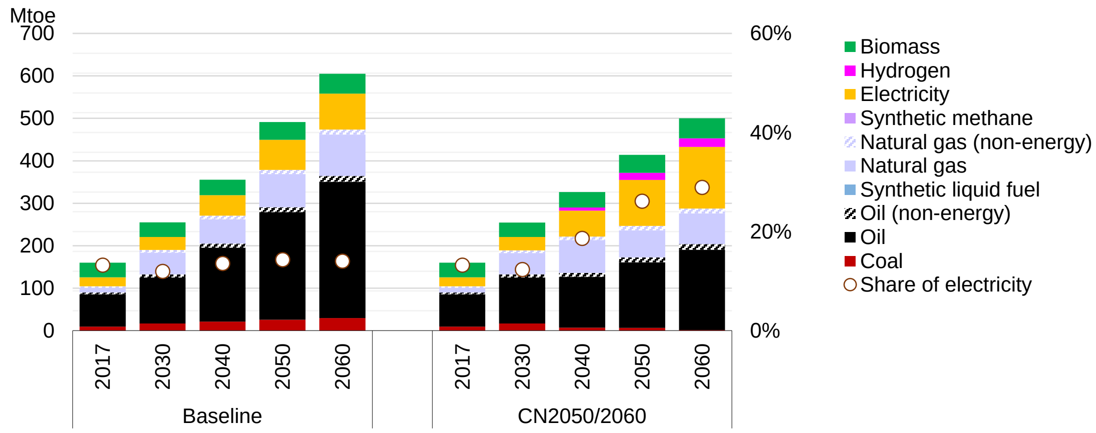
(a) CN2050/2060

Figure A.27. Primary Energy Supply (IDN-CN2050/2060)



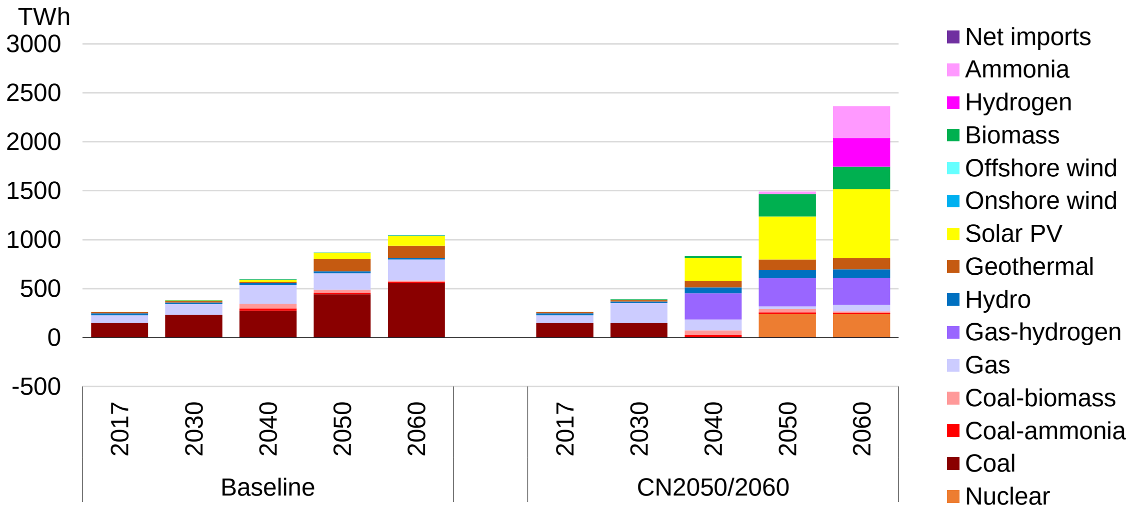
IDN = Indonesia, Mtoe = million tonnes of oil equivalent.
Source: Author.

Figure A.28. Final Energy Consumption (IDN-CN2050/2060)



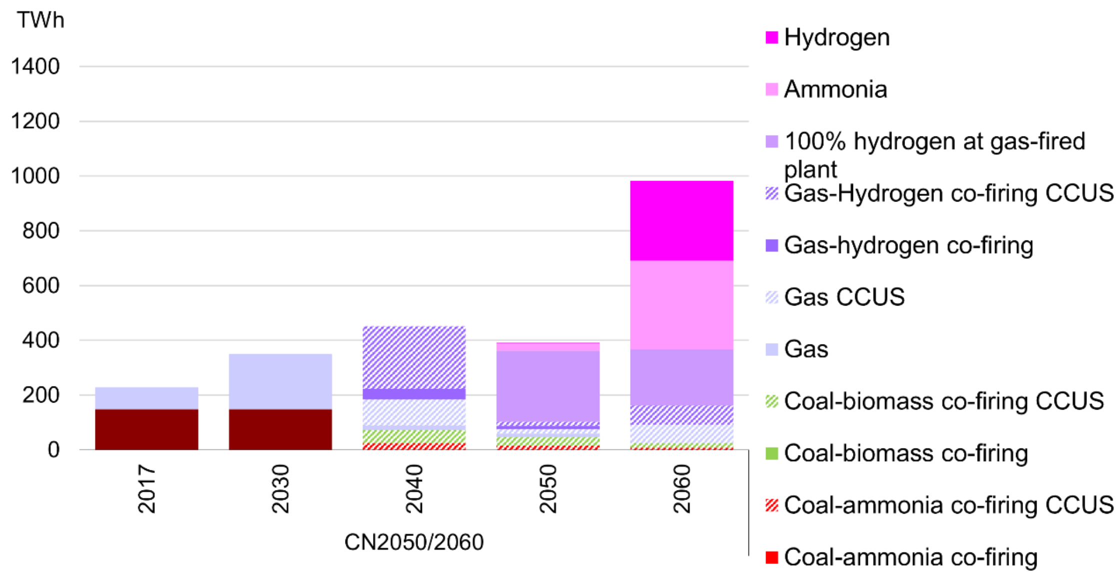
IDN = Indonesia, Mtoe = million tonnes of oil equivalent.
Source: Author.

Figure A.29. Power Generation (IDN-CN2050/2060)



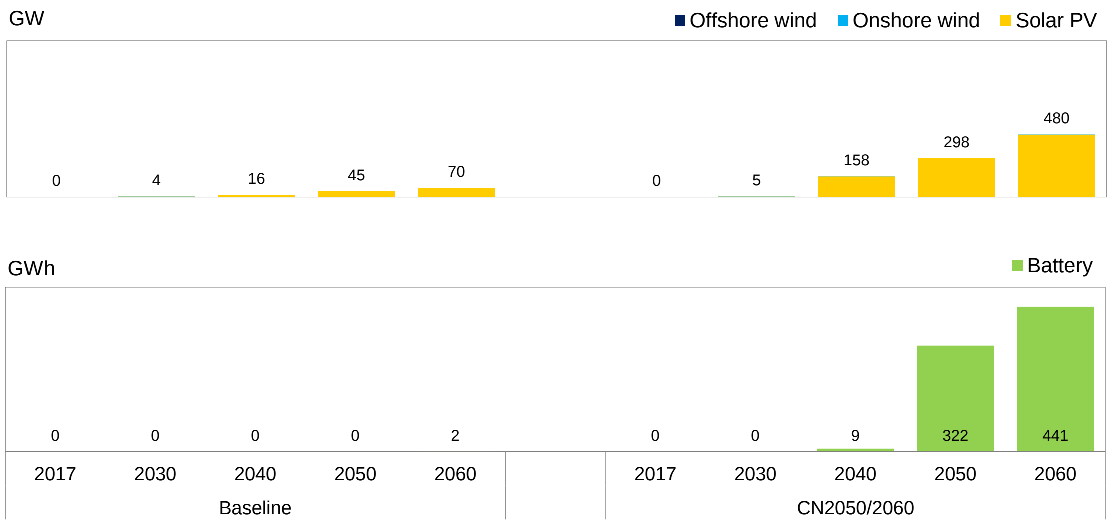
IDN = Indonesia, PV = photovoltaic, TWh = terawatt-hour.
Source: Author.

Figure A.30. Generated Electricity from Coal, Gas, Ammonia, and Hydrogen (IDN-CN2050/2060)



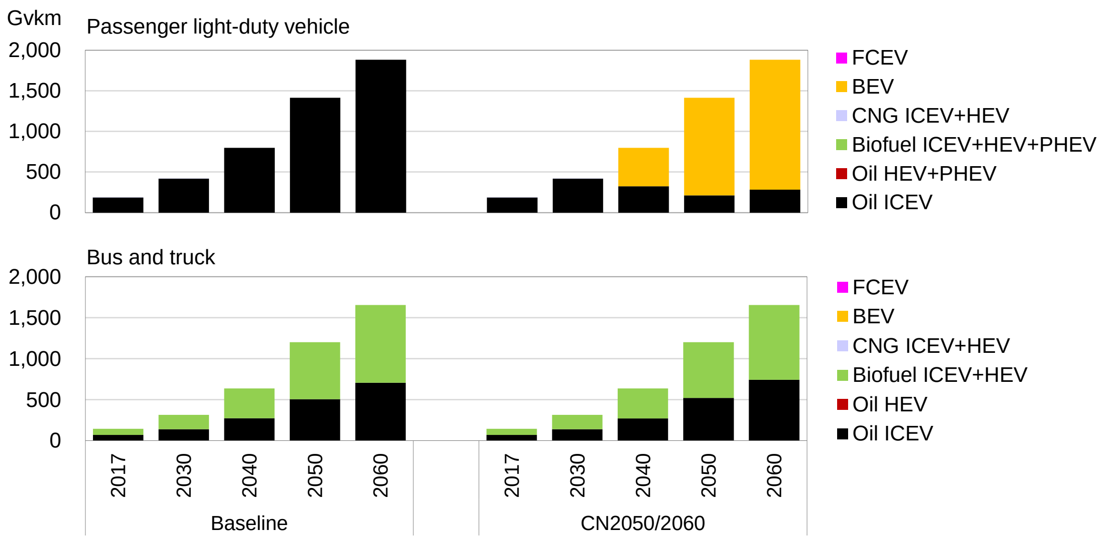
CCUS = CCUS = carbon dioxide capture, utilisation, and storage; IDN = Indonesia; TWh = terawatt-hour.
Source: Author.

Figure A.31. Variable Renewable Energy and Battery (IDN-CN2050/2060)



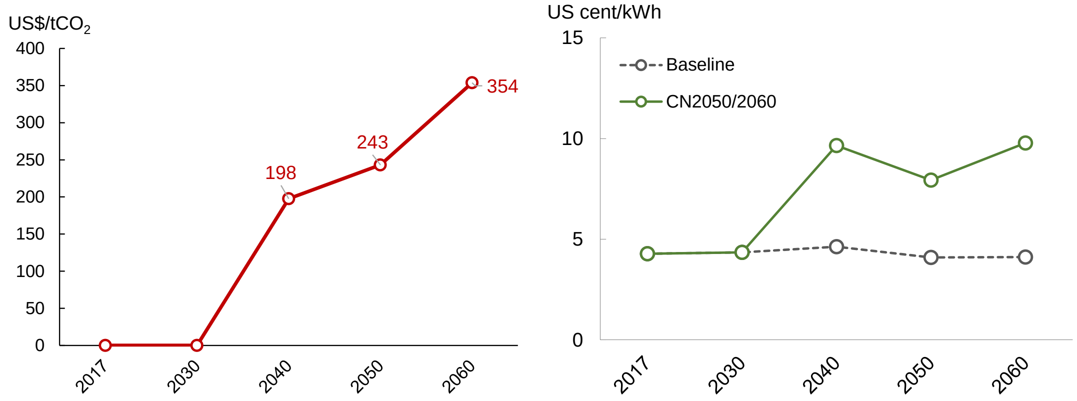
GW = gigawatt, GWh = gigawatt-hour, IDN = Indonesia, PV = photovoltaic.
Source: Author.

Figure A.32. Travel Distance by Vehicle Technology (IDN-CN2050/2060)



BEV = battery electric vehicle, CN = carbon neutral, CNG = compressed natural gas, FCEV = fuel cell electric vehicle, HEV = hybrid electric vehicle, ICEV = internal combustion engine vehicle, IDN = Indonesia, Gvkm = 10^9 vehicle-km, PHEV = plug-in hybrid electric vehicle.
Source: Author.

Figure A.33. Marginal Carbon Dioxide Abatement Cost (Left), Electricity Price (Right) (IDN-CN2050/2060)



IDN = Indonesia, kWh = kilowatt-hour, tCO_2 = tonne of carbon dioxide.
Source: Author.

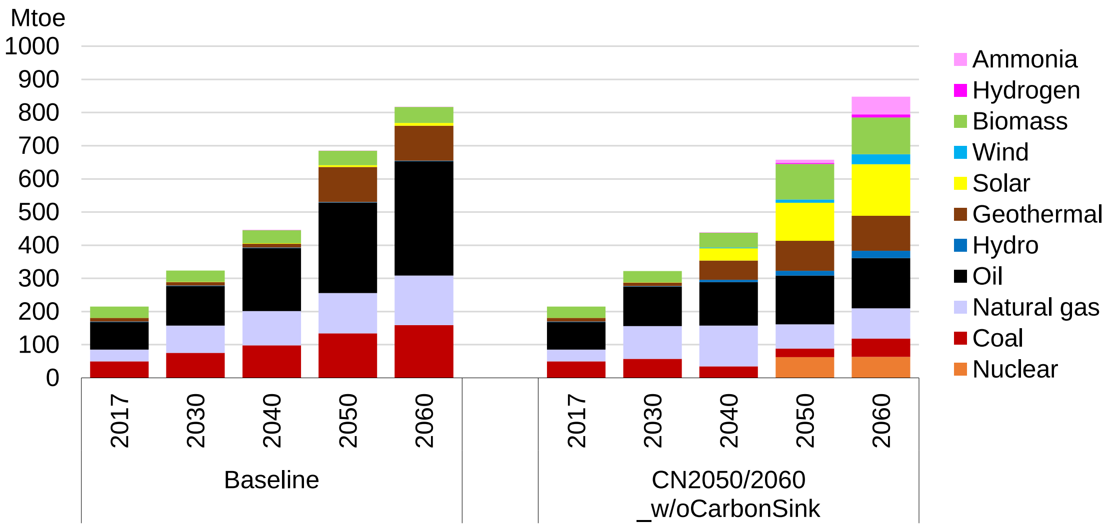
Table A.5. Carbon Dioxide Emission Baseline and with Carbon Sink Scenarios (IDN-CN2050/2060)

	Baseline ($MtCO_2$)					IDN-CN2050/2060 ($MtCO_2$)				
	2017	**2030**	**2040**	**2050**	**2060**	**2017**	**2030**	**2040**	**2050**	**2060**
Electricity	178.60	259.32	359.23	470.06	566.66	178.60	224.50	0.31	-259.26	-262.19
Industry	91.13	145.48	222.11	298.24	381.68	91.13	142.50	143.55	137.60	127.46
Transport	120.26	242.29	400.13	630.51	828.88	120.26	242.29	310.79	418.17	552.03
Other end use	81.58	128.91	127.33	127.04	111.64	81.58	128.88	118.45	92.18	74.23
Other including DACCS	39.36	40.31	54.69	63.38	73.16	39.36	38.67	40.44	40.84	-246.04
LULUCF						635.50	-130.00	-240.00	-300.00	-300.00
Energy-related CO_2 emissions	510.93	816.30	1,163.48	1,589.24	1,962.02	510.93	776.84	613.55	429.53	245.50

IDN = Indonesia, $MtCO_2$ = Million tonne of carbon dioxide, DACCS = Direct Air Carbon Capture and Storage, LULUCF = land use, land-use change and forestry.
Source: Author.

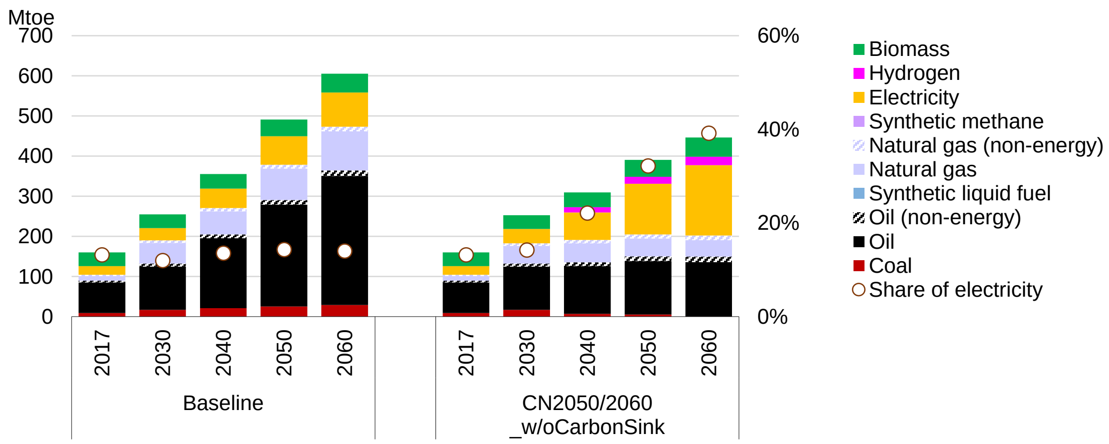
(b) CN2050/2060_w/oCarbonSink

Figure A.34. Primary Energy Supply (IDN-CN2050/2060_w/oCarbonSink)



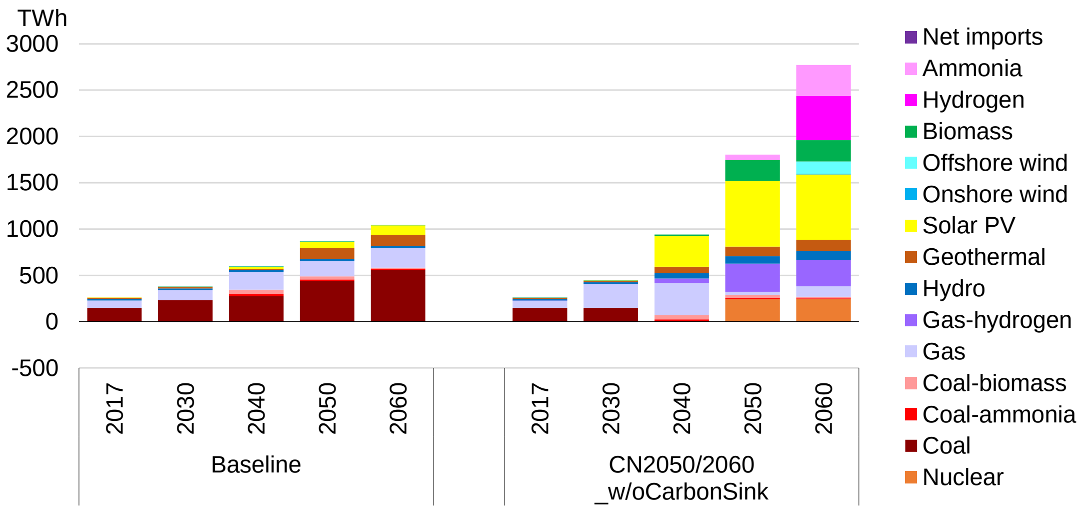
IDN = Indonesia, Mtoe = million tonnes of oil equivalent.
Source: Author.

Figure A.35. Final Energy Consumption (IDN-CN2050/2060_w/oCarbonSink)



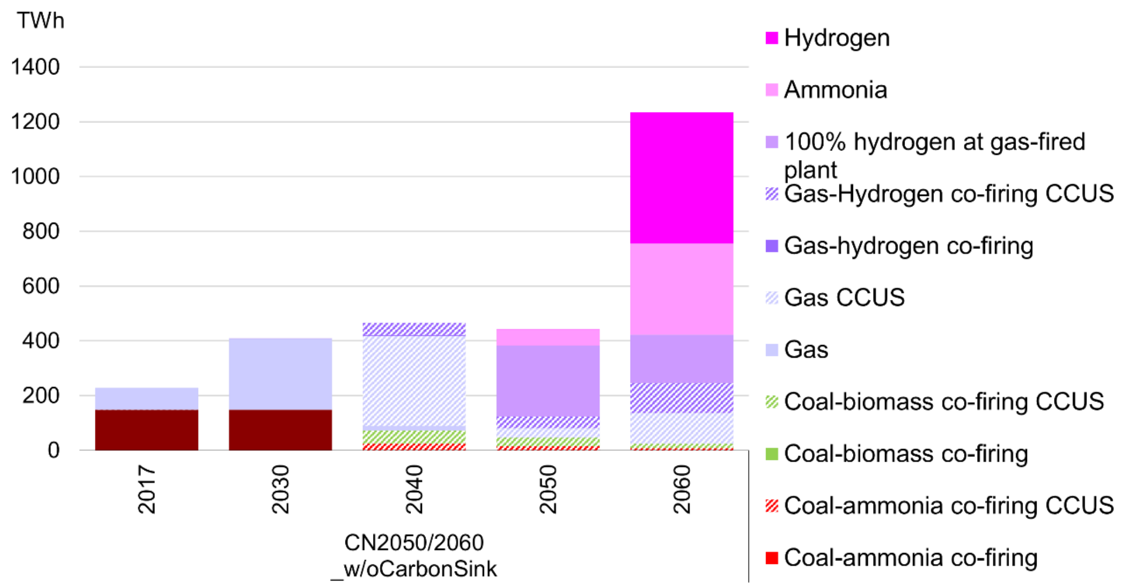
IDN = Indonesia, Mtoe = million tonnes of oil equivalent.
Source: Author.

Figure A.36. Power Generation (IDN-CN2050/2060_w/oCarbonSink)



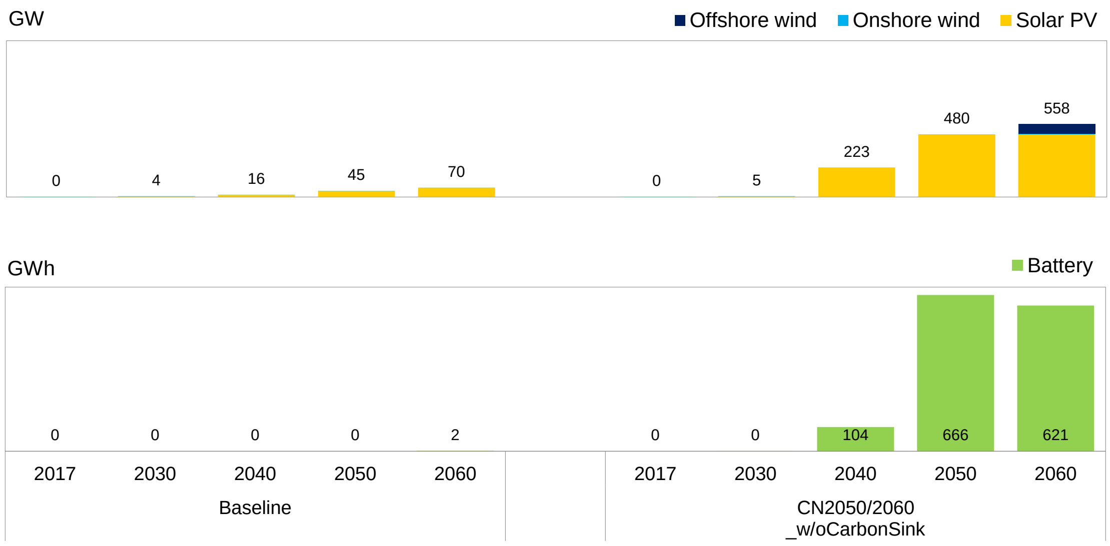
IDN = Indonesia, PV = photovoltaic, TWh = terawatt-hour.
Source: Author.

Figure A.37. Generated Electricity from Coal, Gas, Ammonia, and Hydrogen (IDN-CN2050/2060_w/oCarbonSink)



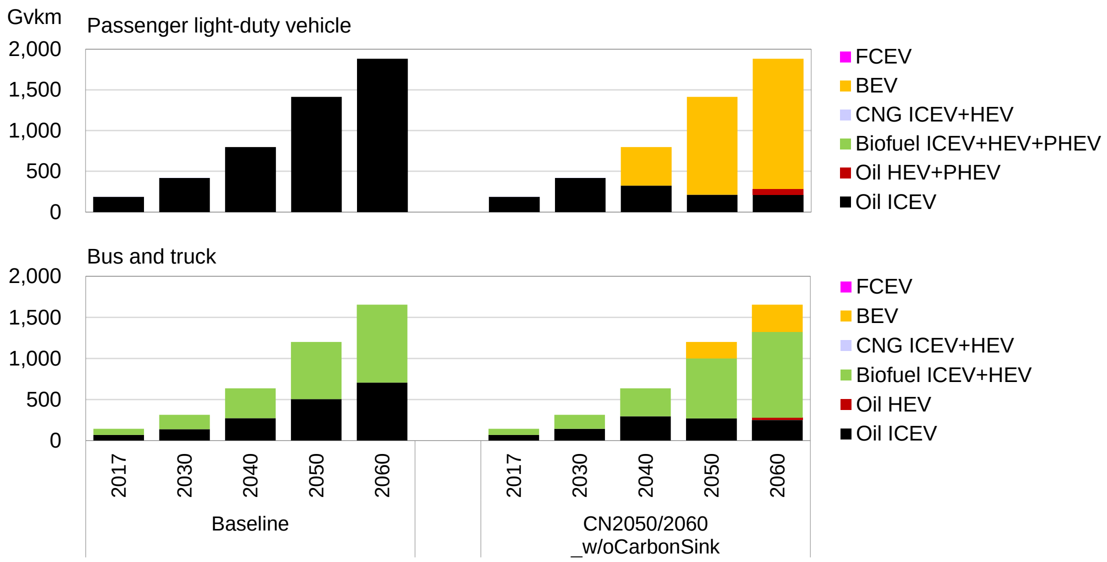
CCUS = carbon dioxide capture, utilisation, and storage; IDN = Indonesia; TWh = terawatt-hour.
Source: Author.

Figure A.38. Variable Renewable Energy and Battery (IDN-CN2050/2060_w/oCarbonSink)



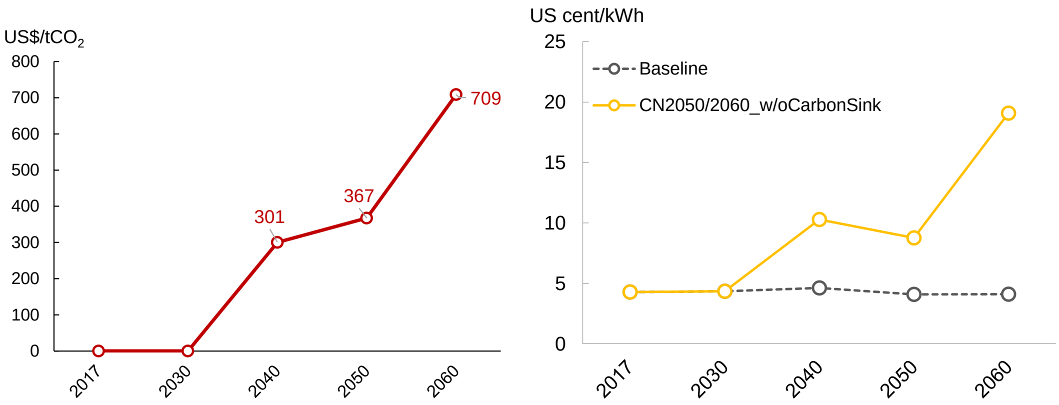
GW = gigawatt, GWh = gigawatt-hour, IDN = Indonesia, PV = photovoltaic.
Source: Author.

Figure A.39. Travel Distance by Vehicle Technology (IDN-CN2050/2060_w/oCarbonSink)



BEV = battery electric vehicle, CNG = compressed natural gas, FCEV = fuel cell electric vehicle, HEV = hybrid electric vehicle, ICEV = internal combustion engine vehicle, IDN = Indonesia, Gvkm = 10^9 vehicle-km, PHEV = plug-in hybrid electric vehicle.
Source: Author.

Figure A.40. Marginal Carbon Dioxide Abatement Cost (Left), Electricity Price (Right) (IDN-CN2050/2060_w/oCarbonSink)



IDN = Indonesia, kWh = kilowatt-hour, tCO_2 = tonne of carbon dioxide.
Source: Author.

Table A.6. Carbon Dioxide Emission Baseline and without Carbon Sink Scenarios (IDN-CN2050/2060_w/oCarbonSink)

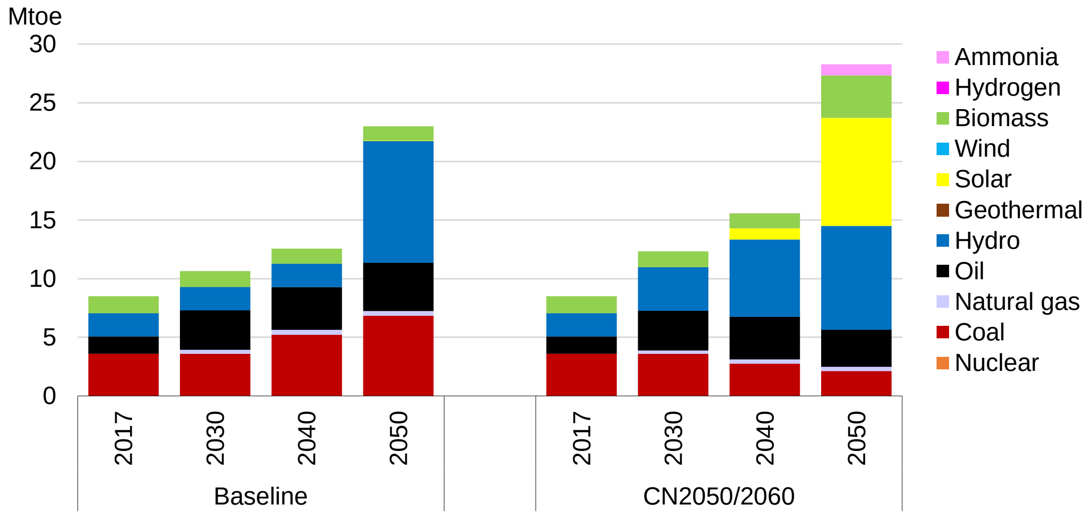
	Baseline ($MtCO_2$)					IDN-CN2050/2060_w/oCarbonSink ($MtCO_2$)				
	2017	**2030**	**2040**	**2050**	**2060**	**2017**	**2030**	**2040**	**2050**	**2060**
Electricity	178.60	259.32	359.23	470.06	566.66	178.62	245.89	-7.75	-265.61	-259.34
Industry	91.13	145.48	222.11	298.24	381.68	91.13	142.51	99.67	86.81	51.81
Transport	120.26	242.29	400.13	630.51	828.88	120.26	242.29	297.92	354.62	387.99
Other end use	81.58	128.91	127.33	127.04	111.64	81.58	113.98	103.94	91.57	73.63
Other including DACCS	39.36	40.31	54.69	63.38	73.16	39.36	38.67	37.94	-1.53	-254.09
LULUCF										
Energy-related CO_2 emissions	510.93	816.30	1,163.48	1,589.24	1,962.02	510.95	783.34	531.72	265.86	0.00

IDN = Indonesia, $MtCO_2$ = Million tonne of carbon dioxide, DACCS = Direct Air Carbon Capture and Storage, LULUCF = land use, land-use change and forestry.
Source: Author.

4. Lao People's Democratic Republic

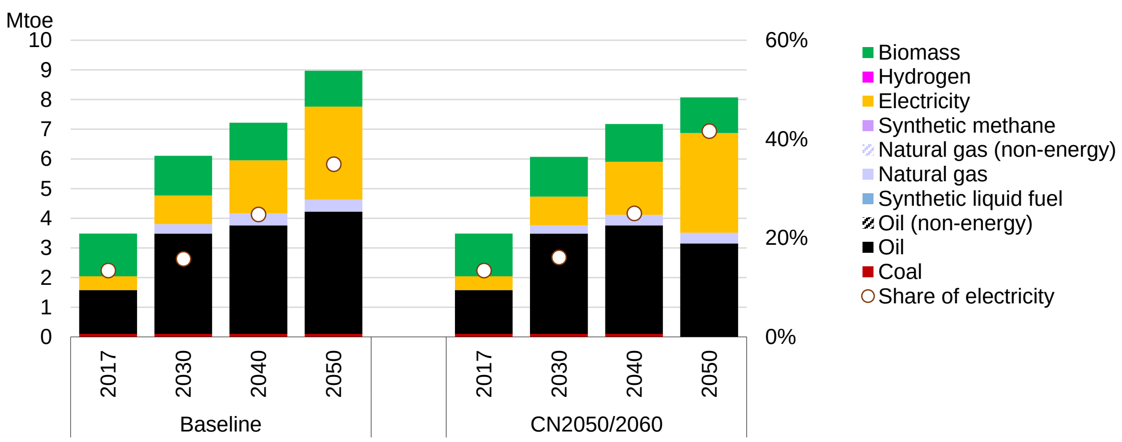
(a) CN2050/2060

Figure A.41. Primary Energy Supply (LAO-CN2050/2060)



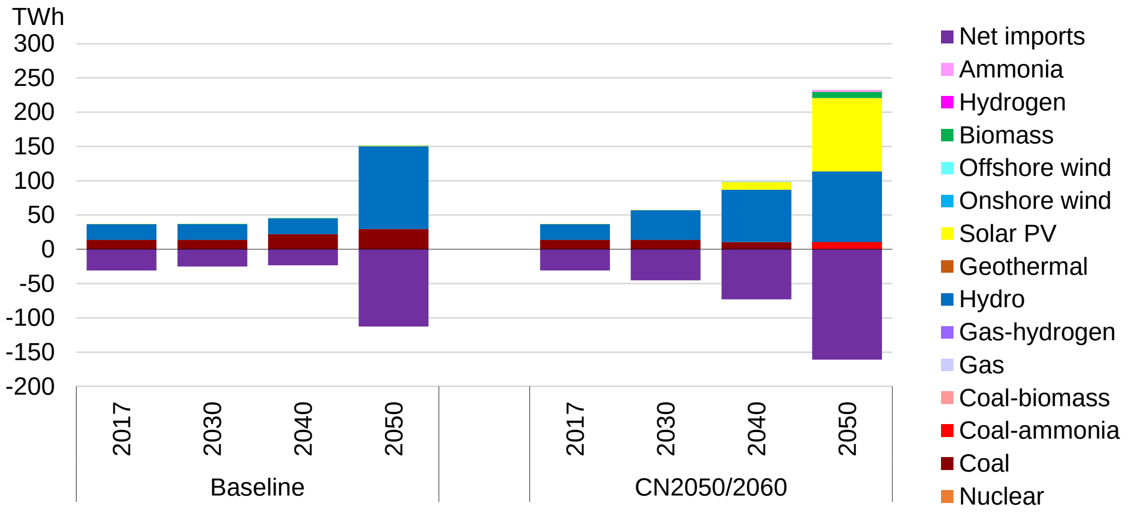
LAO = Lao People's Democratic Republic, Mtoe = million tonnes of oil equivalent.
Source: Author.

Figure A.42. Final Energy Consumption (LAO-CN2050/2060)



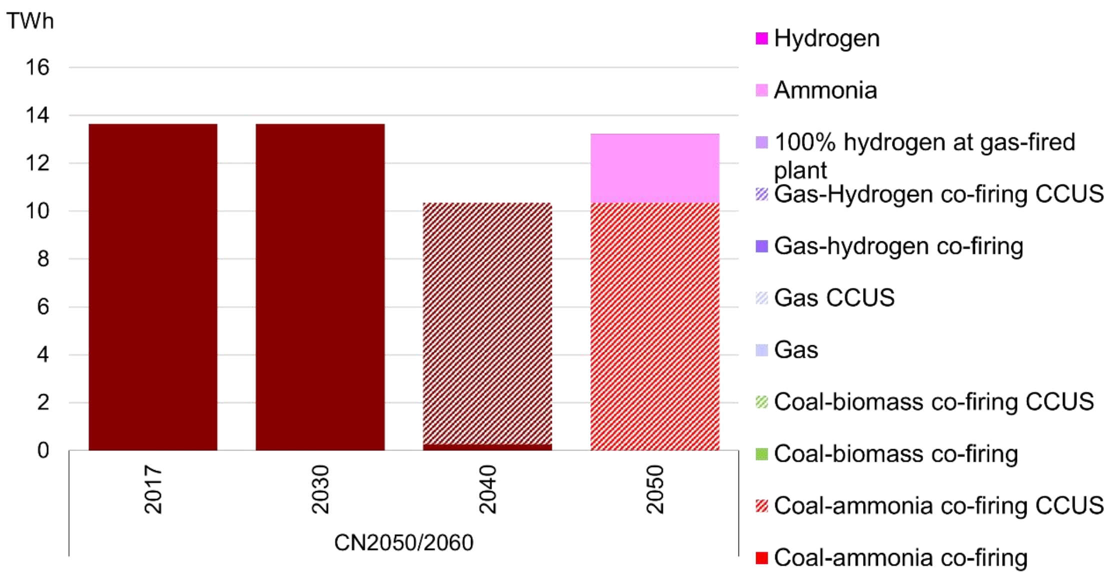
LAO = Lao People's Democratic Republic, Mtoe = million tonnes of oil equivalent.
Source: Author.

Figure A.43. Power Generation (LAO-CN2050/2060)



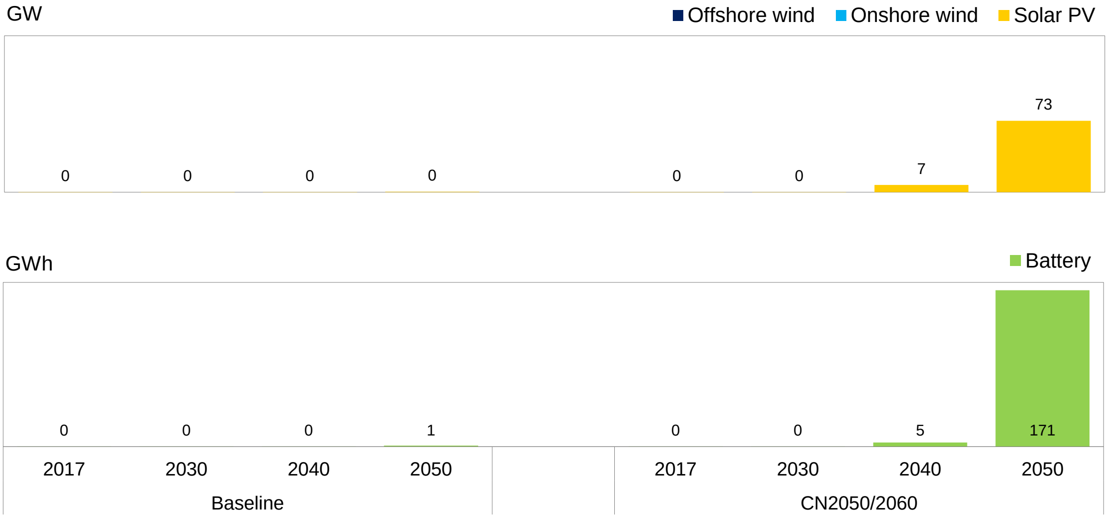
LAO = Lao People's Democratic Republic, PV = photovoltaic, TWh = terawatt-hour.
Source: Author.

Figure A.44. Generated Electricity from Coal, Gas, Ammonia, and Hydrogen (LAO-CN2050/2060)



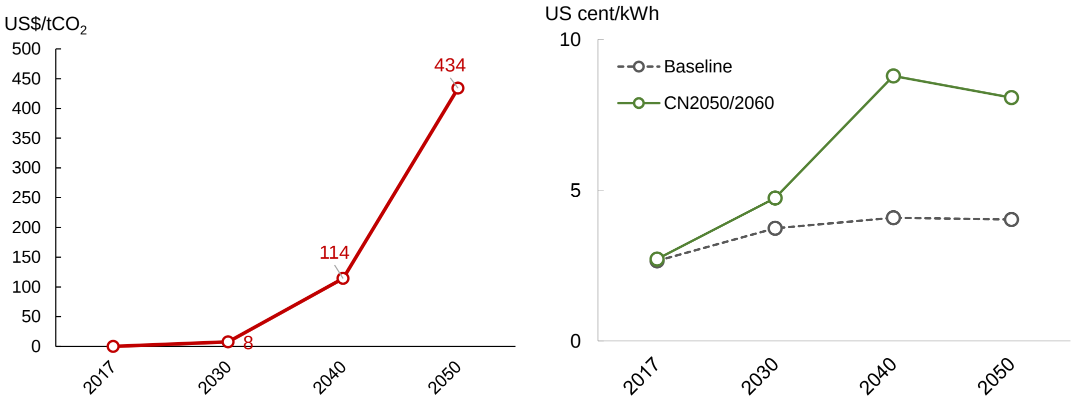
CCUS = carbon dioxide capture, utilisation, and storage; LAO = Lao People's Democratic Republic; TWh = terawatt-hour.
Source: Author.

Figure A.45. Variable Renewable Energy and Battery (LAO-CN2050/2060)



GW = gigawatt, GWh = gigawatt-hour, LAO = Lao People's Democratic Republic, PV = photovoltaic.
Source: Author.

Figure A.46. Marginal Carbon Dioxide Abatement Cost (Left), Electricity Price (Right) (LAO-CN2050/2060)



LAO = Lao People's Democratic Republic, tCO_2 = tonne of carbon dioxide.
Source: Author.

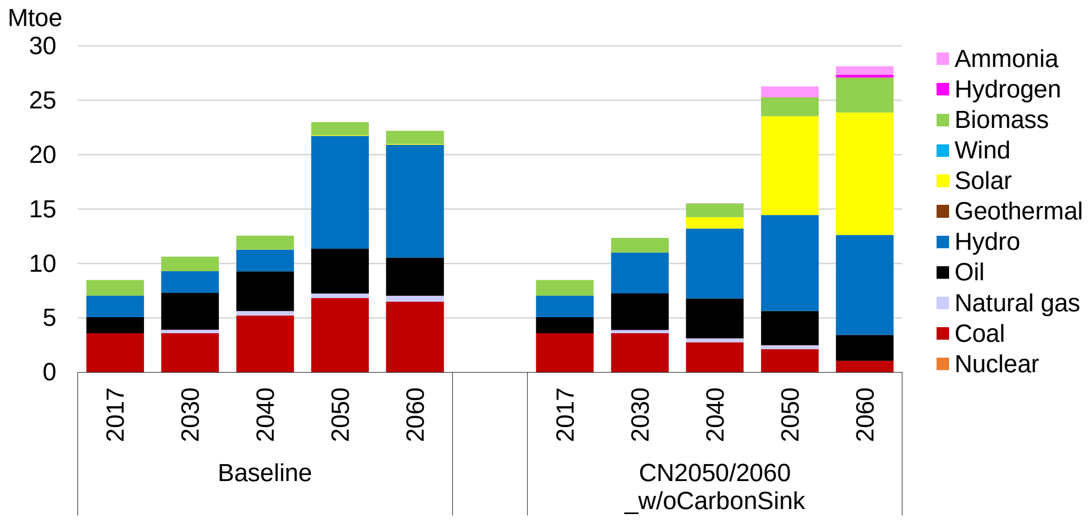
Table A.7. Carbon Dioxide Emission Baseline and with Carbon Sink Scenarios (LAO-CN2050/2060)

	Baseline ($MtCO_2$)					LAO-CN2050/2060 (MtCO2)				
	2017	**2030**	**2040**	**2050**	**2060**	**2017**	**2030**	**2040**	**2050**	**2060**
Electricity	13.84	13.84	20.27	26.63	25.30	13.84	13.84	1.26	-9.32	-8.29
Industry	0.59	1.73	2.94	5.08	5.86	0.59	1.59	2.47	1.25	1.48
Transport	3.15	4.50	4.61	4.69	3.78	3.15	4.50	4.61	4.39	3.78
Other end use	1.23	5.46	5.26	4.57	3.15	1.23	5.35	5.14	4.46	3.04
Other including DACCS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.77	0.00
LULUCF						0.00	0.00	0.00	0.00	0.00
Energy-related CO_2 emissions	18.80	25.54	33.07	40.98	38.09	18.80	25.28	13.47	0.00	0.00

Lao PDR = Lao People's Democratic Republic, $MtCO_2$ = Million tonne of carbon dioxide, DACCS = Direct Air Carbon Capture and Storage, LULUCF = land use, land-use change and forestry.
Source: Author.

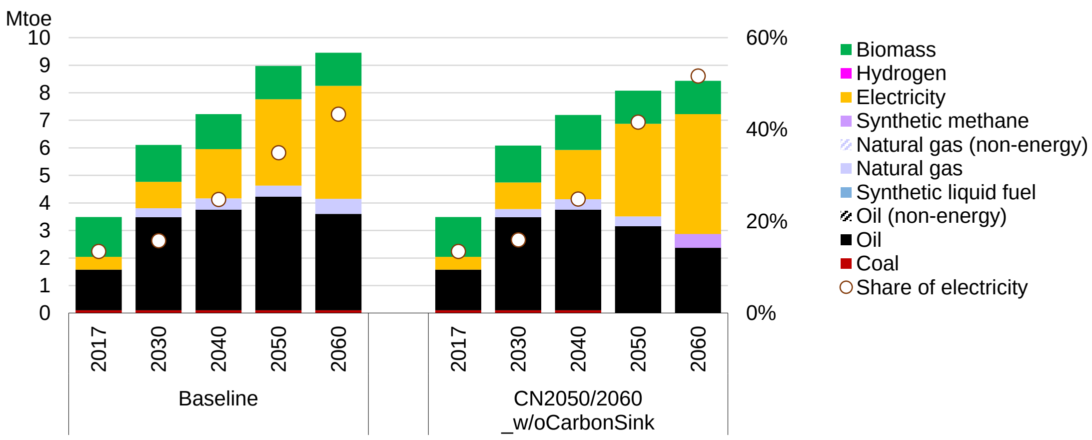
(b) CN2050/2060_w/oCarbonSink

Figure A.47. Primary Energy Supply (LAO-CN2050/2060_w/oCarbonSink)



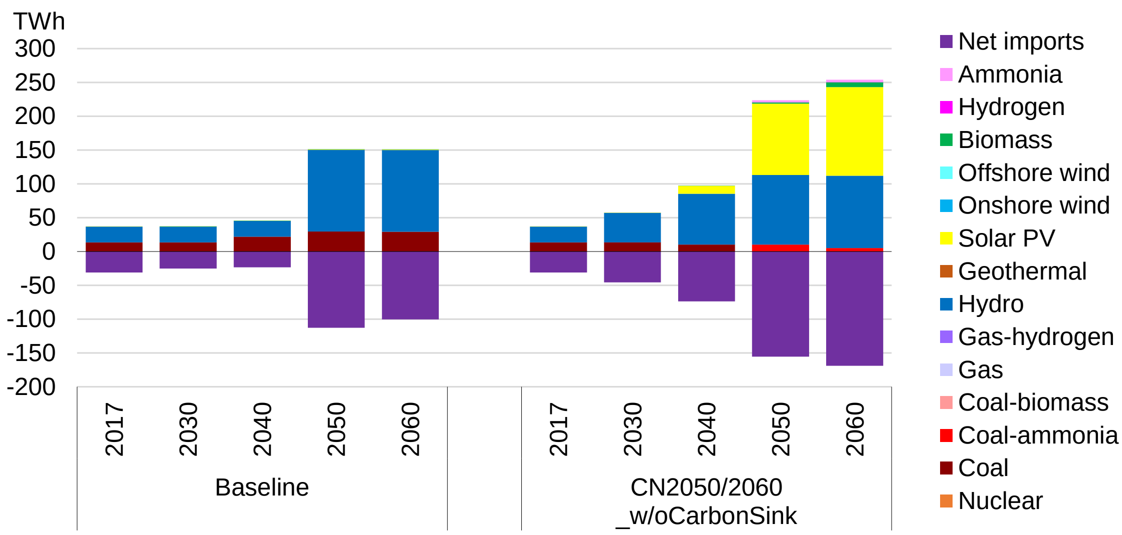
LAO = Lao People's Democratic Republic, Mtoe = million tonnes of oil equivalent.
Source: Author.

Figure A.48. Final Energy Consumption (LAO-CN2050/2060_w/oCarbonSink)



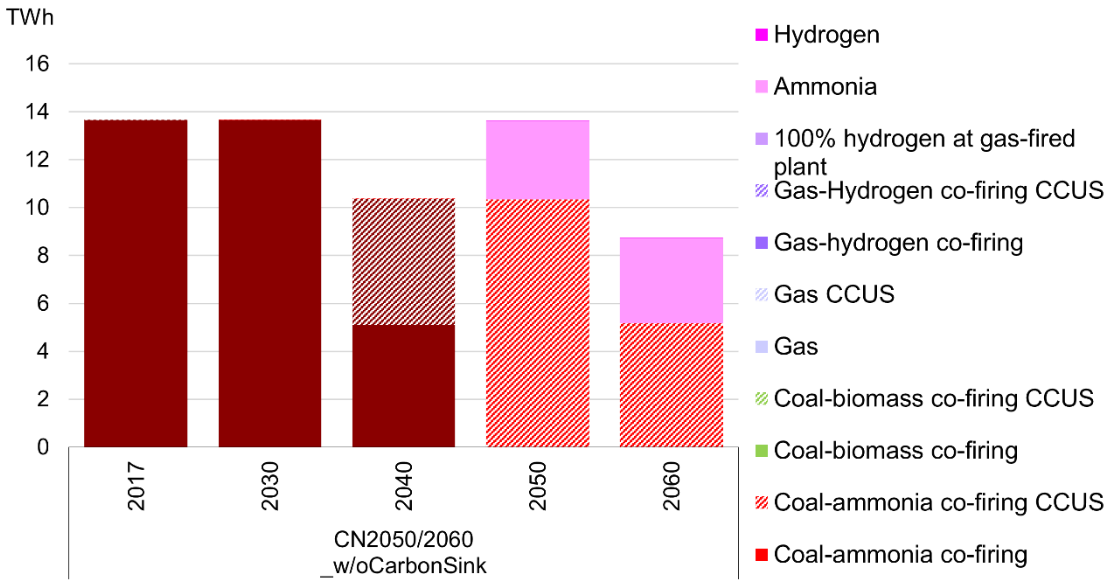
LAO = Lao People's Democratic Republic, Mtoe = million tonnes of oil equivalent.
Source: Author.

Figure A.49. Power Generation (LAO-CN2050/2060_w/oCarbonSink)



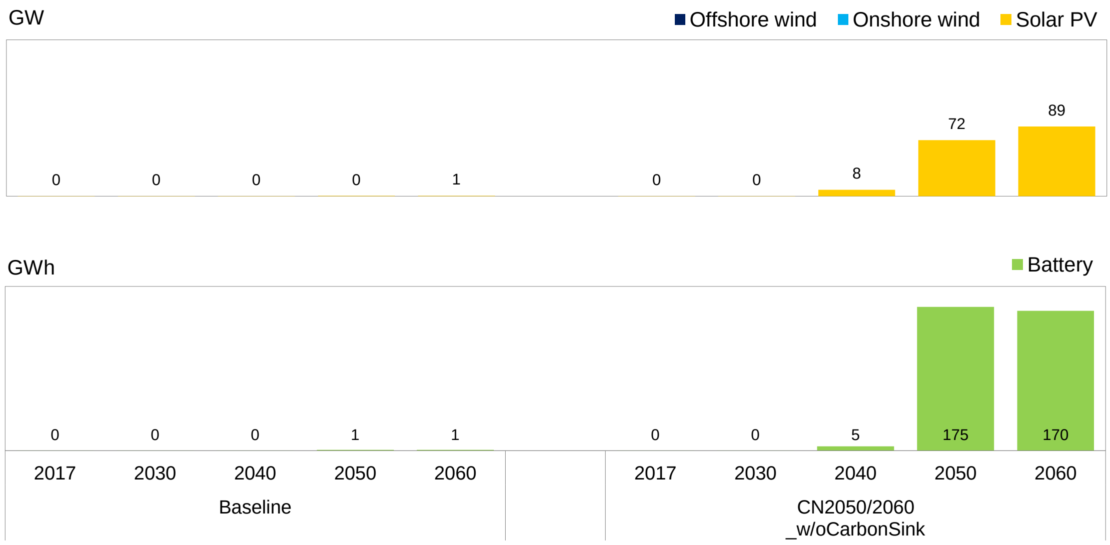
LAO = Lao People's Democratic Republic, PV = photovoltaic, TWh = terawatt-hour.
Source: Author.

Figure A.50. Generated Electricity from coal, Gas, Ammonia, and Hydrogen (LAO-CN2050/2060_w/oCarbonSink)



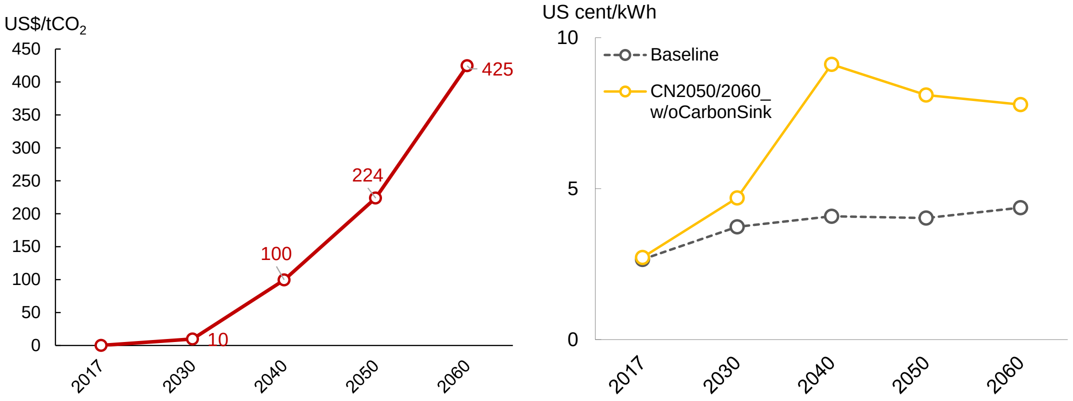
CCUS = carbon dioxide capture, utilisation, and storage; LAO = People's Democratic Republic; TWh = terawatt-hour.
Source: Author.

Figure A.51. Variable Renewable Energy and Battery (LAO-CN2050/2060_w/oCarbonSink)



GW = gigawatt, GWh = gigawatt-hour, LAO = Lao People's Democratic Republic, PV = photovoltaic.
Source: Author.

Figure A.52. Marginal Carbon Dioxide Abatement Cost (Left), Electricity Price (Right) (LAO-CN2050/2060_w/oCarbonSink)



kWh = kilowatt-hour, LAO = Lao People's Democratic Republic, tCO_2 = tonne of carbon dioxide.
Source: Author.

Table A.8. Carbon Dioxide Emission Baseline and without Carbon Sink Scenarios (LAO-CN2050/2060_w/oCarbonSink)

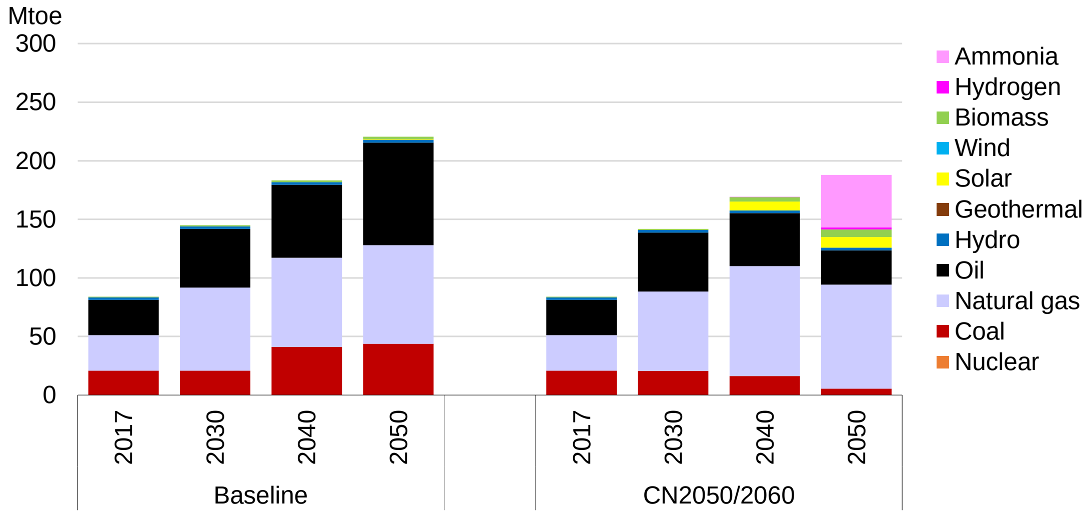
	Baseline ($MtCO_2$)					LAO-CN2050/2060_w/oCarbonSink ($MtCO_2$)				
	2017	**2030**	**2040**	**2050**	**2060**	**2017**	**2030**	**2040**	**2050**	**2060**
Electricity	13.84	13.84	20.27	26.63	25.30	13.84	13.84	5.70	-1.42	-8.01
Industry	0.59	1.73	2.94	5.08	5.86	0.59	1.55	2.47	1.25	1.46
Transport	3.15	4.50	4.61	4.69	3.78	3.15	4.50	4.61	4.69	3.53
Other end use	1.23	5.46	5.26	4.57	3.15	1.23	5.39	5.19	4.47	3.03
Other including DACCS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.02
LULUCF										
Energy-related CO_2 emissions	18.80	25.54	33.07	40.98	38.09	18.80	25.28	17.96	8.98	0.00

Lao PDR = Lao People's Democratic Republic, $MtCO_2$ = Million tonne of carbon dioxide, DACCS = Direct Air Carbon Capture and Storage, LULUCF = land use, land-use change and forestry.
Source: Author.

5. Malaysia

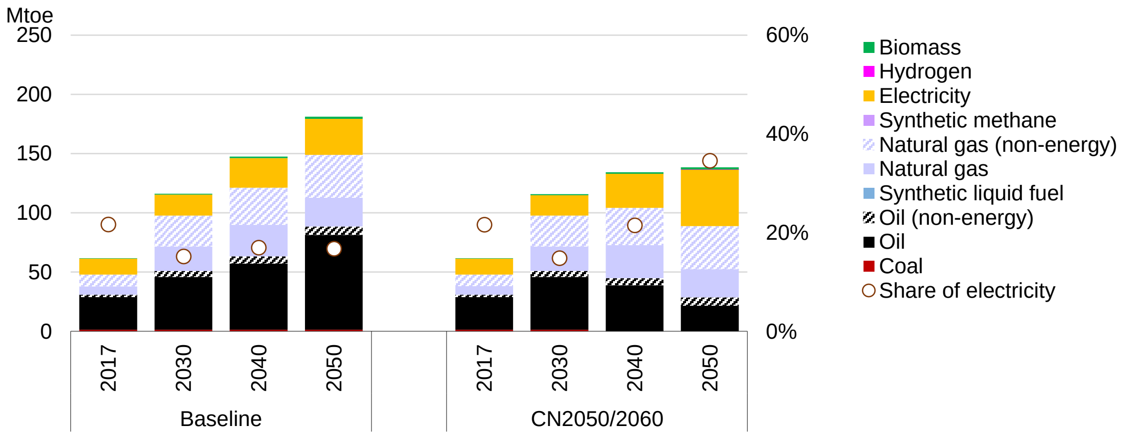
(a) CN2050/2060

Figure A.53. Primary Energy Supply (MYS-CN2050/2060)



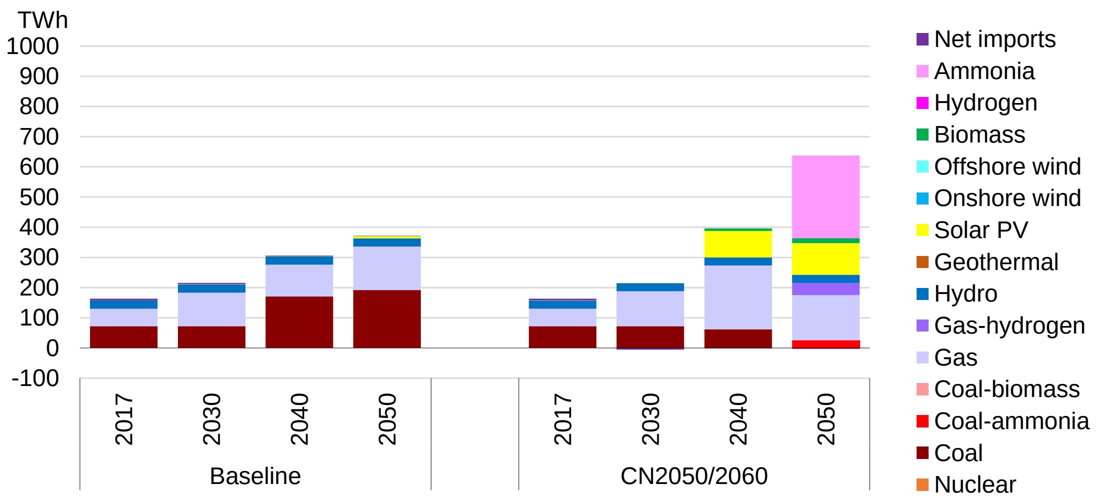
Mtoe = million tonnes of oil equivalent, MYS = Malaysia.
Source: Author.

Figure A.54. Final Energy Consumption (MYS-CN2050/2060)



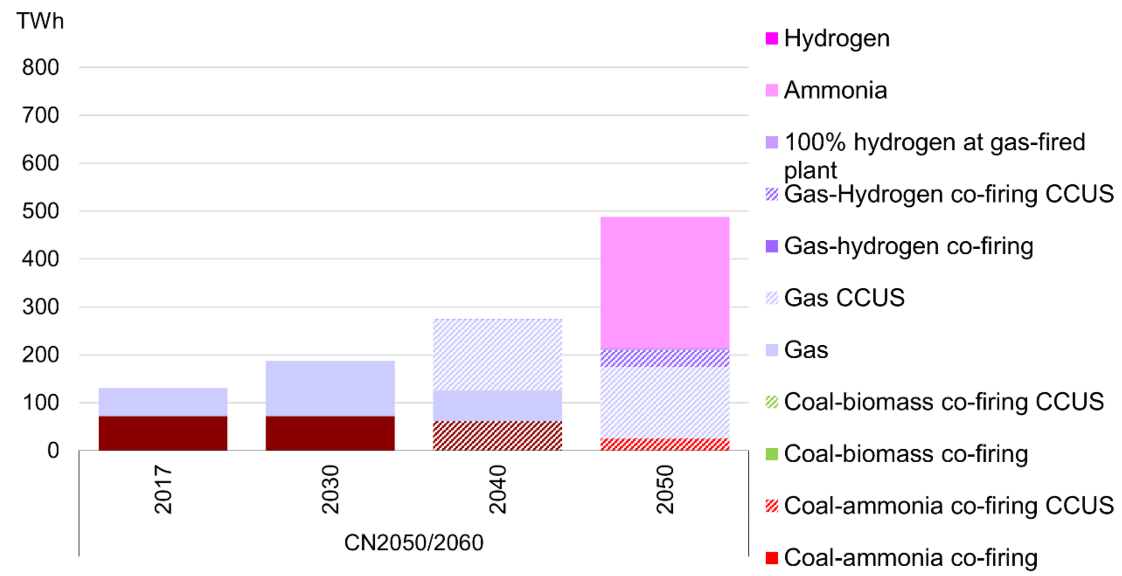
Mtoe = million tonnes of oil equivalent, MYS = Malaysia.
Source: Author.

Figure A.55. Power Generation (MYS-CN2050/2060)



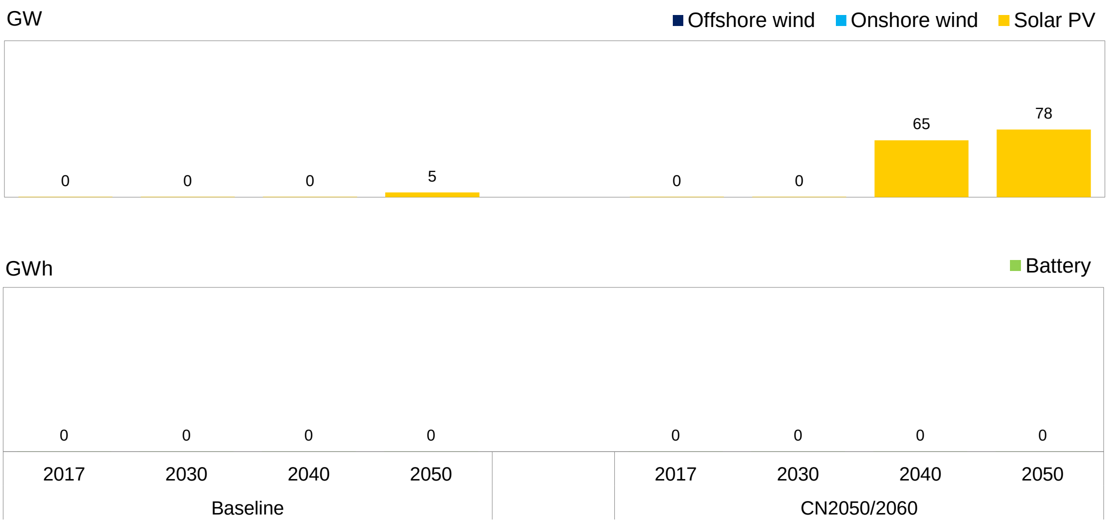
MYS = Malaysia, PV = photovoltaic, TWh = terawatt-hour.
Source: Author.

Figure A.56. Generated Electricity from Coal, Gas, Ammonia, and Hydrogen (MYS-CN2050/2060)



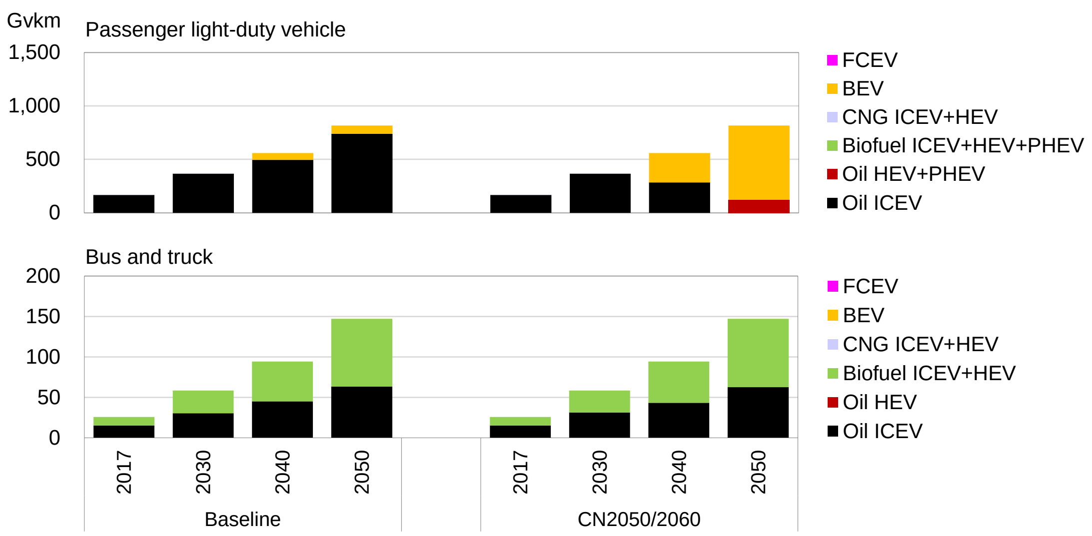
MYS = Malaysia; CCUS = carbon dioxide capture, utilisation, and storage; TWh = terawatt-hour.
Source: Author.

Figure A.57. Variable Renewable Energy and Battery (MYS-CN2050/2060)



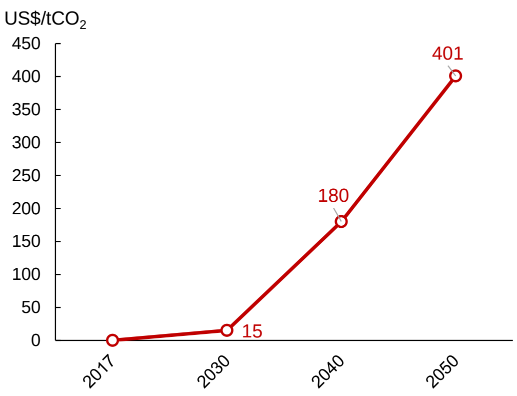
GW = gigawatt, GWh = gigawatt-hour, MYS = Malaysia, PV = photovoltaic.
Source: Author.

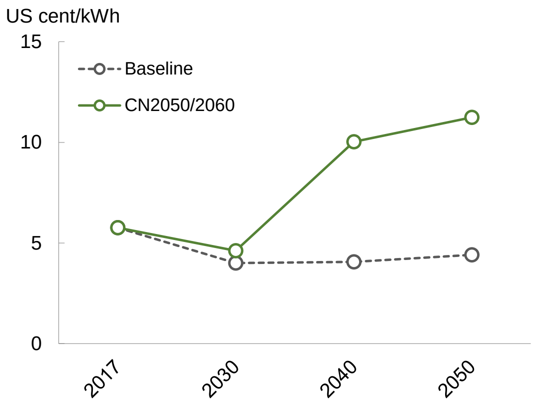
Figure A.58. Travel Distance by Vehicle Technology (MYS-CN2050/2060)



BEV = battery electric vehicle, CN = carbon neutral, CNG = compressed natural gas, FCEV = fuel cell electric vehicle, HEV = hybrid electric vehicle, ICEV = internal combustion engine vehicle, Gvkm = 10^9 vehicle-km, MYS = Malaysia, PHEV = plug-in hybrid electric vehicle.
Source: Author.

Figure A.59. Marginal Carbon Dioxide Abatement Cost (Left), Electricity Price (Right) (MYS-CN2050/2060)





kWh = kilowatt-hour, MYS = Malaysia, tCO_2 = tonne of carbon dioxide.
Source: Author.

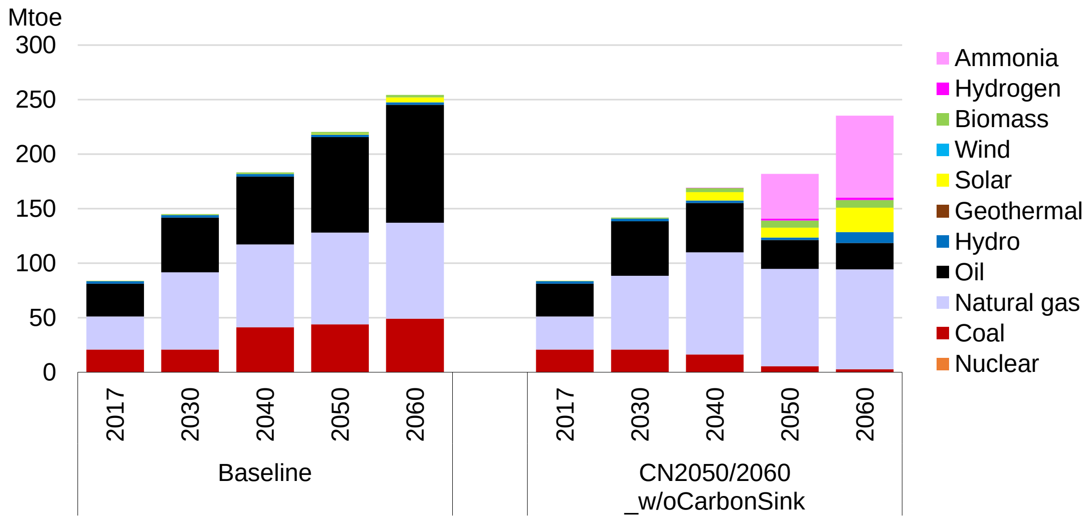
Table A.9. Carbon Dioxide Emission Baseline and with Carbon Sink Scenarios (MYS-CN2050/2060)

	Baseline ($MtCO_2$)					MYS-CN2050/2060 ($MtCO_2$)				
	2017	**2030**	**2040**	**2050**	**2060**	**2017**	**2030**	**2040**	**2050**	**2060**
Electricity	104.75	130.24	196.17	220.09	240.03	104.75	130.24	196.17	220.09	240.03
Industry	29.94	41.97	54.04	68.22	82.53	29.94	41.97	54.04	68.22	82.53
Transport	67.38	123.07	153.51	204.83	252.19	67.38	123.07	153.51	204.83	252.19
Other end use	5.81	20.17	25.07	27.16	23.74	5.81	20.17	25.07	27.16	23.74
Other including DACCS	5.29	5.29	5.29	5.29	5.29	5.29	5.29	5.29	5.29	5.29
LULUCF										
Energy-related CO_2 emissions	213.17	320.74	434.06	525.60	603.78	213.17	320.74	434.06	525.60	603.78

MYS = Malaysia, $MtCO_2$ = Million tonne of carbon dioxide, DACCS = Direct Air Carbon Capture and Storage, LULUCF = land use, land-use change and forestry.
Source: Author.

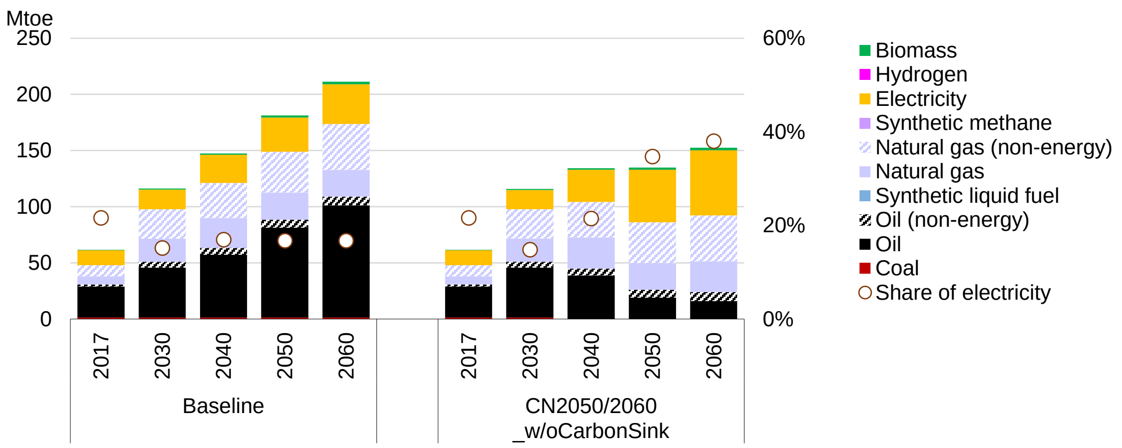
(b) CN2050/2060_w/oCarbonSink

Figure A.60. Primary Energy Supply (MYS-CN2050/2060_w/oCarbonSink)



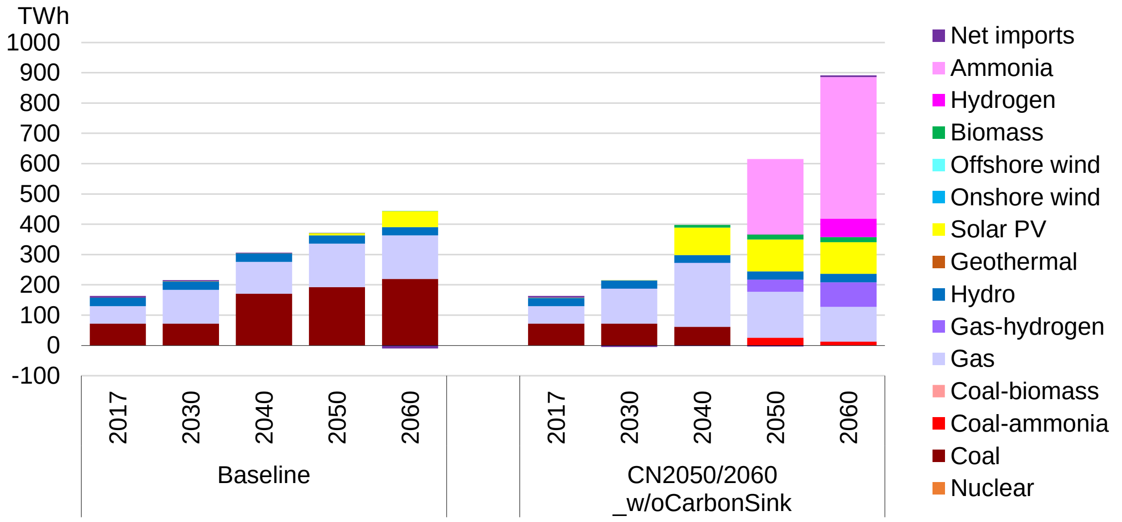
Mtoe = million tonnes of oil equivalent, MYS = Malaysia.
Source: Author.

Figure A.61. Final Energy Consumption (MYS-CN2050/2060_w/oCarbonSink)



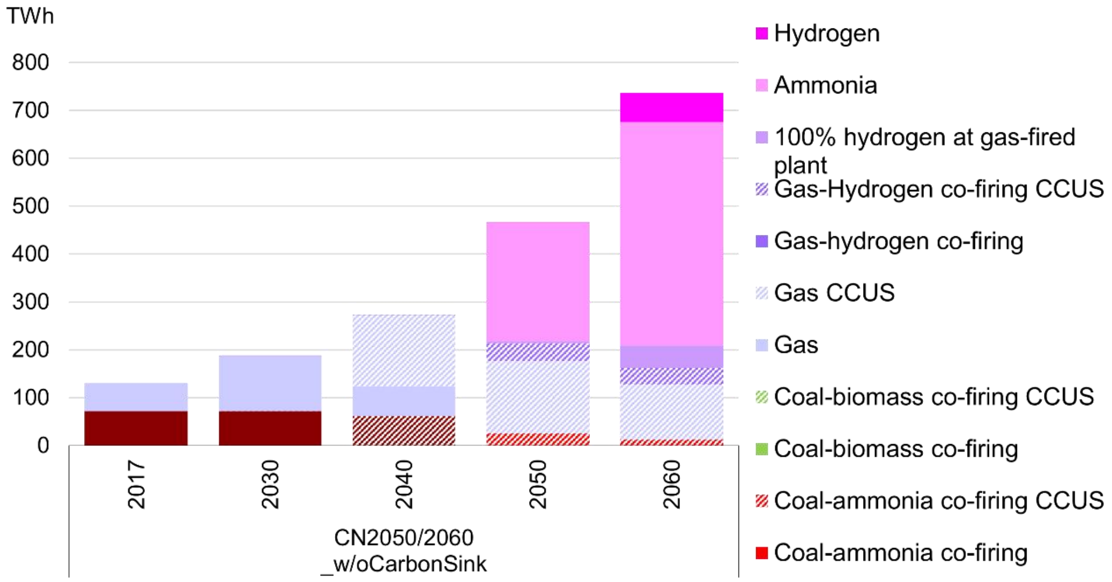
Mtoe = million tonnes of oil equivalent, MYS = Malaysia.
Source: Author.

Figure A.62. Power Generation (MYS-CN2050/2060_w/oCarbonSink)



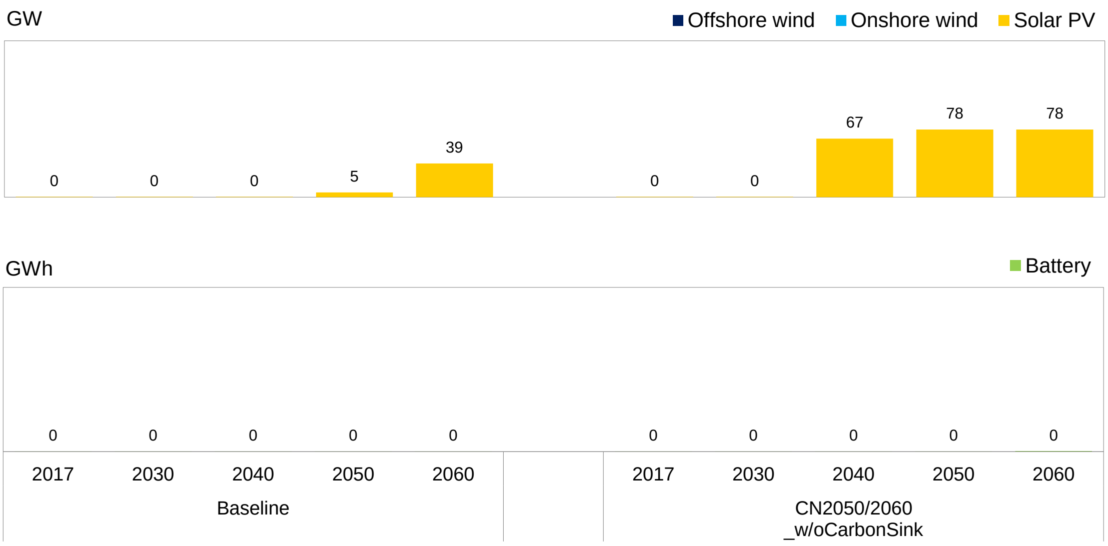
MYS = Malaysia, PV = photovoltaic, TWh = terawatt-hour.
Source: Author.

Figure A.63. Generated Electricity from Coal, Gas, Ammonia, and Hydrogen (MYS-CN2050/2060_w/oCarbonSink)



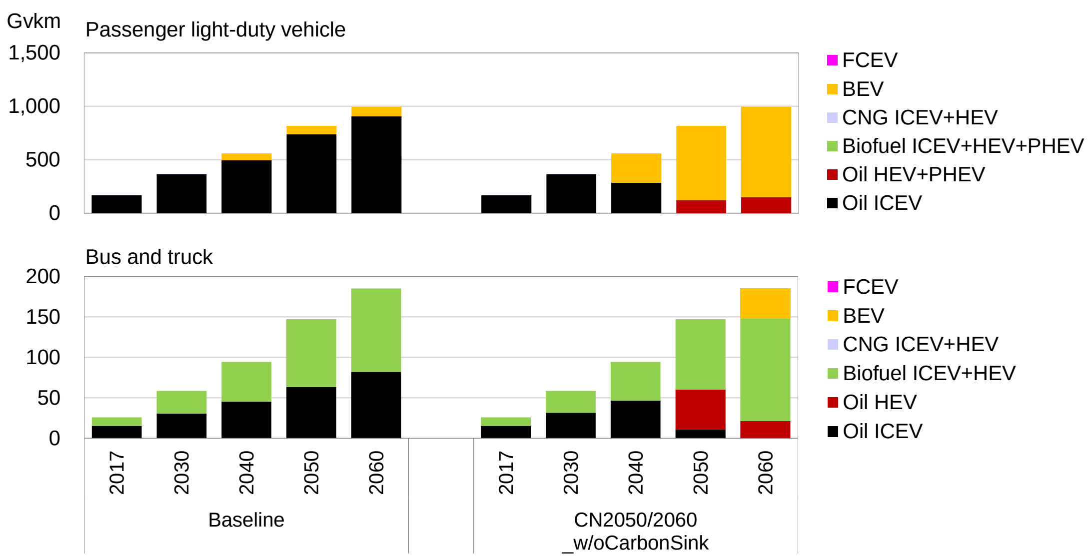
CCUS = carbon dioxide capture, utilisation, and storage; MYS = Malaysia; TWh = terawatt-hour.
Source: Author.

Figure A.64. Variable Renewable Energy and Battery (MYS-CN2050/2060_w/oCarbonSink)



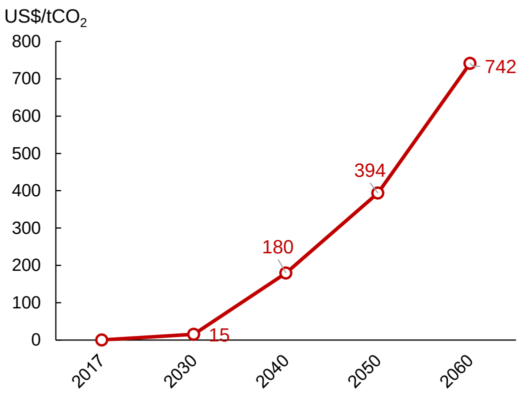
GW = gigawatt, GWh = gigawatt-hour, MYS = Malaysia, PV = photovoltaic.
Source: Author.

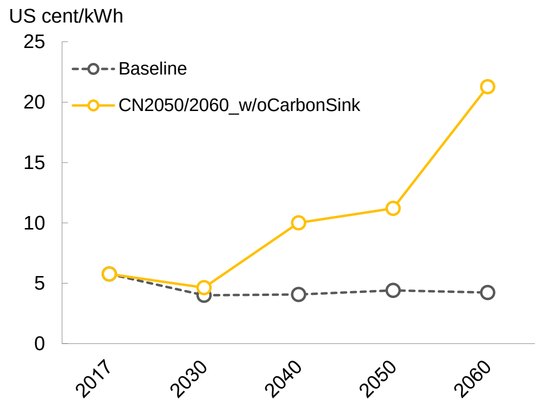
Figure A.65. Travel Distance by Vehicle Technology (MYS-CN2050/2060_w/oCarbonSink)



BEV = battery electric vehicle, CN = carbon neutral, CNG = compressed natural gas, FCEV = fuel cell electric vehicle, HEV = hybrid electric vehicle, ICEV = internal combustion engine vehicle, Gvkm = 10^9 vehicle-km, MYS = Malaysia, PHEV = plug-in hybrid electric vehicle.
Source: Author.

Figure A.66. Marginal Carbon Dioxide Abatement Cost (Left), Electricity Price (Right) (MYS-CN2050/2060_w/oCarbonSink)





kWh = kilowatt-hour, MYS = Malaysia, tCO_2 = tonne of carbon dioxide.
Source: Author.

Table A.10. Carbon Dioxide Emission Baseline and without Carbon Sink Scenarios (MYS-CN2050/2060_w/oCarbonSink)

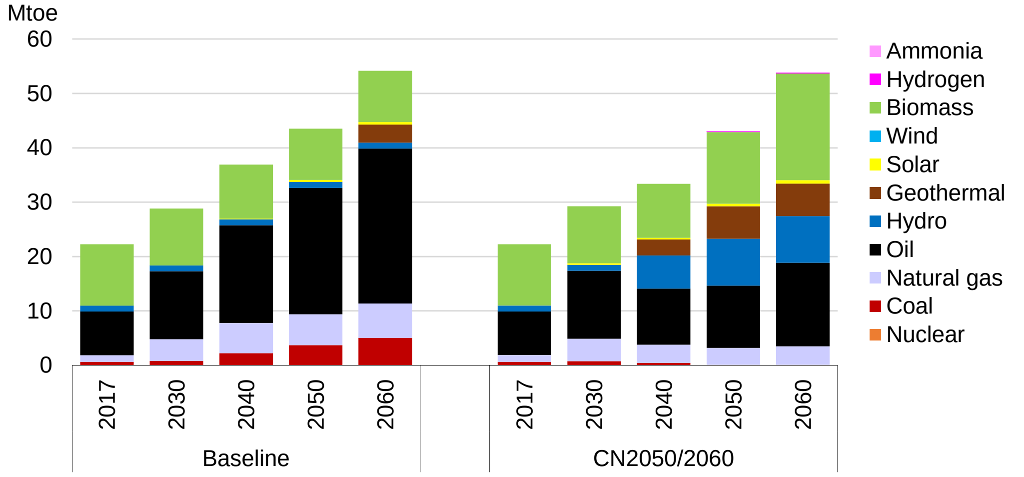
	Baseline ($MtCO_2$)					MYS-CN2050/2060_w/oCarbonSink ($MtCO_2$)				
	2017	**2030**	**2040**	**2050**	**2060**	**2017**	**2030**	**2040**	**2050**	**2060**
Electricity	104.75	130.24	196.17	220.09	240.03	104.67	122.86	24.99	-10.62	-13.11
Industry	29.94	41.97	54.04	68.22	82.53	29.94	42.18	52.18	42.67	49.75
Transport	67.38	123.07	153.51	204.83	252.19	67.48	123.07	103.94	46.55	42.51
Other end use	5.81	20.17	25.07	27.16	23.74	5.81	20.12	24.90	24.76	20.84
Other including DACCS	5.29	5.29	5.29	5.29	5.29	5.29	4.60	2.53	0.90	-99.98
LULUCF										
Energy-related CO_2 emissions	213.17	320.74	434.06	525.60	603.78	213.19	312.82	208.55	104.27	0.00

MYS = Malaysia, $MtCO_2$ = Million tonne of carbon dioxide, DACCS = Direct Air Carbon Capture and Storage, LULUCF = land use, land-use change and forestry.
Source: Author.

6. Myanmar

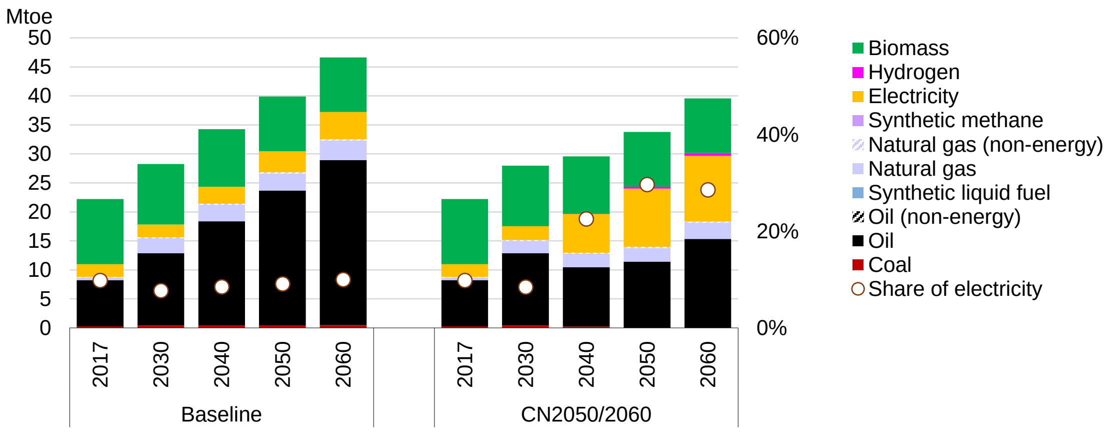
(a) CN2050/2060

Figure A.67. Primary Energy Supply (MMR-CN2050/2060)



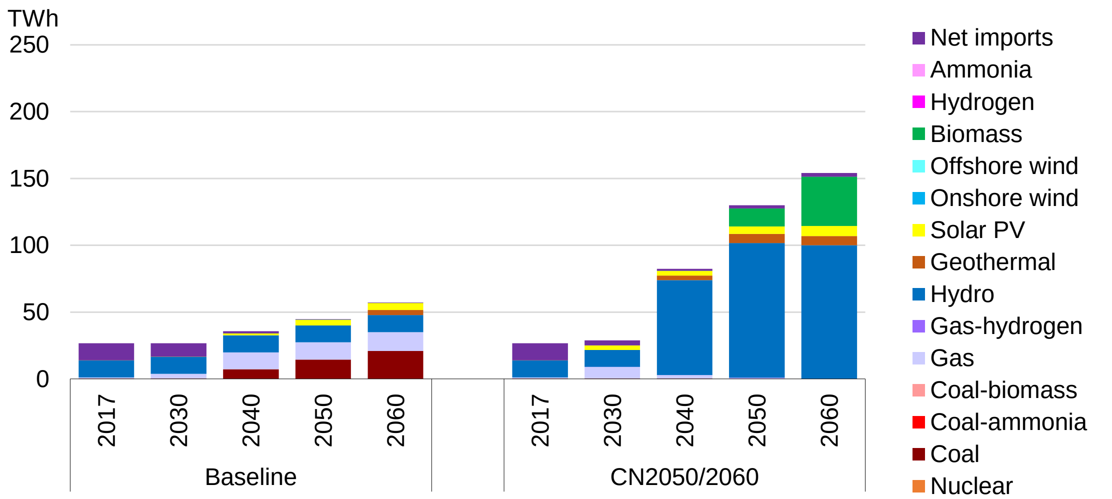
MMR = Myanmar, Mtoe = million tonnes of oil equivalent.
Source: Author.

Figure A.68. Final Energy Consumption (MMR-CN2050/2060)



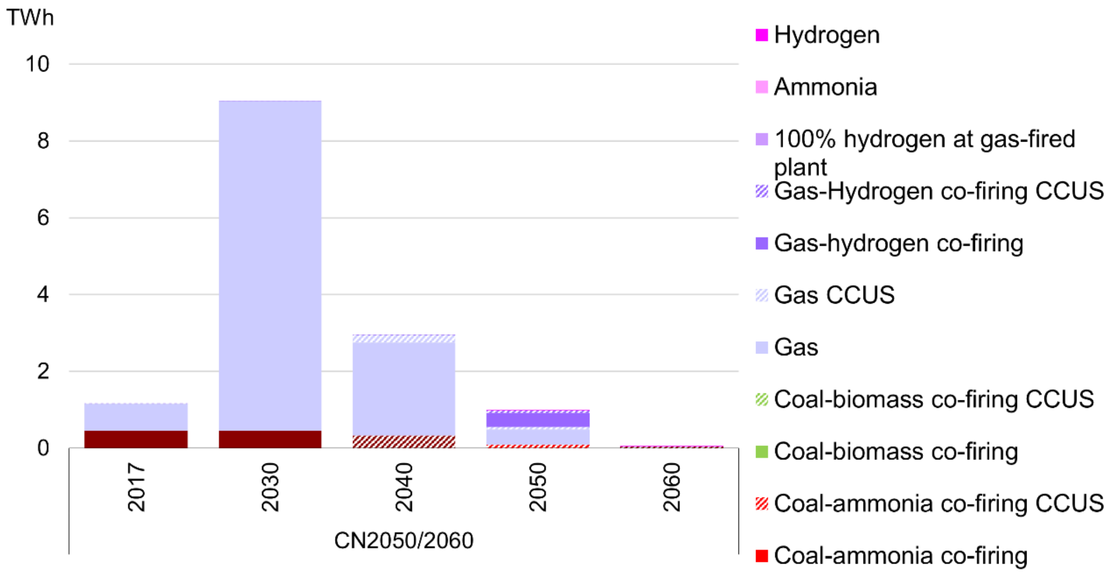
MMR = Myanmar, Mtoe = million tonnes of oil equivalent.
Source: Author.

Figure A.69. Power Generation (MMR-CN2050/2060)



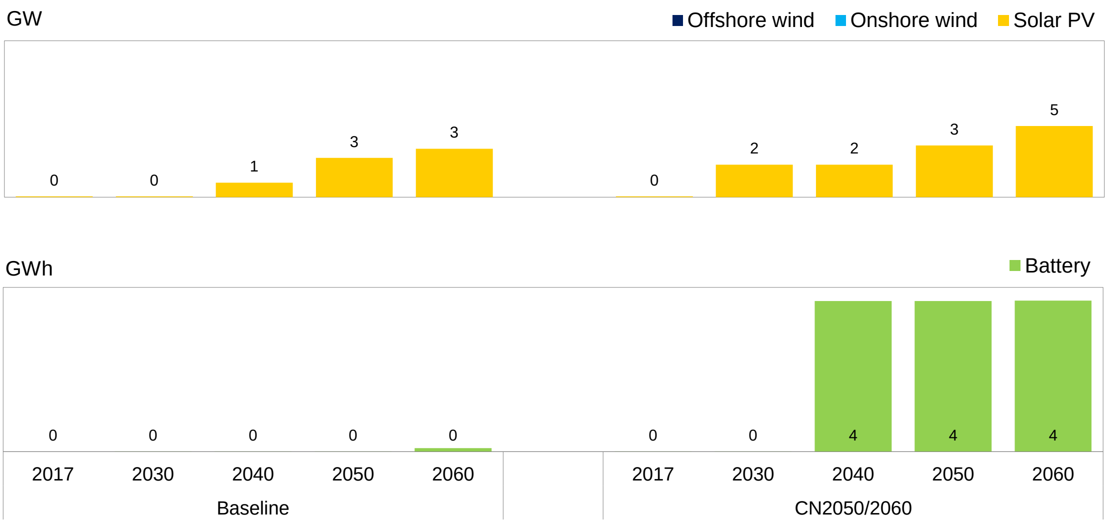
MMR = Myanmar, PV = photovoltaic, TWh = terawatt-hour.
Source: Author.

Figure A.70. Generated Electricity from Coal, Gas, Ammonia, and Hydrogen (MMR-CN2050/2060)



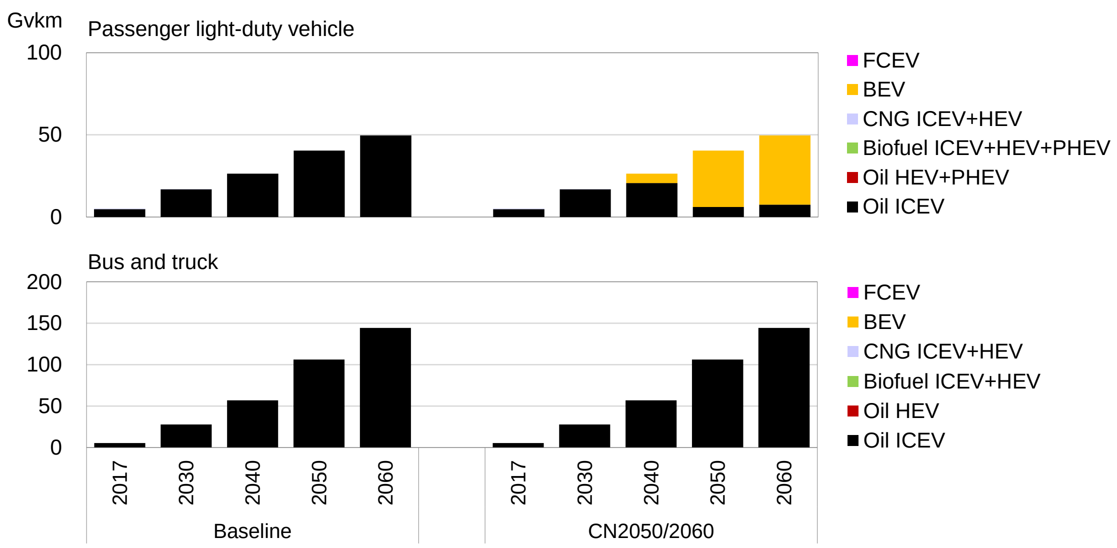
CCUS = carbon dioxide capture, utilisation, and storage; MMR = Myanmar; TWh = terawatt-hour.
Source: Author.

Figure A.71. Variable Renewable Energy and Battery (MMR-CN2050/2060)



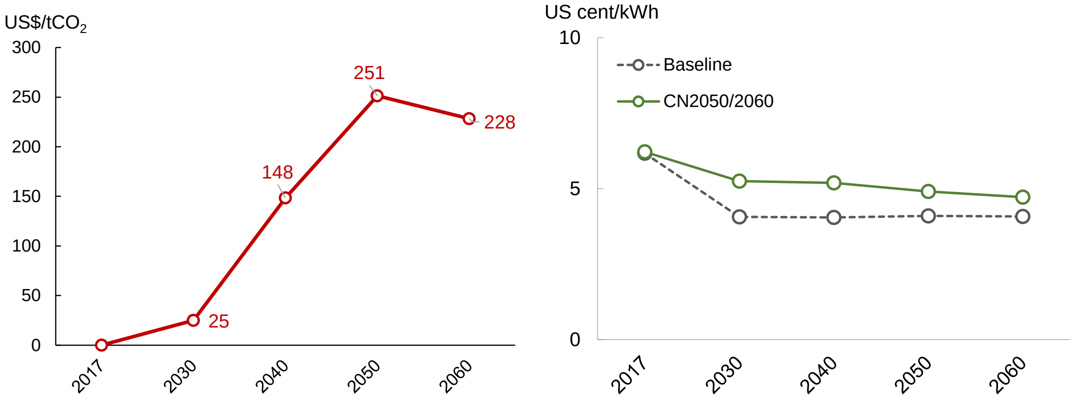
GW = gigawatt, GWh = gigawatt-hour, MMR = Myanmar, PV = photovoltaic.
Source: Author.

Figure A.72. Travel Distance by Vehicle Technology (MMR-CN2050/2060)



BEV = battery electric vehicle, CN = carbon neutral, CNG = compressed natural gas, FCEV = fuel cell electric vehicle, HEV = hybrid electric vehicle, ICEV = internal combustion engine vehicle, Gvkm = 10^9 vehicle-km, MMR = Myanmar, PHEV = plug-in hybrid electric vehicle.
Source: Author.

Figure A.73. Marginal Carbon Dioxide Abatement Cost (Left), Electricity Price (Right) (MMR-CN2050/2060)



kWh = kilowatt-hour, MMR = Myanmar, tCO_2 = tonne of carbon dioxide.
Source: Author.

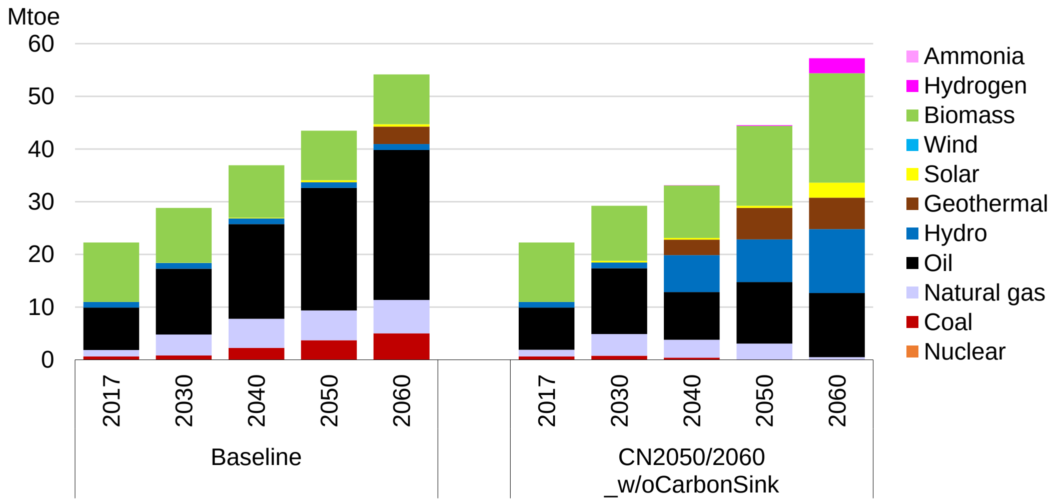
Table A.11. Carbon Dioxide Emission Baseline and without Carbon Sink Scenarios (MMR-CN2050/2060)

	Baseline ($MtCO_2$)					MMR-CN2050/2060 ($MtCO_2$)				
	2017	**2030**	**2040**	**2050**	**2060**	**2017**	**2030**	**2040**	**2050**	**2060**
Electricity	1.53	2.87	11.40	17.20	22.86	1.57	4.31	0.99	-15.52	-42.68
Industry	15.11	24.09	31.87	35.91	41.61	15.11	23.41	6.83	2.56	2.90
Transport	7.84	17.99	27.51	40.16	50.76	7.84	17.99	26.66	32.91	44.37
Other end use	3.09	5.00	5.64	5.64	6.89	3.09	3.84	4.32	4.86	6.26
Other including DACCS	1.70	1.70	1.70	1.70	1.70	1.70	1.56	1.16	1.16	1.16
LULUCF						50.46	25.66	-12.90	-12.90	-12.90
Energy-related CO_2 emissions	29.27	51.63	78.12	100.60	123.82	29.31	51.12	39.95	25.97	12.00

MMR = Myanmar, $MtCO_2$ = Million tonne of carbon dioxide, DACCS = Direct Air Carbon Capture and Storage, LULUCF = land use, land-use change and forestry.
Source: Author.

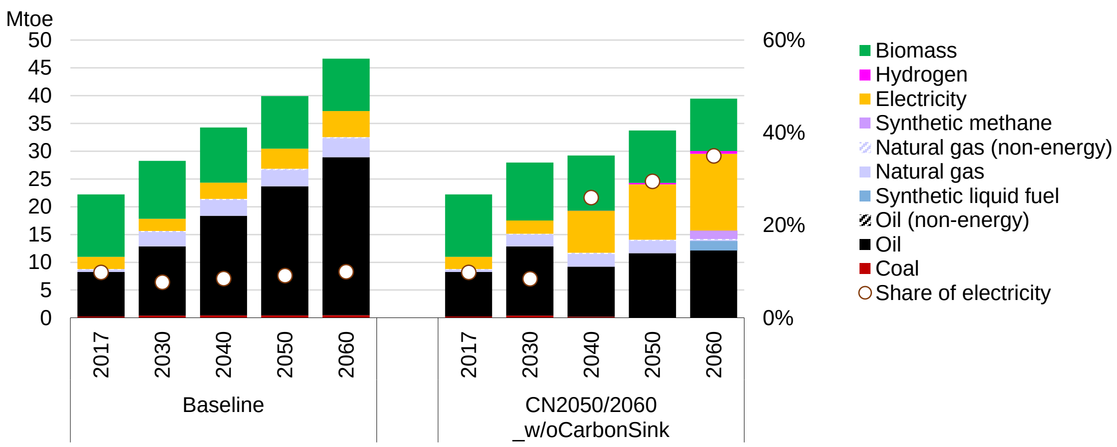
(b) CN2050/2060_w/oCarbonSink

Figure A.74. Primary Energy Supply (MMR-CN2050/2060_w/oCarbonSink)



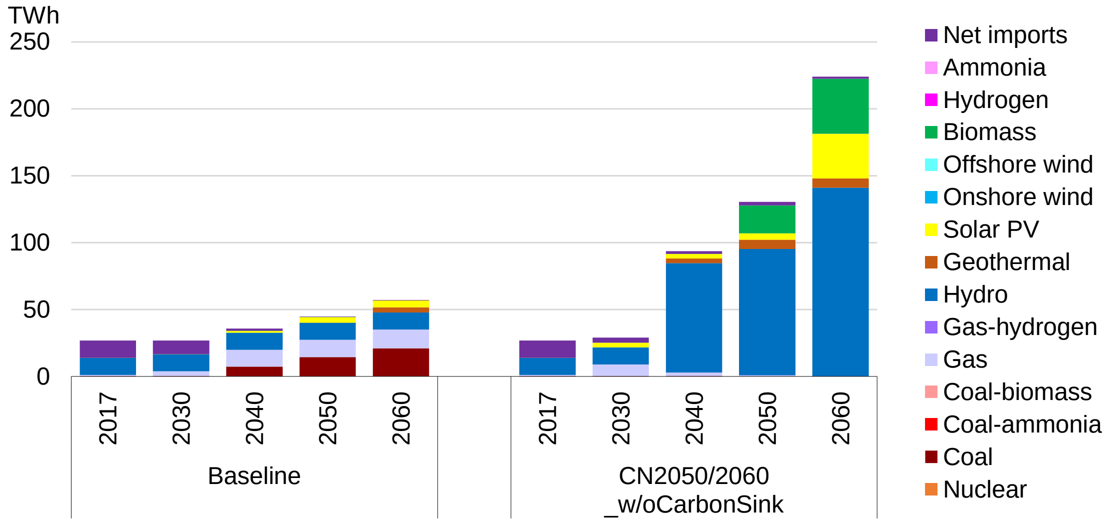
MMR = Myanmar, Mtoe = million tonnes of oil equivalent.
Source: Author.

Figure A.75. Final Energy Consumption (MMR-CN2050/2060_w/oCarbonSink)



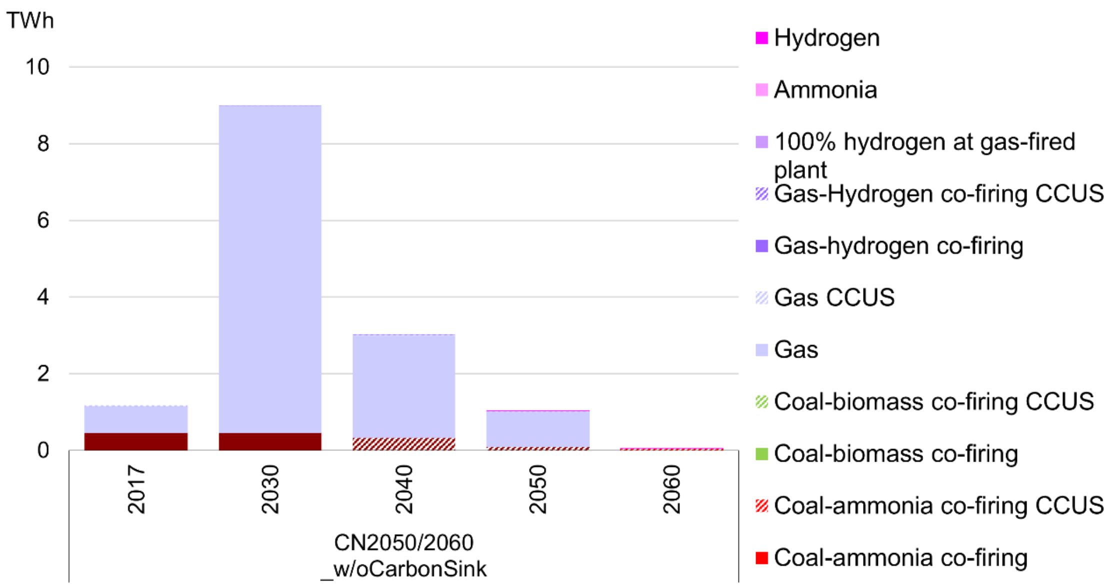
MMR = Myanmar, Mtoe = million tonnes of oil equivalent.
Source: Author.

Figure A.76. Power Generation (MMR-CN2050/2060_w/oCarbonSink)



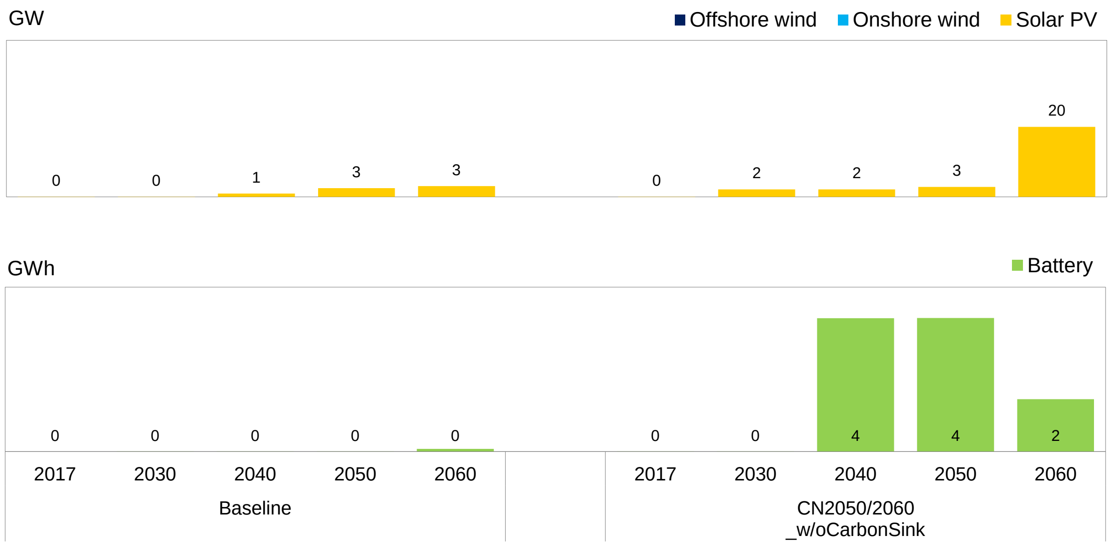
MMR = Myanmar, PV = photovoltaic, TWh = terawatt-hour.
Source: Author.

Figure A.77. Generated electricity from Coal, Gas, Ammonia, and Hydrogen (MMR-CN2050/2060_w/oCarbonSink)



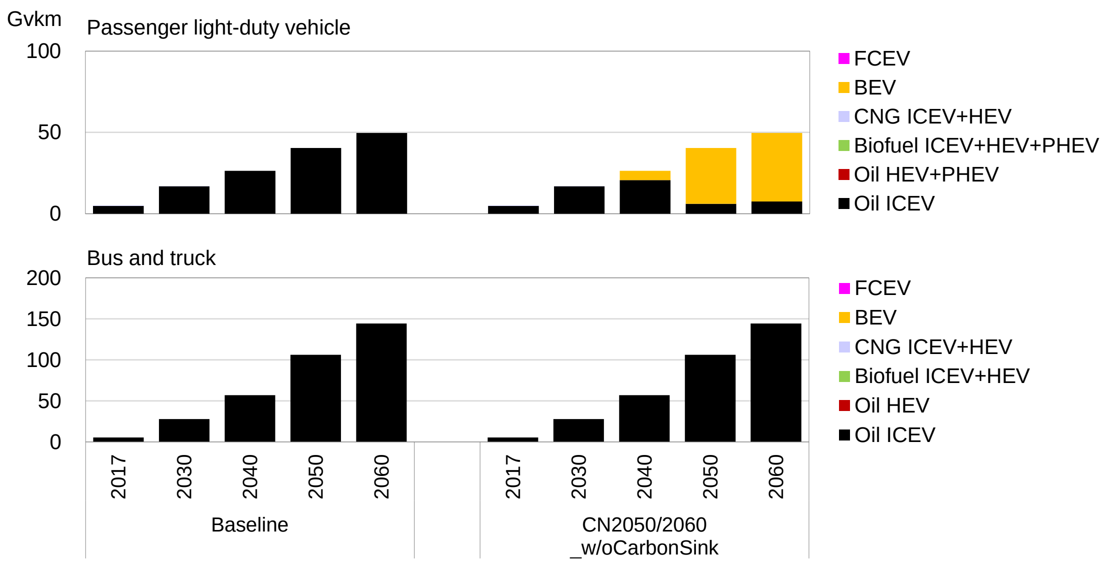
CCUS = carbon dioxide capture, utilisation, and storage; MMR = Myanmar; TWh = terawatt-hour.
Source: Author.

Figure A.78. Variable Renewable Energy and Battery (MMR-CN2050/2060_w/oCarbonSink)



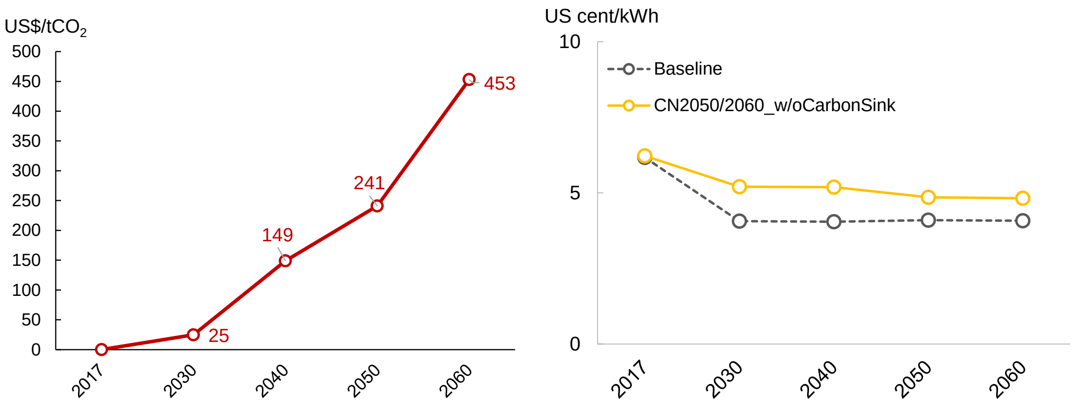
GW = gigawatt, GWh = gigawatt-hour, MMR = Myanmar, PV = photovoltaic.
Source: Author.

Figure A.79. Travel Distance by Vehicle Technology (MMR-CN2050/2060_w/oCarbonSink)



BEV = battery electric vehicle, CN = carbon neutral, CNG = compressed natural gas, FCEV = fuel cell electric vehicle, HEV = hybrid electric vehicle, ICEV = internal combustion engine vehicle, Gvkm = 10^9 vehicle-km, MMR = Myanmar, PHEV = plug-in hybrid electric vehicle.
Source: Author.

Figure A.80. Marginal Carbon Dioxide Abatement Cost (Left), Electricity Price (Right) (MMR-CN2050/2060_w/oCarbonSink)



kWh = kilowatt-hour, MMR = Myanmar, tCO_2 = tonne of carbon dioxide.
Source: Author.

Table A.12. Carbon Dioxide Emission Baseline and without Carbon Sink Scenarios (MMR-CN2050/2060_w/oCarbonSink)

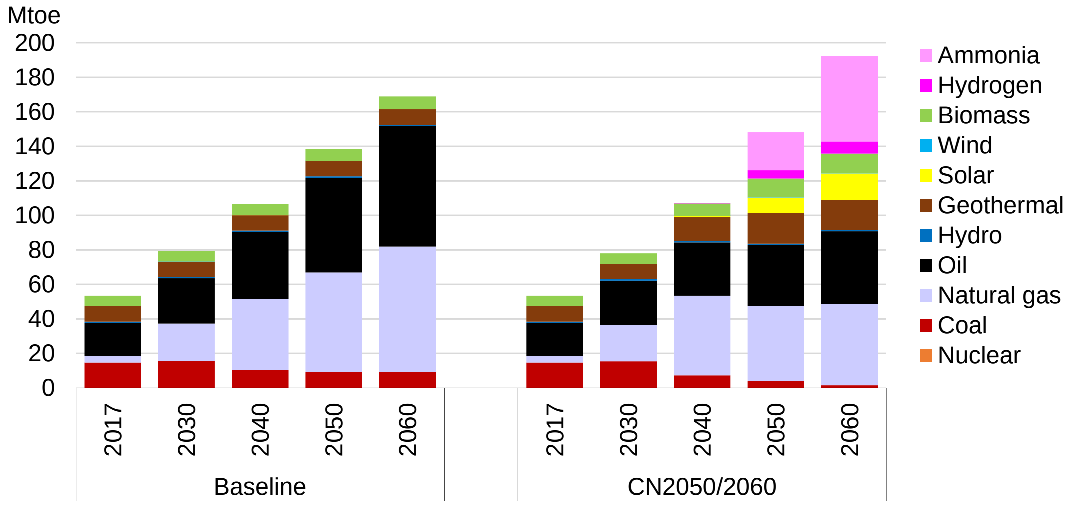
	Baseline ($MtCO_2$)					MMR-CN2050/2060_w/oCarbonSink ($MtCO_2$)				
	2017	**2030**	**2040**	**2050**	**2060**	**2017**	**2030**	**2040**	**2050**	**2060**
Electricity	1.53	2.87	11.40	17.20	22.86	1.57	4.29	1.08	-23.90	-47.80
Industry	15.11	24.09	31.87	35.91	41.61	15.11	23.44	2.74	2.56	2.78
Transport	7.84	17.99	27.51	40.16	50.76	7.84	17.99	26.66	33.84	39.46
Other end use	3.09	5.00	5.64	5.64	6.89	3.09	3.84	4.32	4.32	3.71
Other including DACCS	1.70	1.70	1.70	1.70	1.70	1.70	1.56	1.16	1.16	1.86
LULUCF										
Energy-related CO_2 emissions	29.27	51.63	78.12	100.60	123.82	29.31	51.12	35.95	17.98	0.00

MMR = Myanmar, $MtCO_2$ = Million tonne of carbon dioxide, DACCS = Direct Air Carbon Capture and Storage, LULUCF = land use, land-use change and forestry.
Source: Author.

7. Philippines

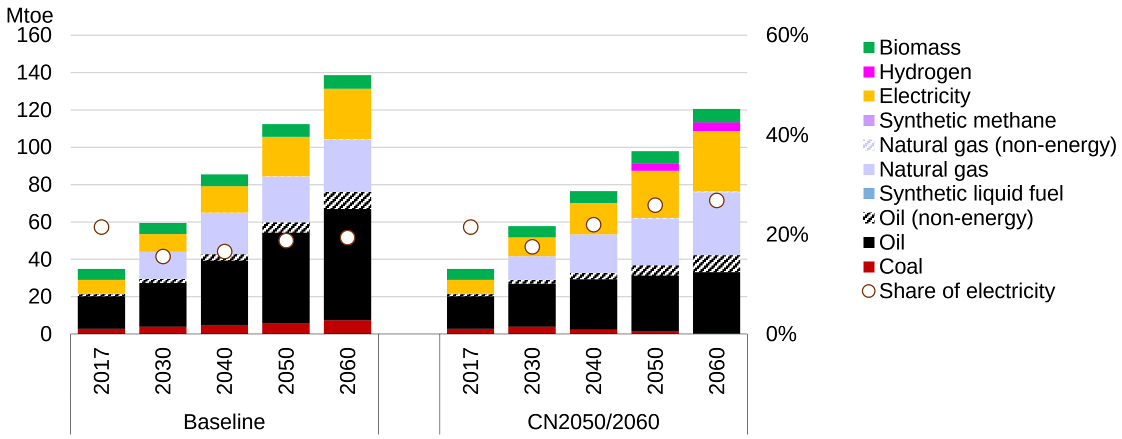
(a) CN2050/2060

Figure A.81. Primary Energy Supply (PHL-CN2050/2060)



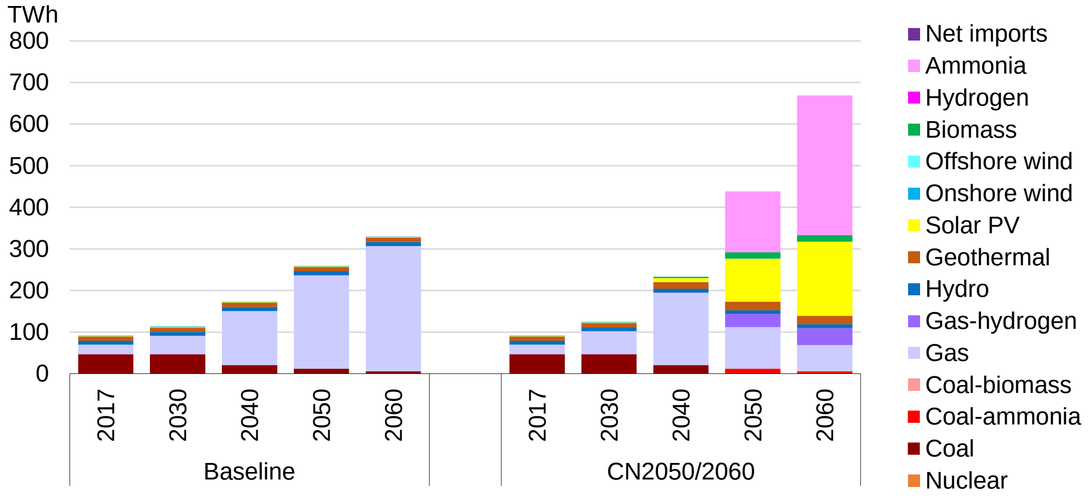
Mtoe = million tonnes of oil equivalent, PHL = Philippines.
Source: Author.

Figure A.82. Final Energy Consumption (PHL-CN2050/2060)



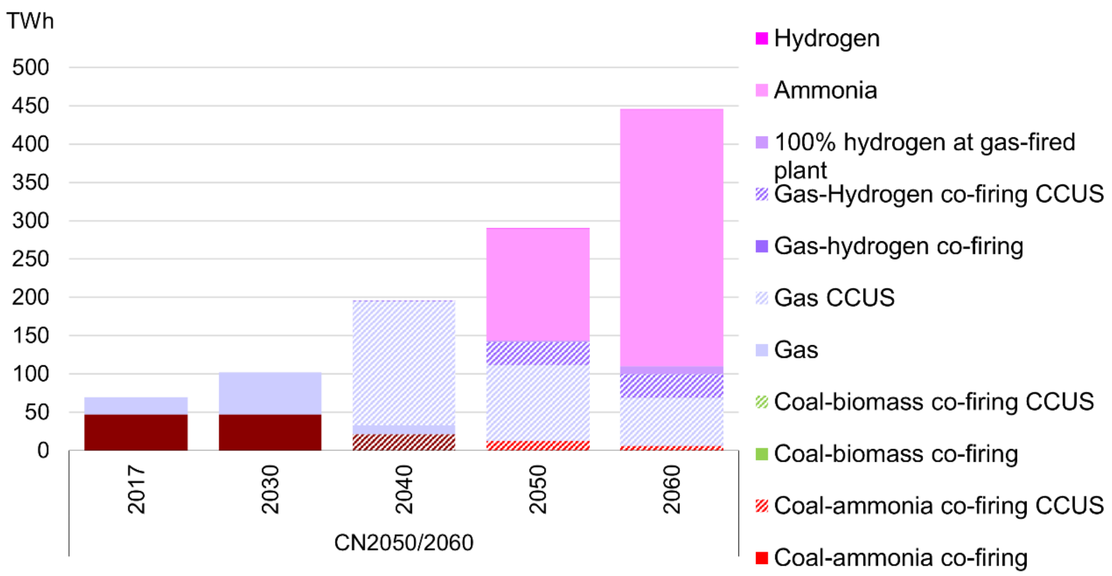
Mtoe = million tonnes of oil equivalent, PHL = Philippines.
Source: Author.

Figure A.83. Power Generation (PHL-CN2050/2060)



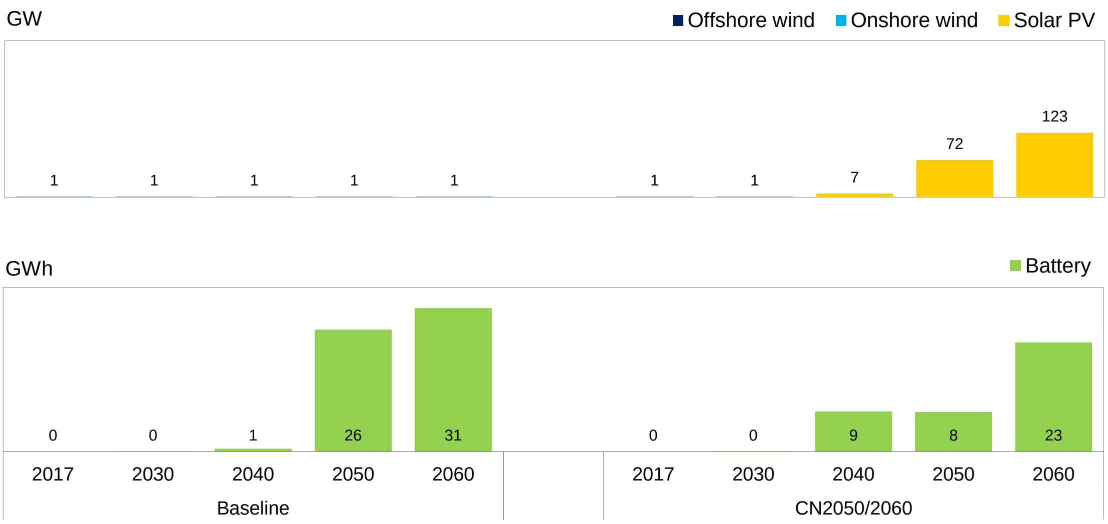
PHL = Philippines, PV = photovoltaic, TWh = terawatt-hour.
Source: Author.

Figure A.84. Generated Electricity from Coal, Gas, Ammonia, and Hydrogen (PHL-CN2050/2060)



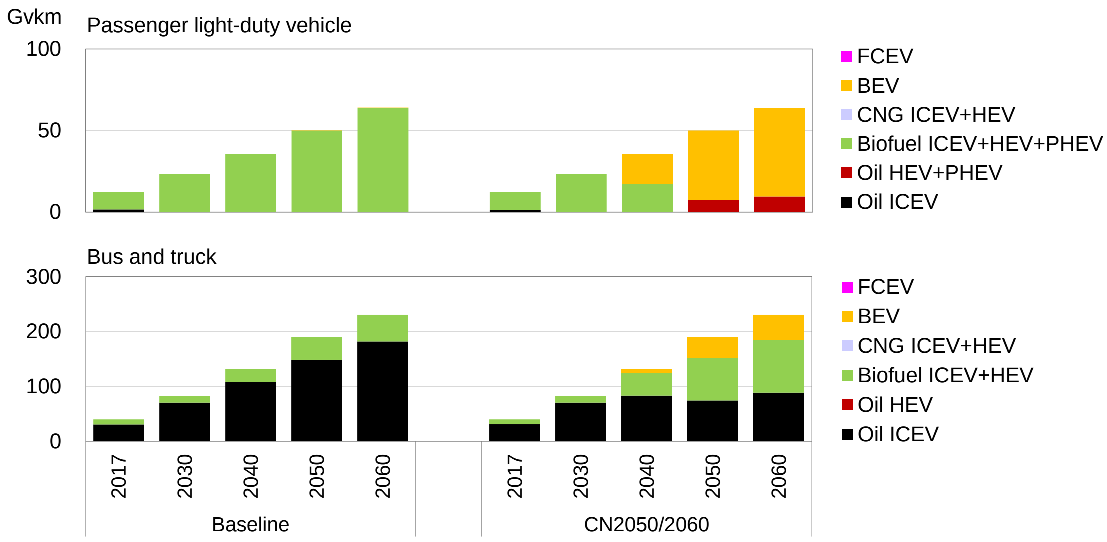
CCUS = carbon dioxide capture, utilisation, and storage; PHL = Philippines; TWh = terawatt-hour.
Source: Author.

Figure A.85. Variable Renewable Energy and Battery (PHL-CN2050/2060)



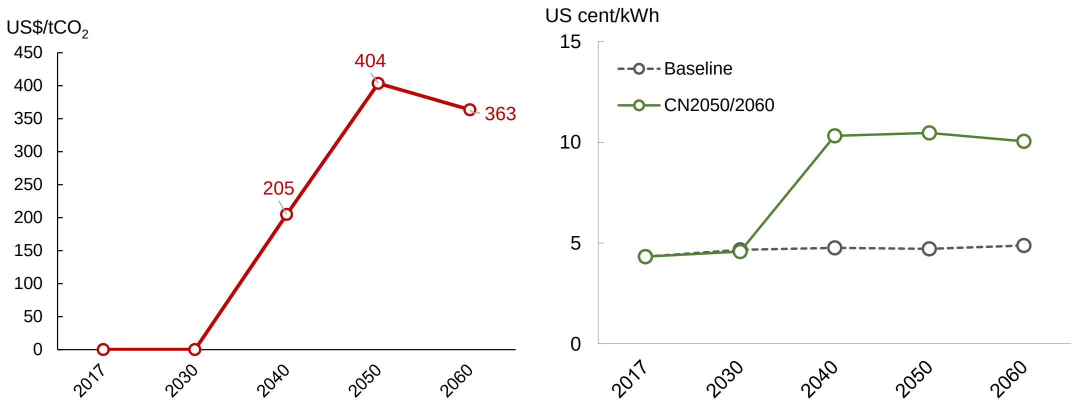
GW = gigawatt, GWh = gigawatt-hour, PHL = Philippines, PV = photovoltaic.
Source: Author.

Figure A.86. Travel Distance by Vehicle Technology (PHL-CN2050/2060)



BEV = battery electric vehicle, CN = carbon neutral, CNG = compressed natural gas, FCEV = fuel cell electric vehicle, HEV = hybrid electric vehicle, ICEV = internal combustion engine vehicle, Gvkm = 10^9 vehicle-km, PHEV = plug-in hybrid electric vehicle, PHL = Philippines.
Source: Author.

Figure A.87. Marginal Carbon Dioxide Abatement Cost (Left), Electricity Price (Right) (PHL-CN2050/2060)



kWh = kilowatt-hour, PHL = Philippines, tCO_2 = tonne of carbon dioxide.
Source: Author.

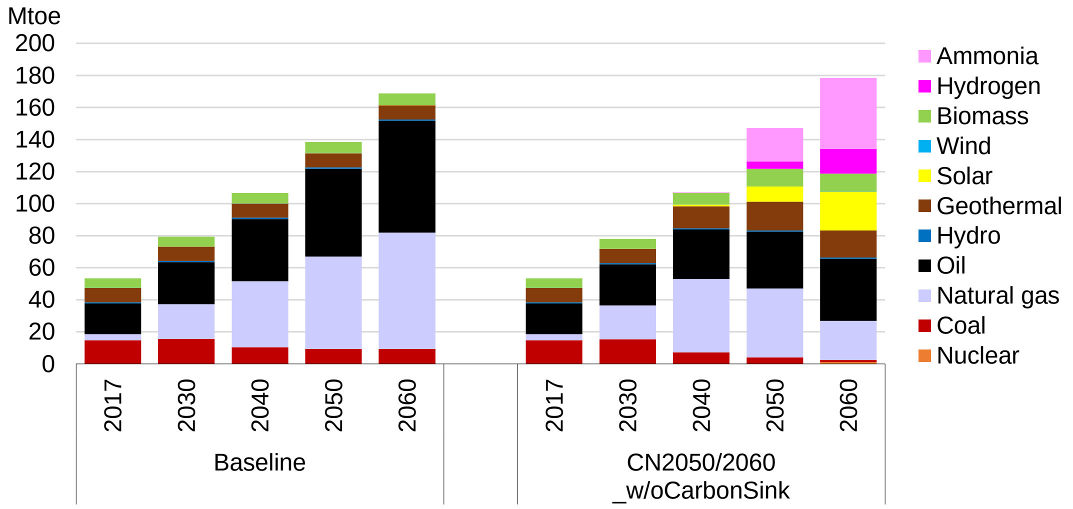
Table A.13. Carbon Dioxide Emission Baseline and with Carbon Sink Scenarios (PHL-CN2050/2060)

	Baseline ($MtCO_2$)					PHL-CN2050/2060 ($MtCO_2$)				
	2017	**2030**	**2040**	**2050**	**2060**	**2017**	**2030**	**2040**	**2050**	**2060**
Electricity	52.31	60.29	64.83	89.15	109.99	52.31	63.54	7.99	-12.33	-14.00
Industry	15.70	30.08	44.91	67.23	95.25	15.70	28.85	23.26	28.79	36.61
Transport	32.71	57.94	83.46	108.35	127.91	32.71	57.94	75.75	74.04	86.24
Other end use	15.70	34.63	49.63	55.70	58.00	15.70	29.42	41.69	53.04	57.79
Other including DACCS	5.33	4.11	4.47	4.79	5.23	5.33	3.35	1.42	-68.49	-166.63
LULUCF						0.00	0.00	0.00	0.00	0.00
Energy-related CO_2 emissions	121.75	187.04	247.29	325.23	396.38	121.75	183.09	150.11	75.05	0.00

PHL = Philippines, $MtCO_2$ = Million tonne of carbon dioxide, DACCS = Direct Air Carbon Capture and Storage, LULUCF = land use, land-use change and forestry.
Source: Author.

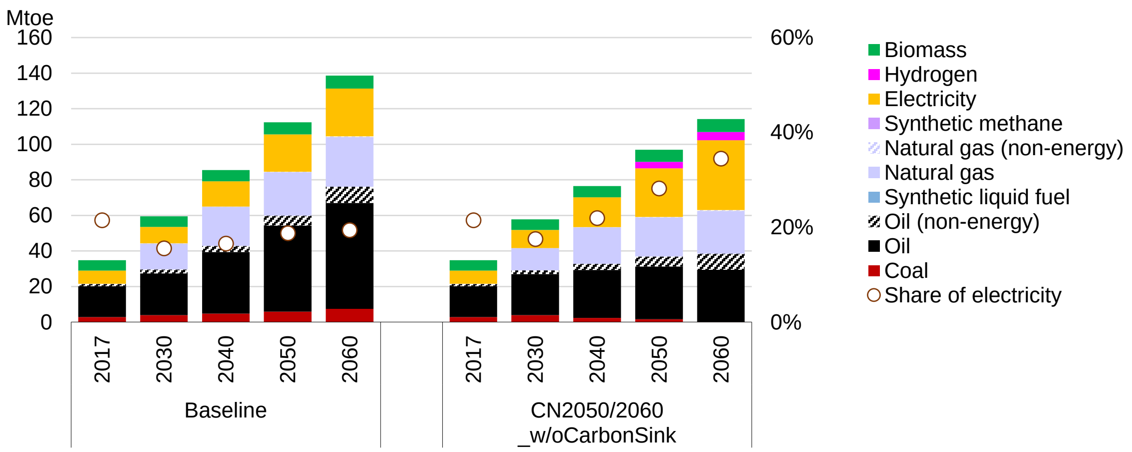
(b) CN2050/2060_w/oCarbonSink

Figure A.88. Primary energy supply (PHL-CN2050/2060_w/oCarbonSink)



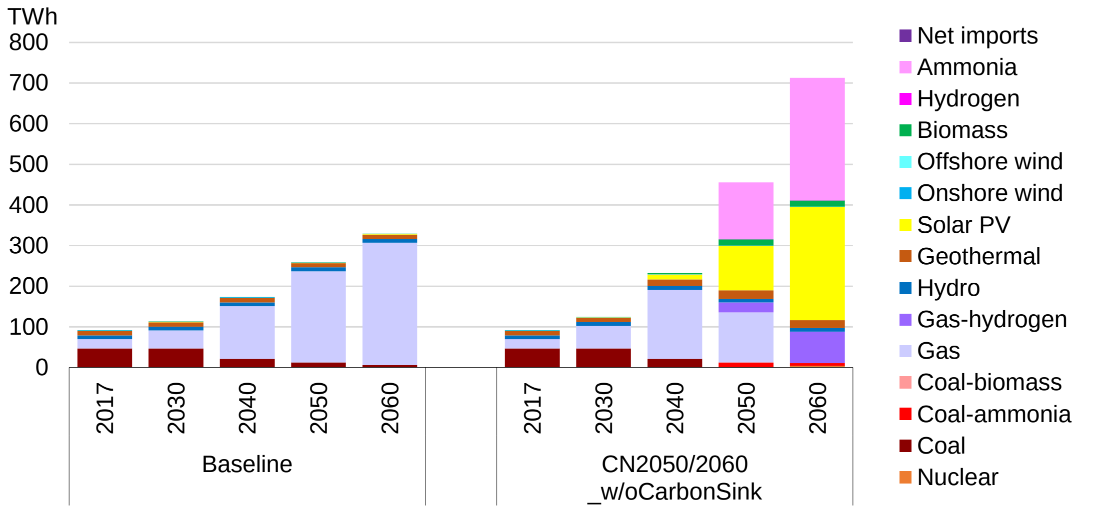
Mtoe = million tonnes of oil equivalent, PHL = Philippines.
Source: Author.

Figure A.89. Final Energy Consumption (PHL-CN2050/2060_w/oCarbonSink)



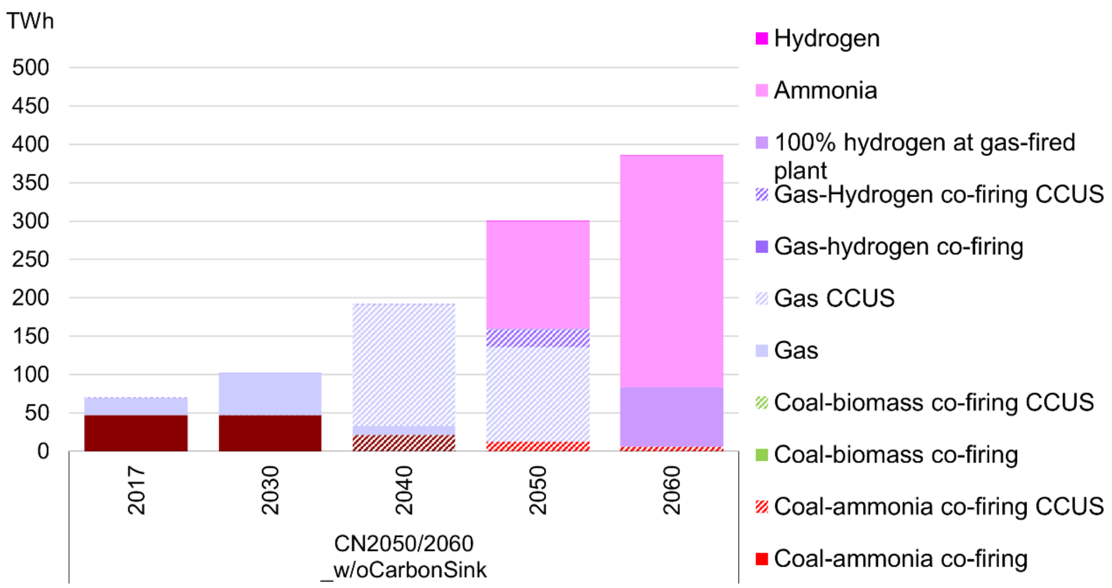
Mtoe = million tonnes of oil equivalent, PHL = Philippines.
Source: Author.

Figure A.90. Power Generation (PHL-CN2050/2060_w/oCarbonSink)



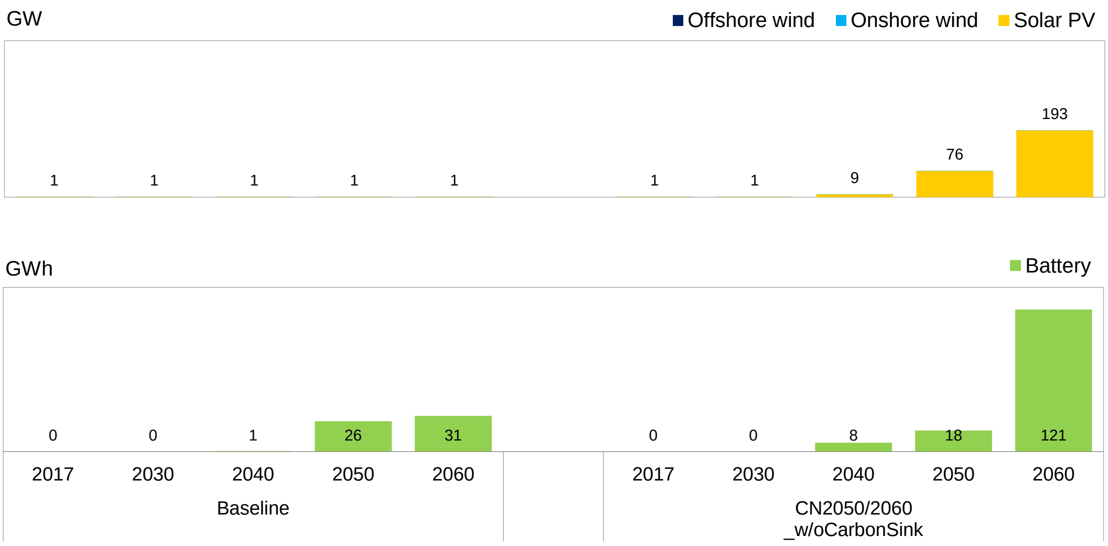
PHL = Philippines, PV = photovoltaic, TWh = terawatt-hour.
Source: Author.

Figure A.91. Generated Electricity from Coal, Gas, Ammonia, and Hydrogen (PHL-CN2050/2060_w/oCarbonSink)



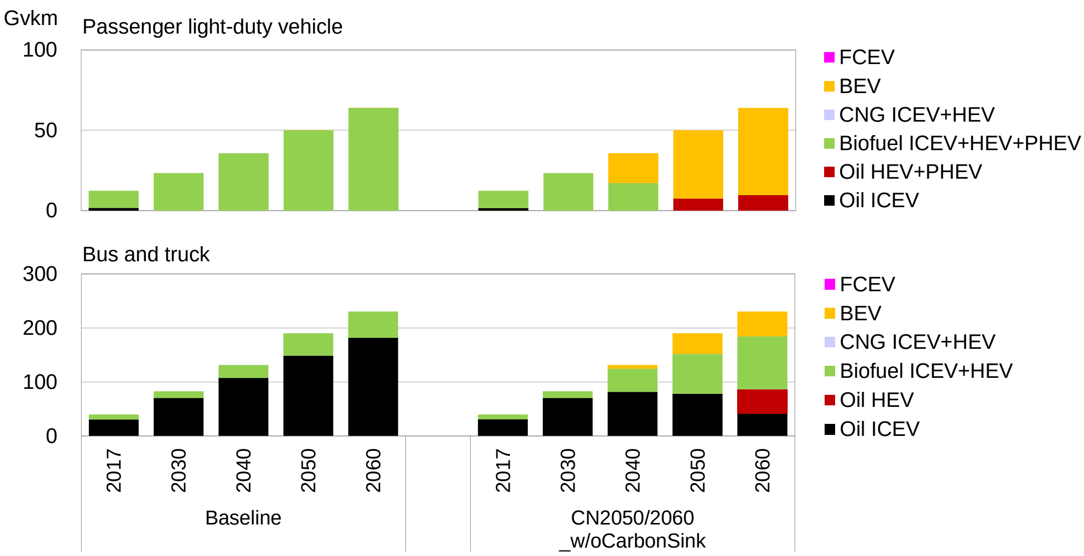
CCUS = carbon dioxide capture, utilisation, and storage; PHL = Philippines; TWh = terawatt-hour.
Source: Author.

Figure A.92. Variable Renewable Energy and Battery (PHL-CN2050/2060_w/oCarbonSink)



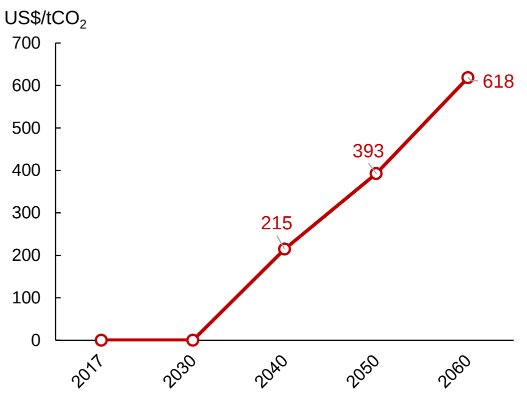
GW = gigawatt, GWh = gigawatt-hour, PHL = Philippines, PV = photovoltaic.
Source: Author.

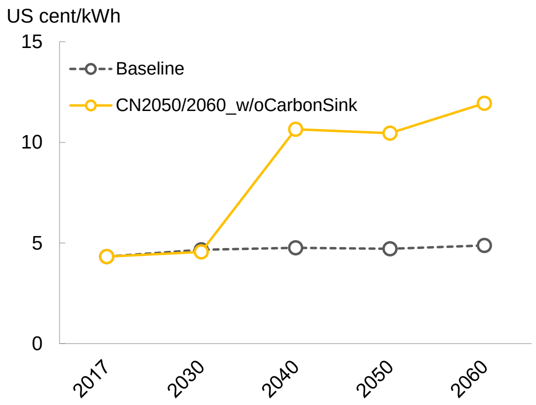
Figure A.93. Travel Distance by Vehicle Technology (PHL-CN2050/2060_w/oCarbonSink)



BEV = battery electric vehicle, CN = carbon neutral, CNG = compressed natural gas, FCEV = fuel cell electric vehicle, HEV = hybrid electric vehicle, ICEV = internal combustion engine vehicle, Gvkm = 10^9 vehicle-km, PHEV = plug-in hybrid electric vehicle, PHL = Philippines.
Source: Author.

Figure A.94. Marginal Carbon Dioxide Abatement Cost (Left), Electricity Price (Right) (PHL-CN2050/2060_w/oCarbonSink)





kWh = kilowatt-hour, PHL = Philippines, tCO_2 = tonne of carbon dioxide.
Source: Author.

Table A.14. Carbon Dioxide Emission Baseline and without Carbon Sink Scenarios (PHL-CN2050/2060_w/oCarbonSink)

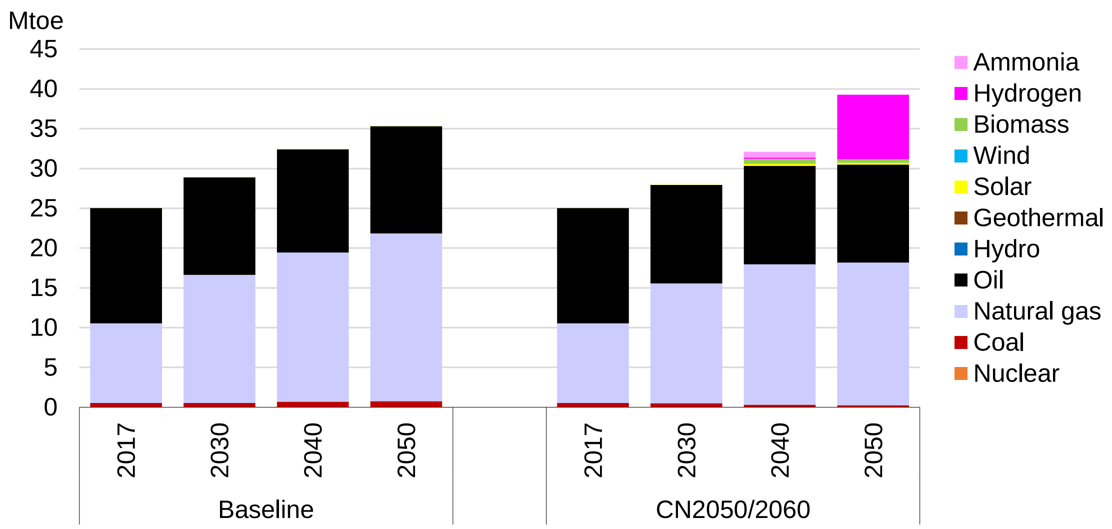
	Baseline ($MtCO_2$)					PHL-CN2050/2060_w/oCarbonSink ($MtCO_2$)				
	2017	**2030**	**2040**	**2050**	**2060**	**2017**	**2030**	**2040**	**2050**	**2060**
Electricity	52.31	60.29	64.83	89.15	109.99	52.31	63.53	7.89	-11.66	-17.09
Industry	15.70	30.08	44.91	67.23	95.25	15.70	28.85	23.27	22.48	15.71
Transport	32.71	57.94	83.46	108.35	127.91	32.71	57.94	75.84	74.04	75.99
Other end use	15.70	34.63	49.63	55.70	58.00	15.70	29.42	41.69	52.42	54.24
Other including DACCS	5.33	4.11	4.47	4.79	5.23	5.33	3.35	1.43	-62.22	-128.86
LULUCF										
Energy-related CO_2 emissions	121.75	187.04	247.29	325.23	396.38	121.75	183.09	150.11	75.05	0.00

PHL = Philippines, $MtCO_2$ = Million tonne of carbon dioxide, DACCS = Direct Air Carbon Capture and Storage, LULUCF = land use, land-use change and forestry.
Source: Author.

8. Singapore

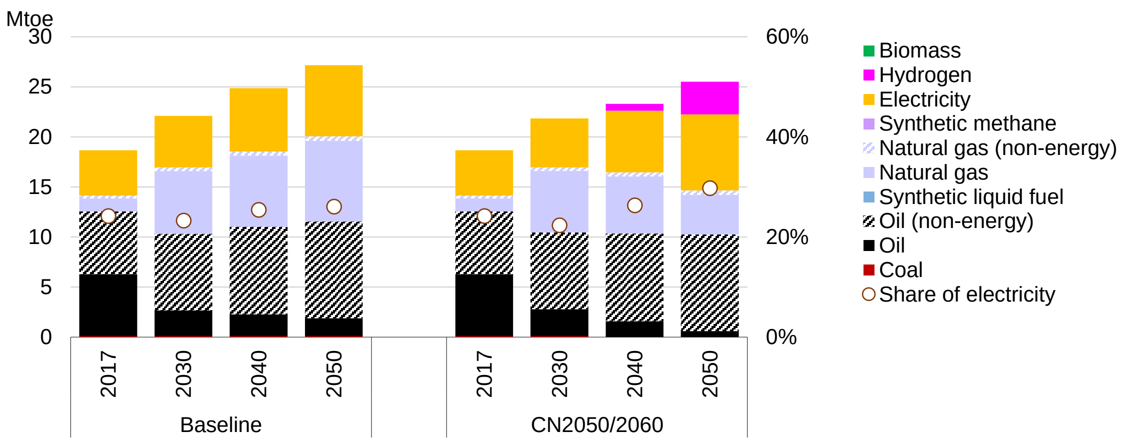
(a) CN2050/2060

Figure A.95. Primary Energy Supply (SGP-CN2050/2060)



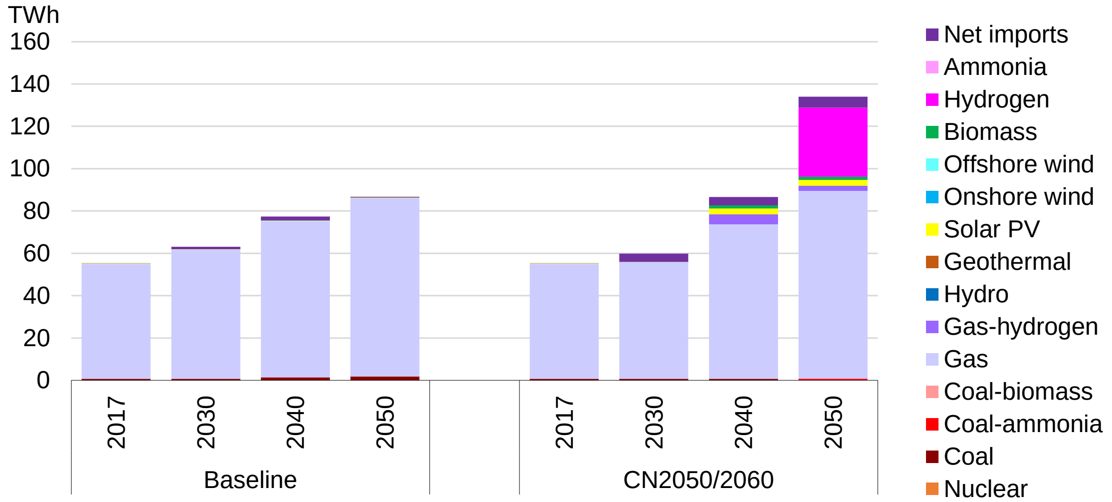
Mtoe = million tonnes of oil equivalent, SGP = Singapore.
Source: Author.

Figure A.96. Final Energy Consumption (SGP-CN2050/2060)



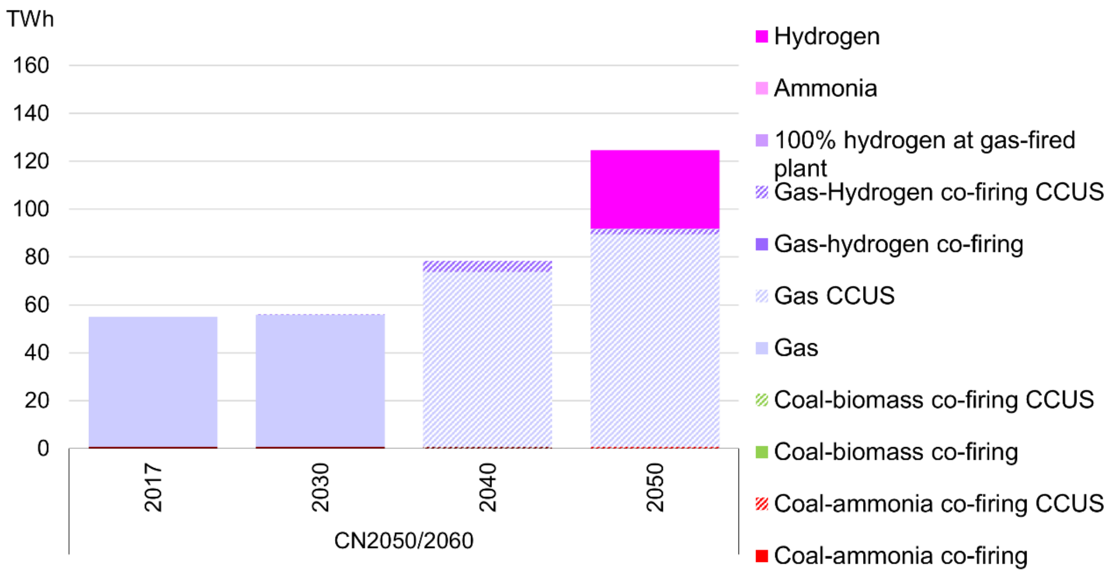
Mtoe = million tonnes of oil equivalent, SGP = Singapore.
Source: Author.

Figure A.97. Power Generation (SGP-CN2050/2060)



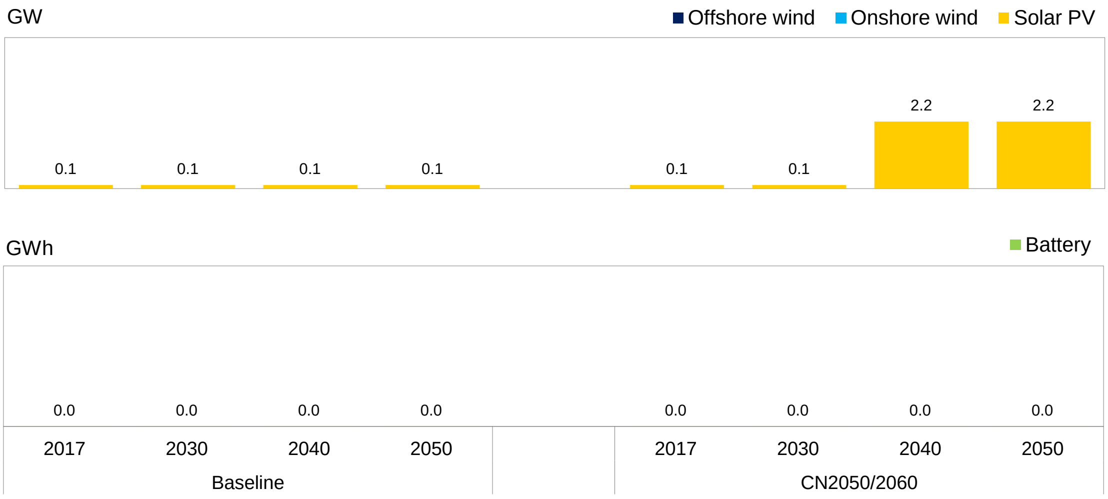
PV = photovoltaic, SGP = Singapore, TWh = terawatt-hour.
Source: Author.

Figure A.98. Generated Electricity from Coal, Gas, Ammonia, and Hydrogen (SGP-CN2050/2060)



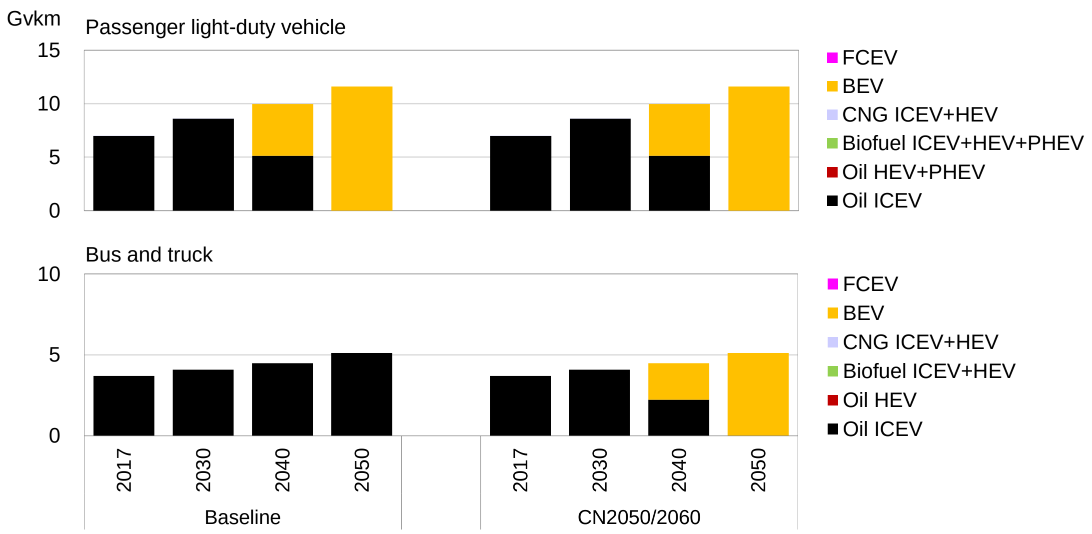
CCUS = carbon dioxide capture, utilisation, and storage; SGP = Singapore; TWh = terawatt-hour.
Source: Author.

Figure A.99. Variable Renewable Energy and Battery (SGP-CN2050/2060)



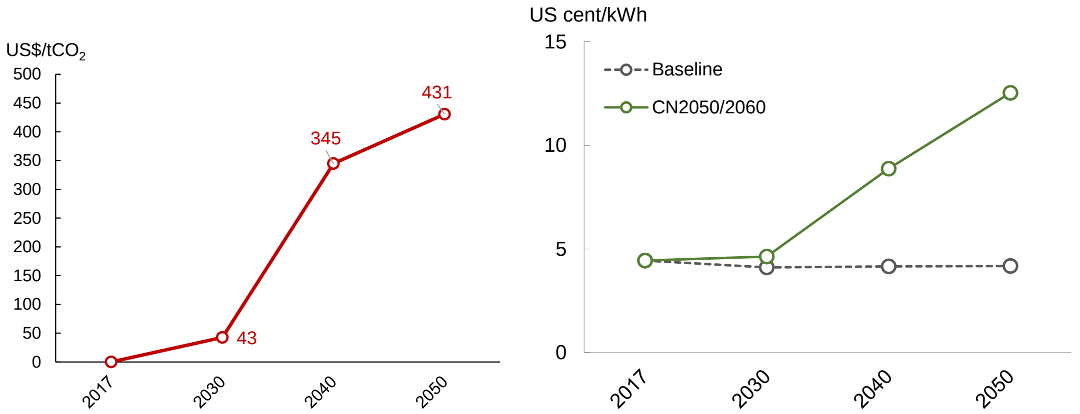
GW = gigawatt, GWh = gigawatt-hour, PV = photovoltaic, SGP = Singapore.
Source: Author.

Figure A.100. Travel Distance by Vehicle Technology (SGP-CN2050/2060)



BEV = battery electric vehicle, CN = carbon neutral, CNG = compressed natural gas, FCEV = fuel cell electric vehicle, HEV = hybrid electric vehicle, ICEV = internal combustion engine vehicle, Gvkm = 10^9 vehicle-km, PHEV = plug-in hybrid electric vehicle, SGP = Singapore.
Source: Author.

Figure A.101. Marginal Carbon Dioxide Abatement Cost (Left), Electricity Price (Right) (SGP-CN2050/2060)



SGP = Singapore, tCO_2 = tonne of carbon dioxide.
Source: Author.

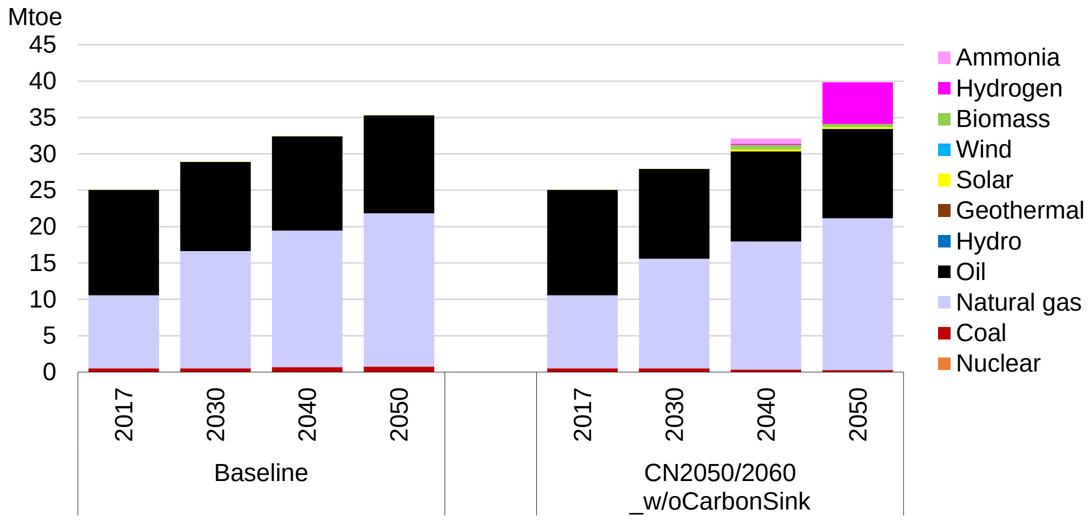
Table A.15. Carbon Dioxide Emission Baseline and with Carbon Sink Scenarios (SGP-CN2050/2060)

	Baseline ($MtCO_2$)					SGP-CN2050/2060 ($MtCO_2$)				
	2017	**2030**	**2040**	**2050**	**2060**	**2017**	**2030**	**2040**	**2050**	**2060**
Electricity	21.10	23.54	28.38	31.70	31.70	21.10	21.37	0.88	1.49	0.78
Industry	15.52	13.98	15.90	18.17	21.29	15.52	14.03	12.21	8.40	9.49
Transport	6.60	7.93	6.91	5.85	6.18	6.60	7.93	5.09	1.84	1.95
Other end use	0.60	0.95	0.93	0.89	0.94	0.60	0.95	0.92	0.87	0.91
Other including DACCS	6.57	6.57	6.57	6.57	6.57	6.57	6.51	6.30	-12.60	-13.13
LULUCF						0.00	0.00	0.00	0.00	0.00
Energy-related CO_2 emissions	50.40	52.97	58.68	63.18	66.68	50.40	50.79	25.39	0.00	0.00

SGP = Singapore, $MtCO_2$ = Million tonne of carbon dioxide, DACCS = Direct Air Carbon Capture and Storage, LULUCF = land use, land-use change and forestry.
Source: Author.

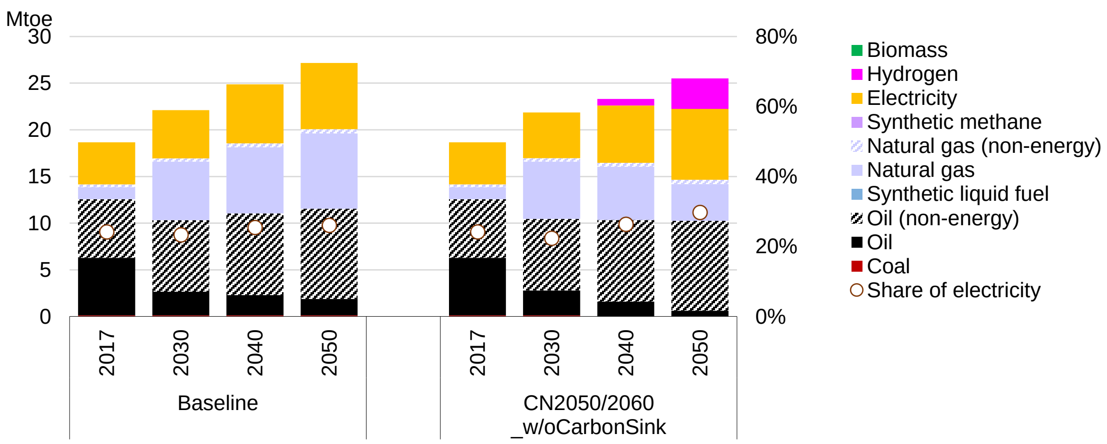
(b) CN2050/2060_w/oCarbonSink

Figure A.102. Primary Energy Supply (SGP-CN2050/2060_w/oCarbonSink)



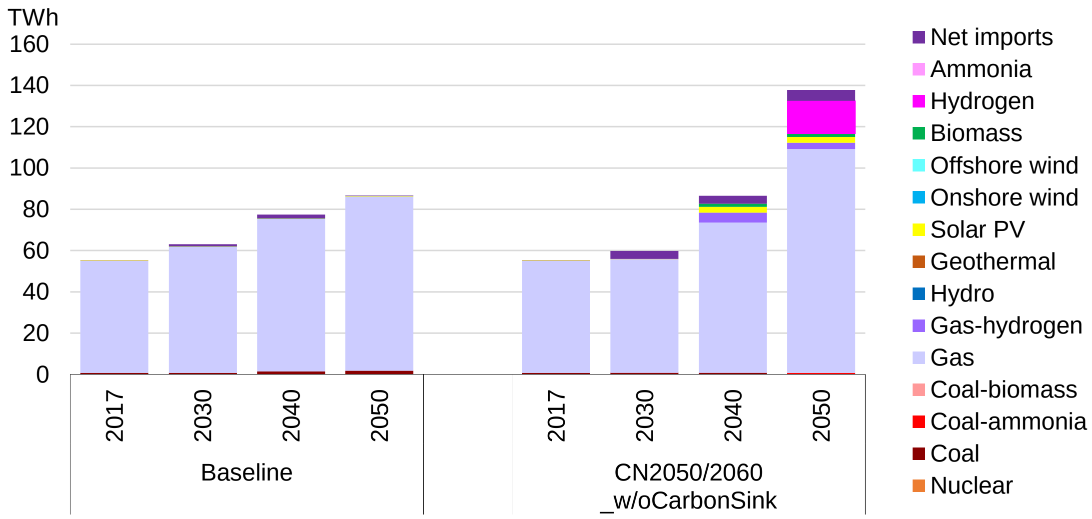
Mtoe = million tonnes of oil equivalent, SGP = Singapore.
Source: Author.

Figure A.103. Final Energy Consumption (SGP-CN2050/2060_w/oCarbonSink)



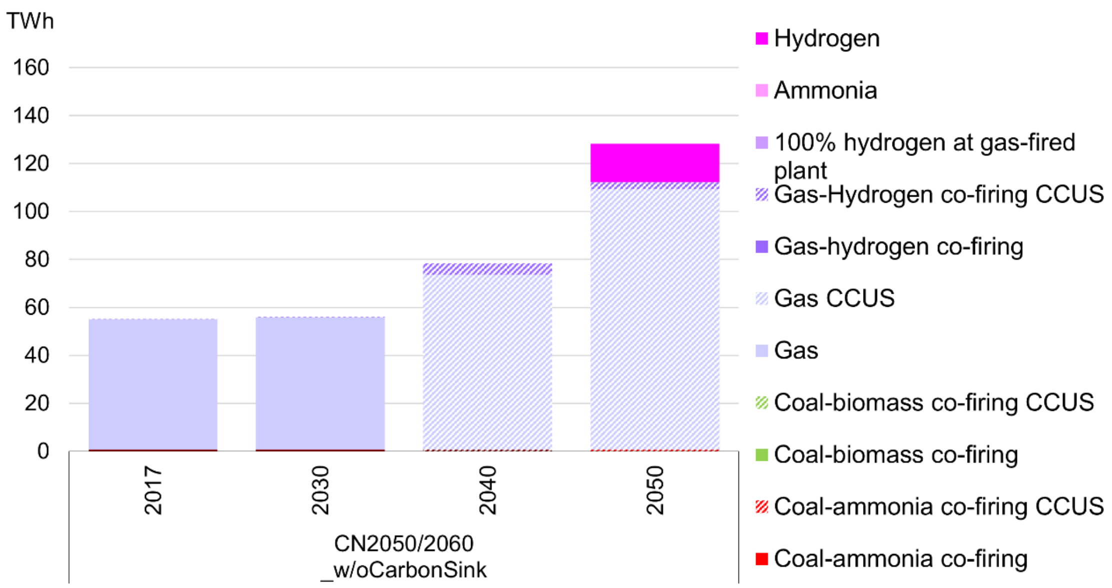
Mtoe = million tonnes of oil equivalent, SGP = Singapore.
Source: Author.

Figure A.104. Power Generation (SGP-CN2050/2060_w/oCarbonSink)



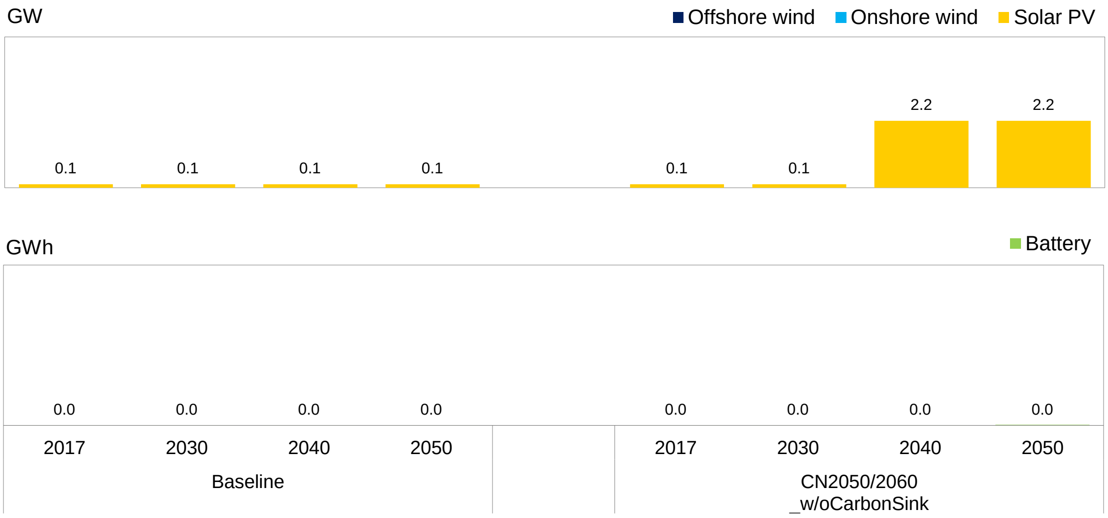
PV = photovoltaic, SGP = Singapore, TWh = terawatt-hour.
Source: Author.

Figure A.105. Generated Electricity from Coal, Gas, Ammonia, and Hydrogen (SGP-CN2050/2060_w/oCarbonSink)



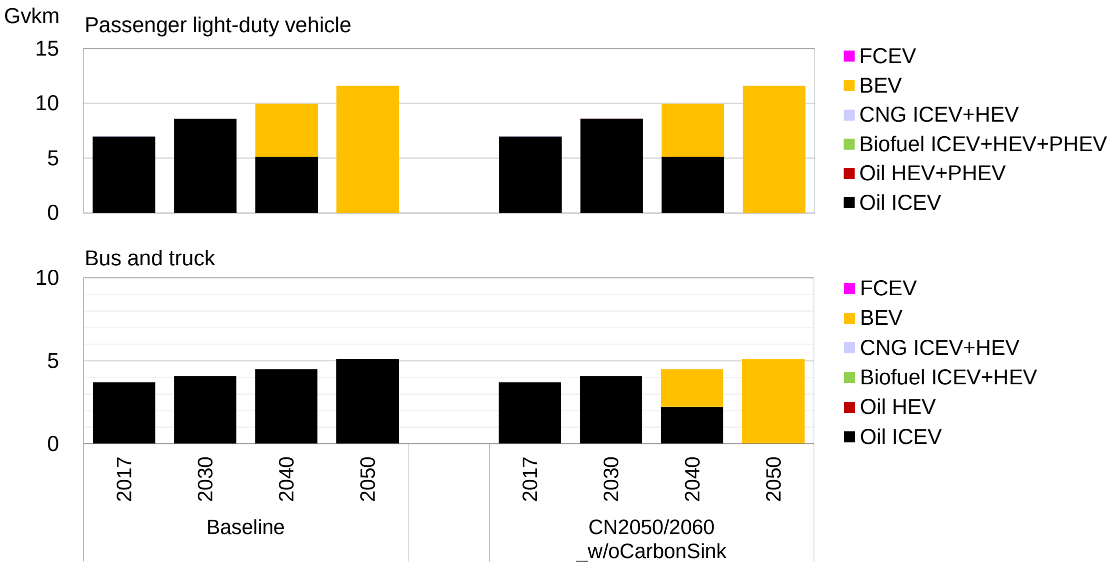
CCUS = carbon dioxide capture, utilisation, and storage; SGP = Singapore; TWh = terawatt-hour.
Source: Author.

Figure A.106. Variable Renewable Energy and Battery (SGP-CN2050/2060_w/oCarbonSink)



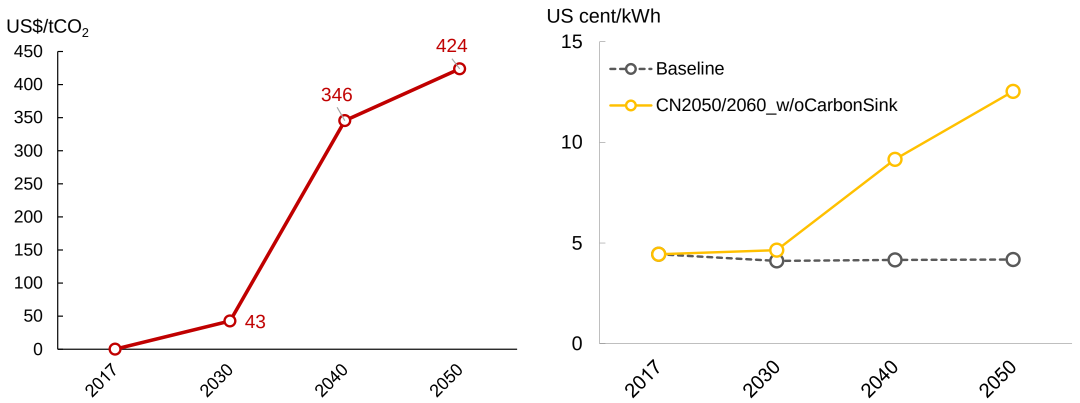
GW = gigawatt, GWh = gigawatt-hour, PV = photovoltaic, SGP = Singapore.
Source: Author.

Figure A.107. Travel Distance by Vehicle Technology (SGP-CN2050/2060_w/oCarbonSink)



BEV = battery electric vehicle, CN = carbon neutral, CNG = compressed natural gas, FCEV = fuel cell electric vehicle, HEV = hybrid electric vehicle, ICEV = internal combustion engine vehicle, Gvkm = 10^9 vehicle-km, PHEV = plug-in hybrid electric vehicle, SGP = Singapore.
Source: Author.

Figure A.108. Marginal Carbon Dioxide Abatement Cost (Left), Electricity Price (Right) (SGP-CN2050/2060_w/oCarbonSink)



kWh = kilowatt-hour, SGP = Singapore, tCO_2 = tonne of carbon dioxide.
Source: Author.

Table A.16. Carbon Dioxide Emission Baseline and without Carbon Sink Scenarios (SGP-CN2050/2060_w/oCarbonSink)

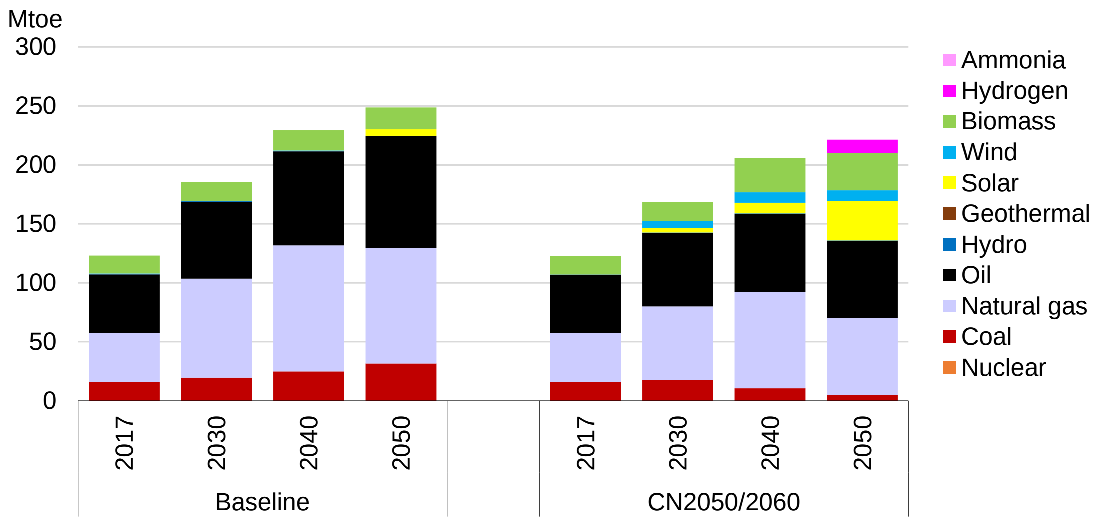
	Baseline ($MtCO_2$)					SGP-CN2050/2060_w/oCarbonSink ($MtCO_2$)				
	2017	**2030**	**2040**	**2050**	**2060**	**2017**	**2030**	**2040**	**2050**	**2060**
Electricity	21.10	23.54	28.38	31.70	31.70	21.10	21.37	0.88	2.19	0.97
Industry	15.52	13.98	15.90	18.17	21.29	15.52	14.03	12.21	8.40	9.49
Transport	6.60	7.93	6.91	5.85	6.18	6.60	7.93	5.09	1.84	1.95
Other end use	0.60	0.95	0.93	0.89	0.94	0.60	0.95	0.92	0.87	0.91
Other including DACCS	6.57	6.57	6.57	6.57	6.57	6.57	6.51	6.30	-13.29	-13.33
LULUCF										
Energy-related CO_2 emissions	50.40	52.97	58.68	63.18	66.68	50.40	50.79	25.39	0.00	0.00

SGP = Singapore, $MtCO_2$ = Million tonne of carbon dioxide, DACCS = Direct Air Carbon Capture and Storage, LULUCF = land use, land-use change and forestry.
Source: Author.

9. Thailand

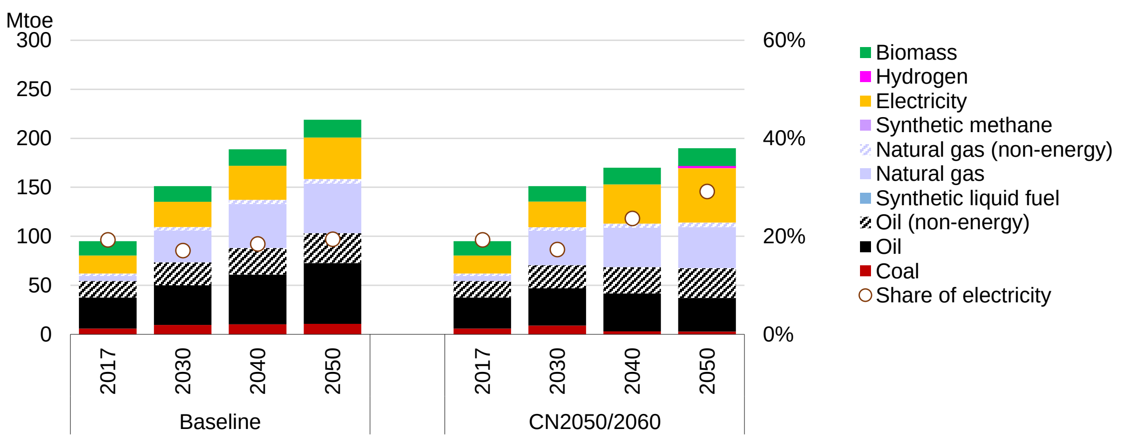
(a) CN2050/2060

Figure A.109. Primary Energy Supply (THA-CN2050/2060)



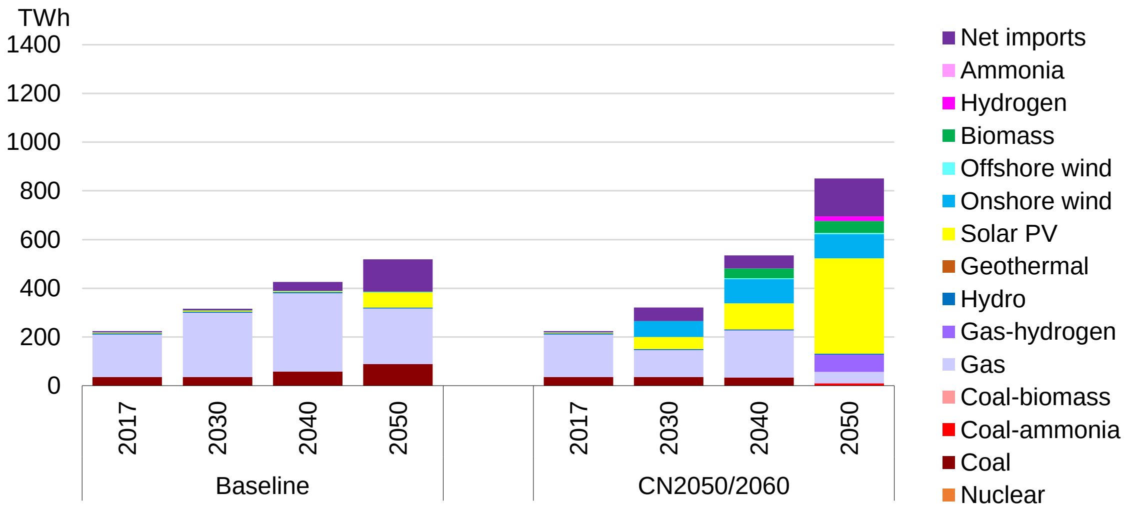
Mtoe = million tonnes of oil equivalent, THA = Thailand.
Source: Author.

Figure A.110. Final Energy Consumption (THA-CN2050/2060)



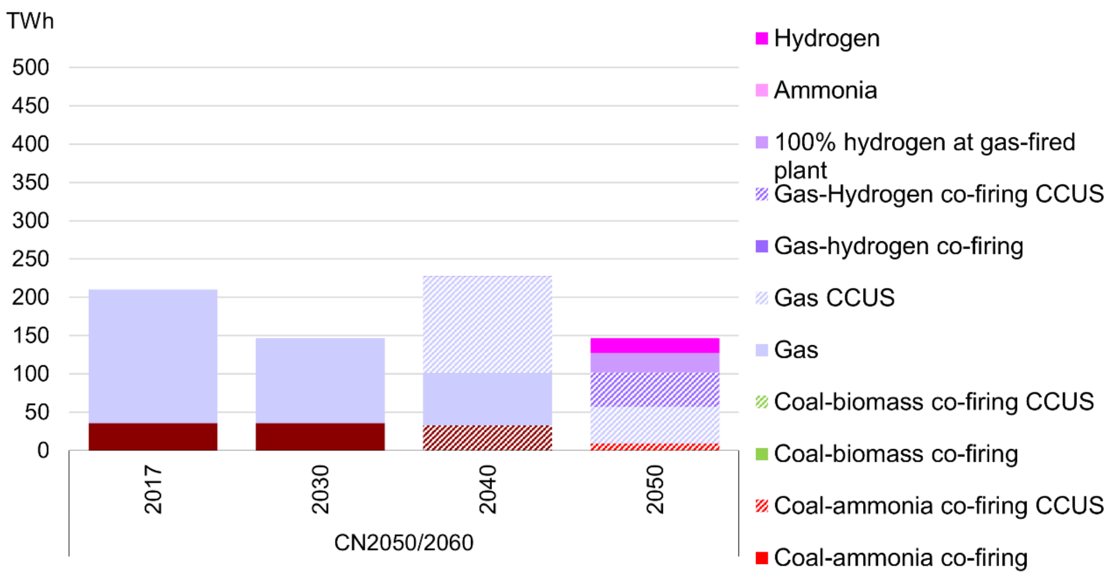
Mtoe = million tonnes of oil equivalent, THA = Thailand.
Source: Author.

Figure A.111. Power Generation (THA-CN2050/2060)



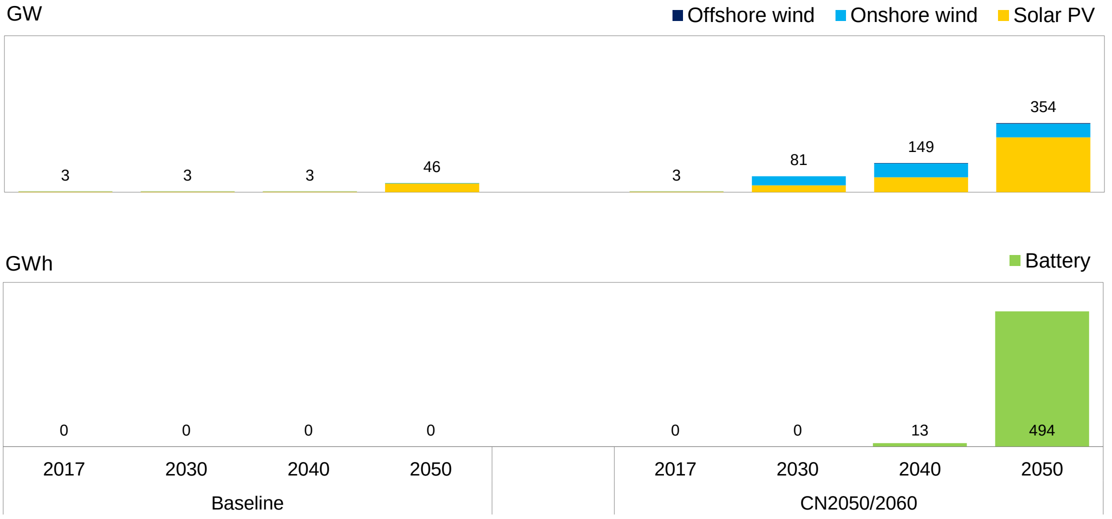
PV = photovoltaic, THA = Thailand, TWh = terawatt-hour.
Source: Author.

Figure A.112. Generated Electricity from Coal, Gas, Ammonia, and Hydrogen (THA-CN2050/2060)



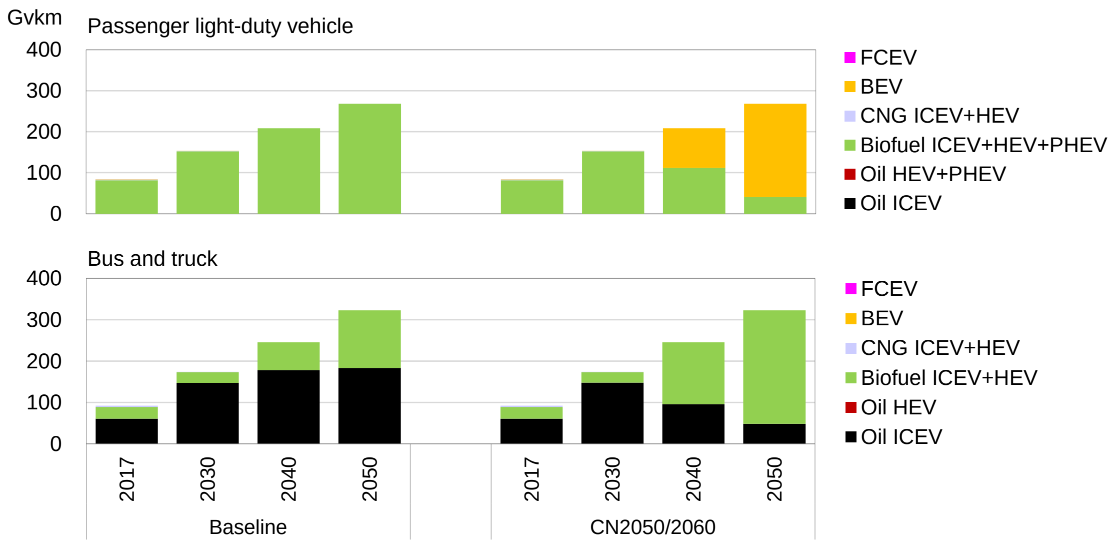
CCUS = carbon dioxide capture, utilisation, and storage; THA = Thailand; TWh = terawatt-hour.
Source: Author.

Figure A.113. Variable Renewable Energy and Battery (THA-CN2050/2060)



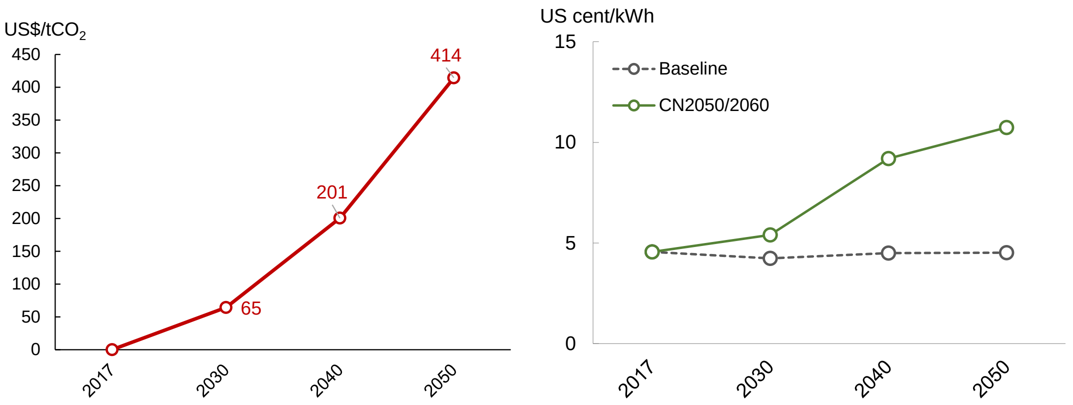
GW = gigawatt, GWh = gigawatt-hour, PV = photovoltaic, THA = Thailand.
Source: Author.

Figure A.114. Travel Distance by Vehicle Technology (THA-CN2050/2060)



BEV = battery electric vehicle, CN = carbon neutral, CNG = compressed natural gas, FCEV = fuel cell electric vehicle, HEV = hybrid electric vehicle, ICEV = internal combustion engine vehicle, Gvkm = 10^9 vehicle-km, PHEV = plug-in hybrid electric vehicle, THA = Thailand.
Source: Author.

Figure A.115. Marginal Carbon Dioxide Abatement Cost (Left), Electricity Price (Right) (THA-CN2050/2060)



kWh = kilowatt-hour, tCO_2 = tonne of carbon dioxide, THA = Thailand.
Source: Author.

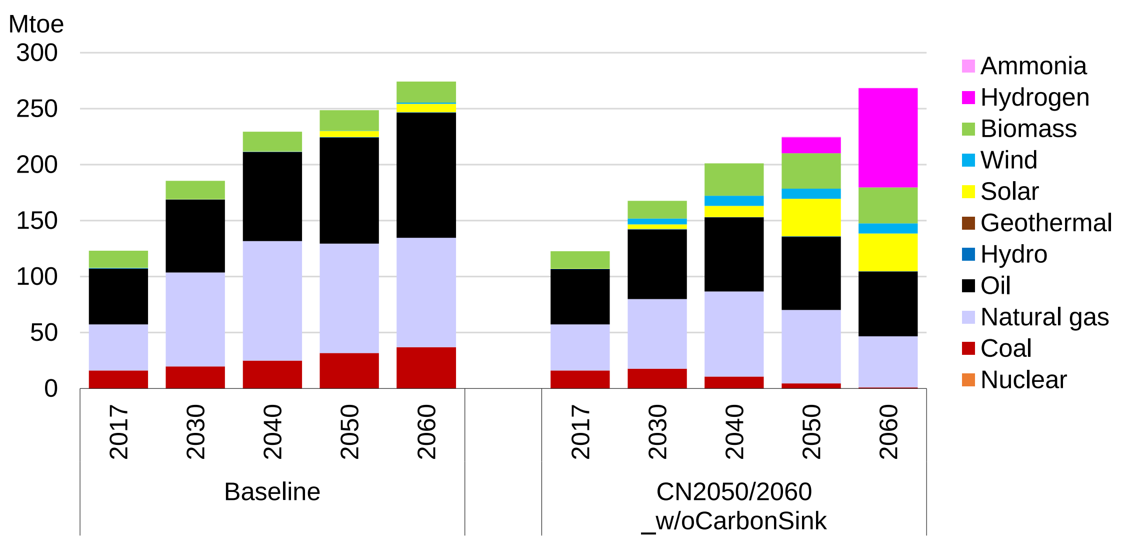
Table A.17. Carbon Dioxide Emission Baseline and with Carbon Sink Scenarios (THA-CN2050/2060)

	Baseline ($MtCO_2$)					THA-CN2050/2060 ($MtCO_2$)				
	2017	**2030**	**2040**	**2050**	**2060**	**2017**	**2030**	**2040**	**2050**	**2060**
Electricity	97.27	130.66	172.12	161.54	183.92	97.25	73.45	-17.37	-52.72	-53.13
Industry	43.07	101.30	143.12	182.23	223.42	43.07	97.80	82.47	80.43	93.20
Transport	71.29	104.55	120.16	127.37	131.07	71.29	104.55	103.81	91.02	92.05
Other end use	16.38	32.35	39.01	43.35	38.77	16.38	32.28	38.74	42.60	37.96
Other including DACCS	25.60	25.71	28.16	30.01	30.83	24.29	18.44	16.61	-39.33	-48.08
LULUCF						-91.00	-115.40	-117.70	-120.00	-120.00
Energy-related CO_2 emissions	253.60	394.55	502.57	544.50	608.01	252.27	326.51	224.25	122.00	122.00

THA = Thailand, $MtCO_2$ = Million tonne of carbon dioxide, DACCS = Direct Air Carbon Capture and Storage, LULUCF = land use, land-use change and forestry.
Source: Author.

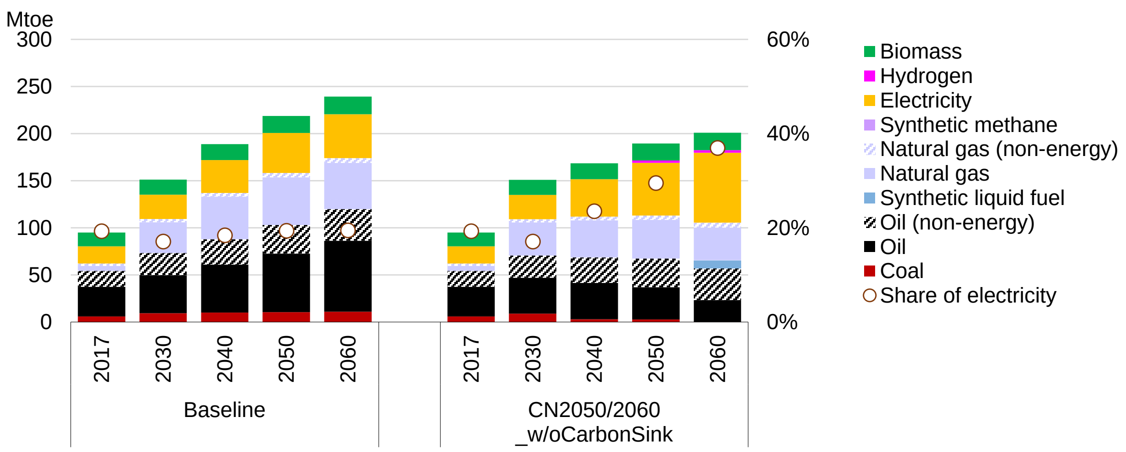
(b) CN2050/2060_w/oCarbonSink

Figure A.116. Primary Energy Supply (THA-CN2050/2060_w/oCarbonSink)



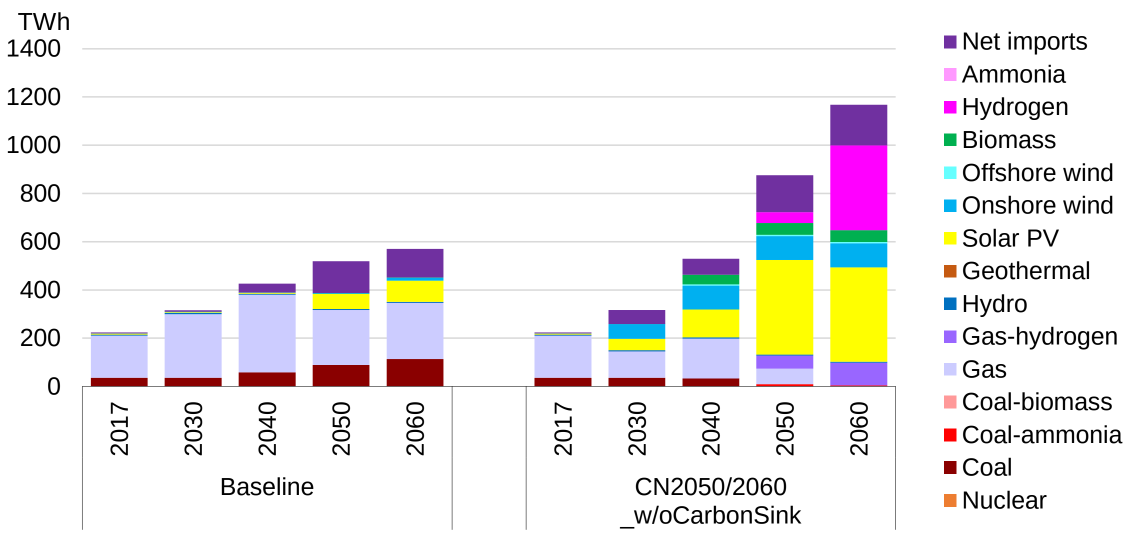
Mtoe = million tonnes of oil equivalent, THA = Thailand.
Source: Author.

Figure A.117. Final Energy Consumption (THA-CN2050/2060_w/oCarbonSink)



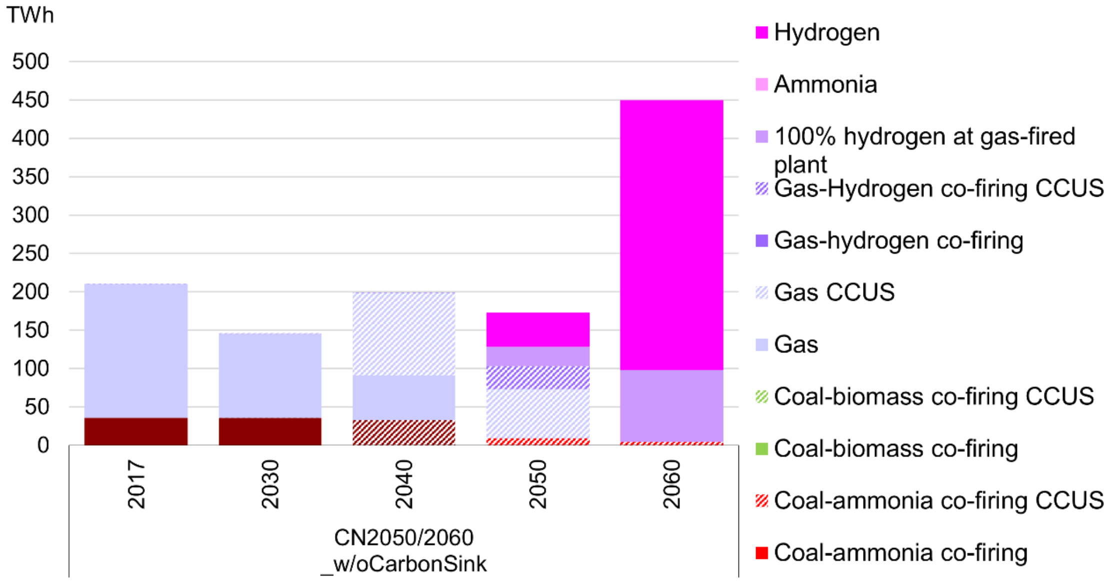
Mtoe = million tonnes of oil equivalent, THA = Thailand.
Source: Author.

Figure A.118. Power Generation (THA-CN2050/2060_w/oCarbonSink)



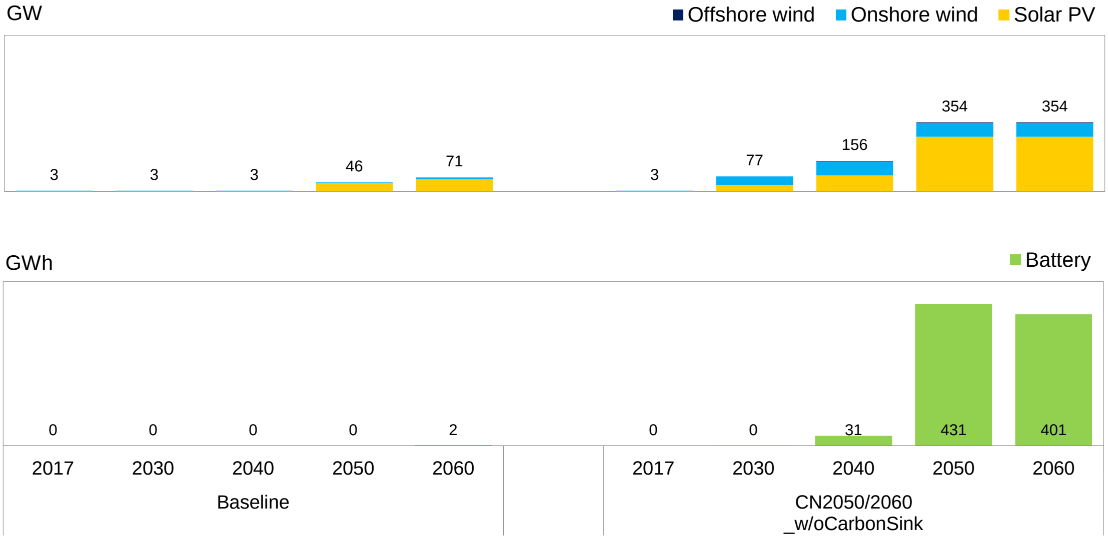
PV = photovoltaic, THA = Thailand, TWh = terawatt-hour.
Source: Author.

Figure A.119. Generated Electricity from Coal, Gas, Ammonia, and Hydrogen (THA-CN2050/2060_w/oCarbonSink)



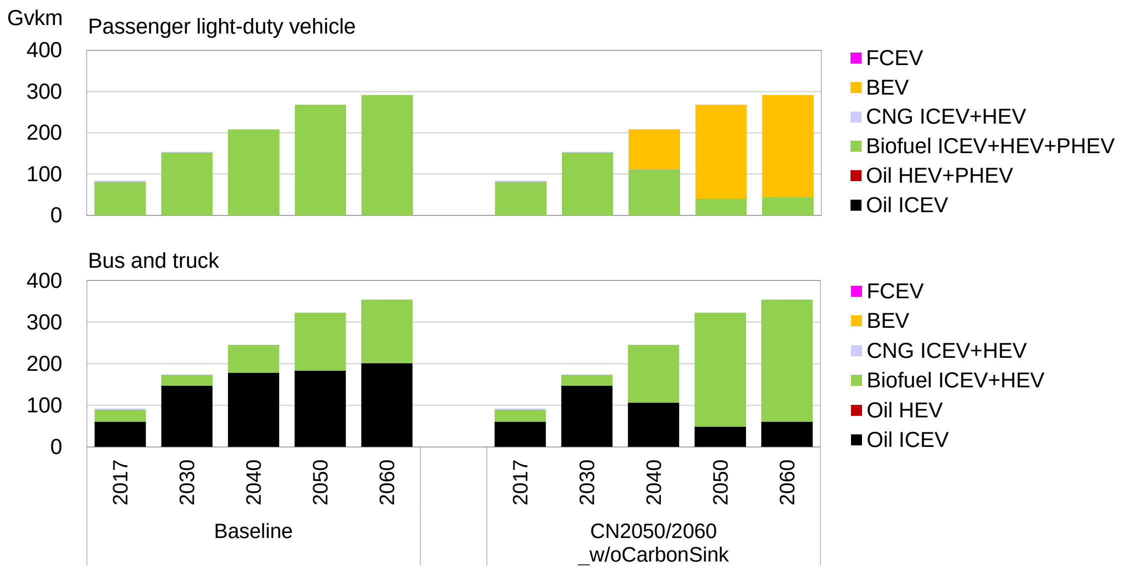
CCUS = carbon dioxide capture, utilisation, and storage; THA = Thailand; TWh = terawatt-hour.
Source: Author.

Figure A.120. Variable Renewable Energy and Battery (THA-CN2050/2060_w/oCarbonSink)



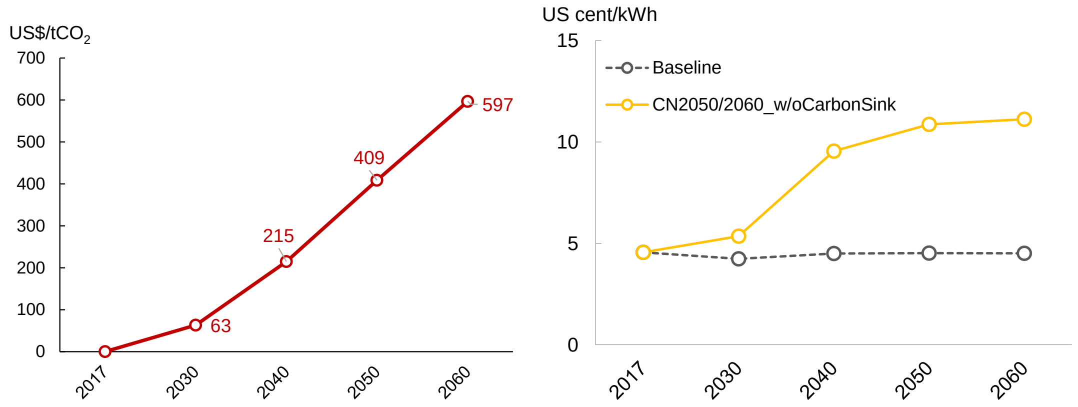
GW = gigawatt, GWh = gigawatt-hour, PV = photovoltaic, THA = Thailand.
Source: Author.

Figure A.121. Travel Distance by Vehicle Technology (THA-CN2050/2060_w/oCarbonSink)



BEV = battery electric vehicle, CN = carbon neutral, CNG = compressed natural gas, FCEV = fuel cell electric vehicle, HEV = hybrid electric vehicle, ICEV = internal combustion engine vehicle, Gvkm = 10^9 vehicle-km, PHEV = plug-in hybrid electric vehicle, THA = Thailand.
Source: Author.

Figure A.122. (Left) Marginal Carbon Dioxide Abatement Cost, (Right) Electricity Price (THA-CN2050/2060_w/oCarbonSink)



kWh = kilowatt-hour, tCO_2 = tonne of carbon dioxide, THA = Thailand.
Source: Author.

Table A.18. Carbon Dioxide Emission Baseline and without Carbon Sink Scenarios (THA-CN2050/2060_w/oCarbonSink)

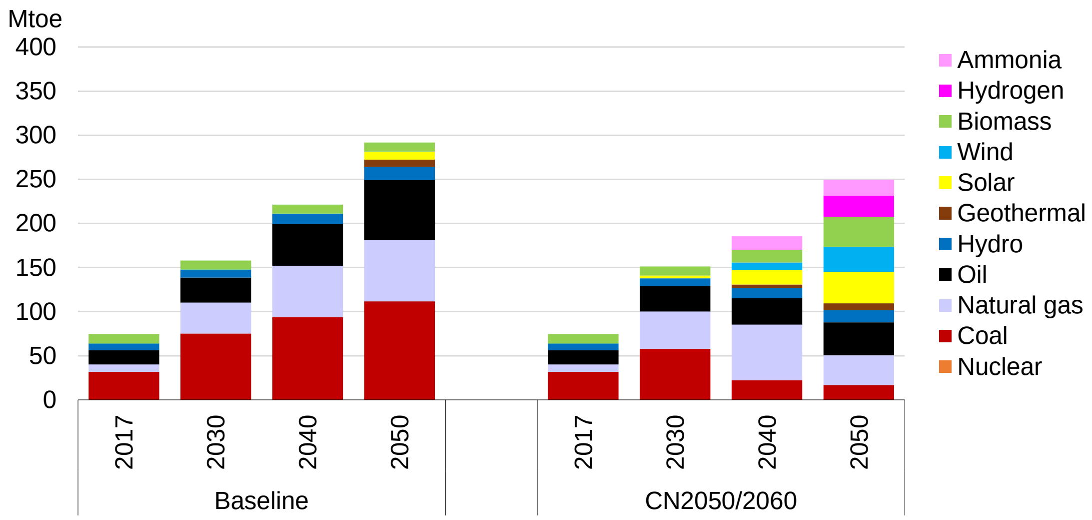
	Baseline ($MtCO_2$)					THA-CN2050/2060_w/oCarbonSink ($MtCO_2$)				
	2017	**2030**	**2040**	**2050**	**2060**	**2017**	**2030**	**2040**	**2050**	**2060**
Electricity	97.27	130.66	172.12	161.54	183.92	97.25	73.12	-21.81	-52.52	-56.34
Industry	43.07	101.30	143.12	182.23	223.42	43.07	98.13	80.36	78.32	52.26
Transport	71.29	104.55	120.16	127.37	131.07	71.29	104.55	103.81	91.02	91.32
Other end use	16.38	32.35	39.01	43.35	38.77	16.38	32.24	38.74	42.60	35.59
Other including DACCS	25.60	25.71	28.16	30.01	30.83	24.29	18.47	16.58	-50.58	-122.82
LULUCF										
Energy-related CO_2 emissions	253.60	394.55	502.57	544.50	608.01	252.27	326.51	217.67	108.84	0.00

THA = Thailand, MtCO2 = Million tonne of carbon dioxide, DACCS = Direct Air Carbon Capture and Storage, LULUCF = land use, land-use change and forestry.
Source: Author.

10. Viet Nam

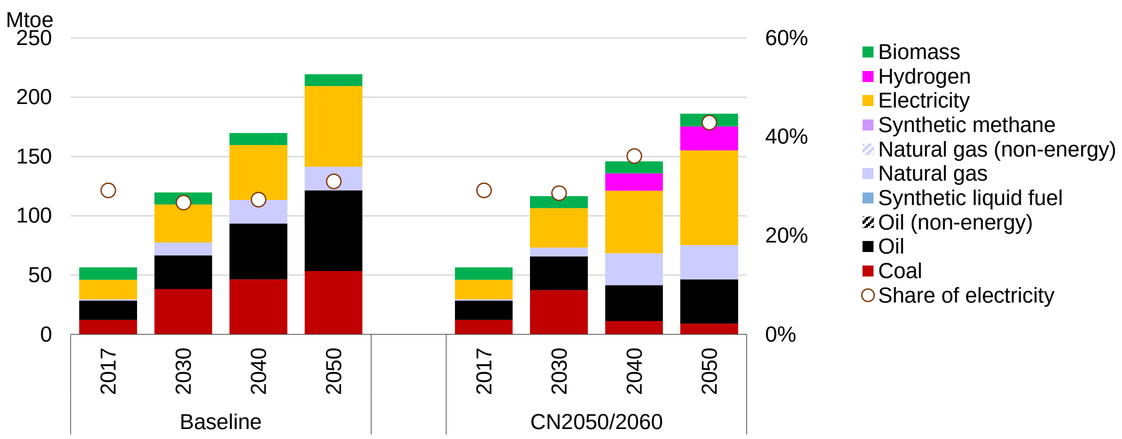
(a) CN2050/2060

Figure A.123. Primary Energy Supply (VNM-CN2050/2060)



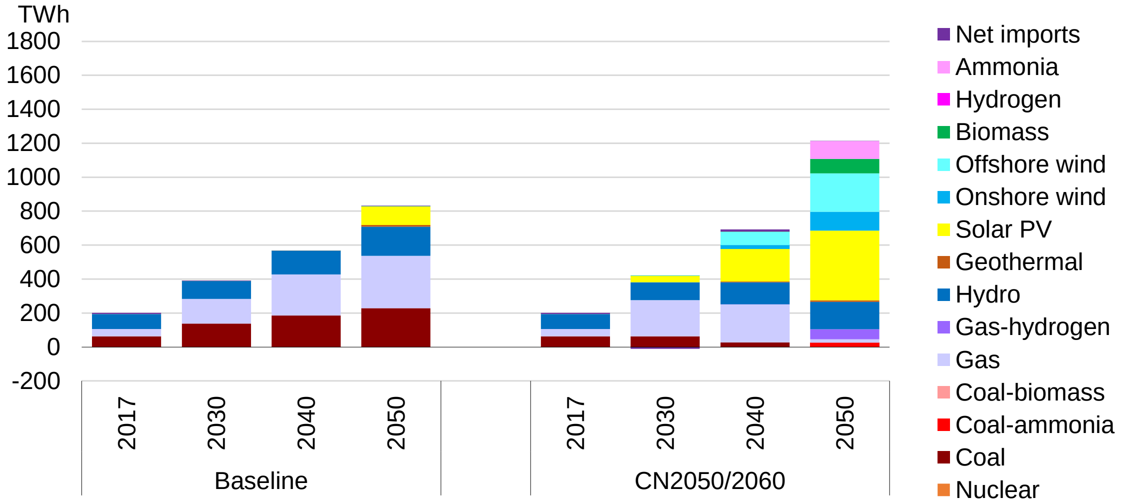
Mtoe = million tonnes of oil equivalent, VNM = Viet Nam.
Source: Author.

Figure A.124. Final Energy Consumption (VNM-CN2050/2060)



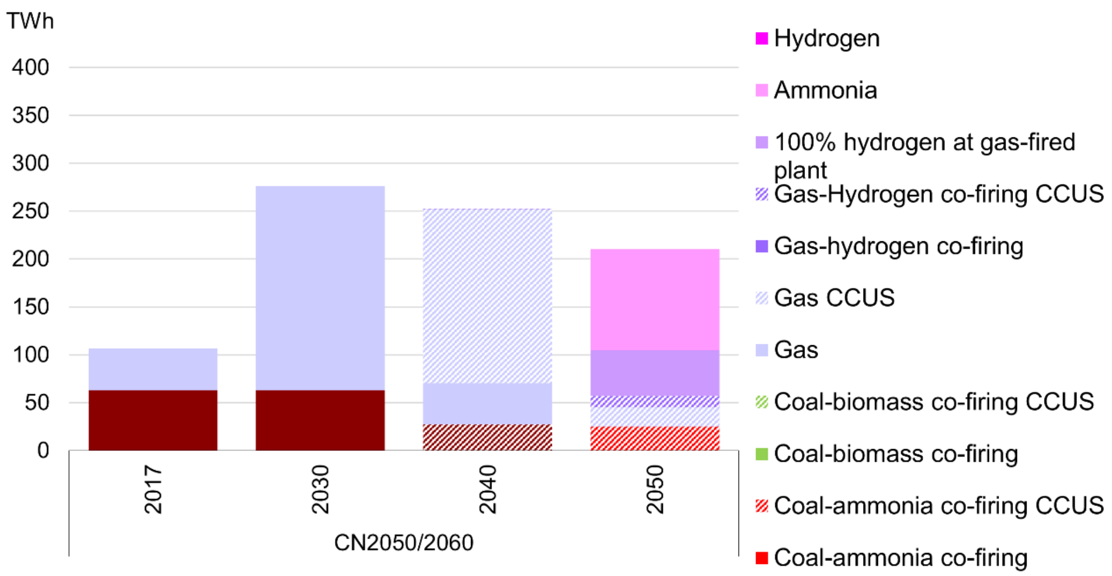
Mtoe = million tonnes of oil equivalent, VNM = Viet Nam.
Source: Author.

Figure A.125. Power Generation (VNM-CN2050/2060)



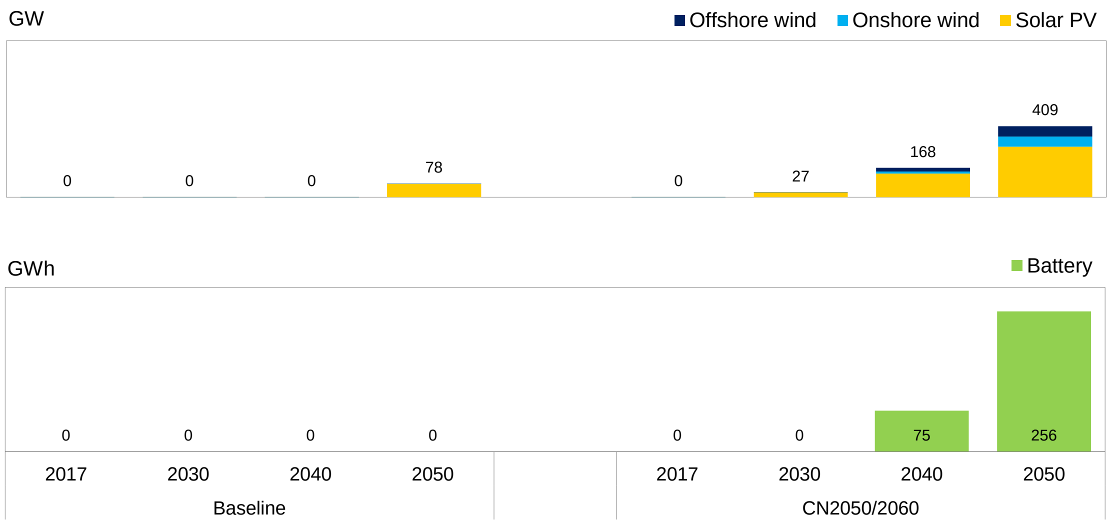
TWh = terawatt-hour, VNM = Viet Nam.
Source: Author.

Figure A.126. Generated Electricity from Coal, Gas, Ammonia, and Hydrogen (VNM-CN2050/2060)



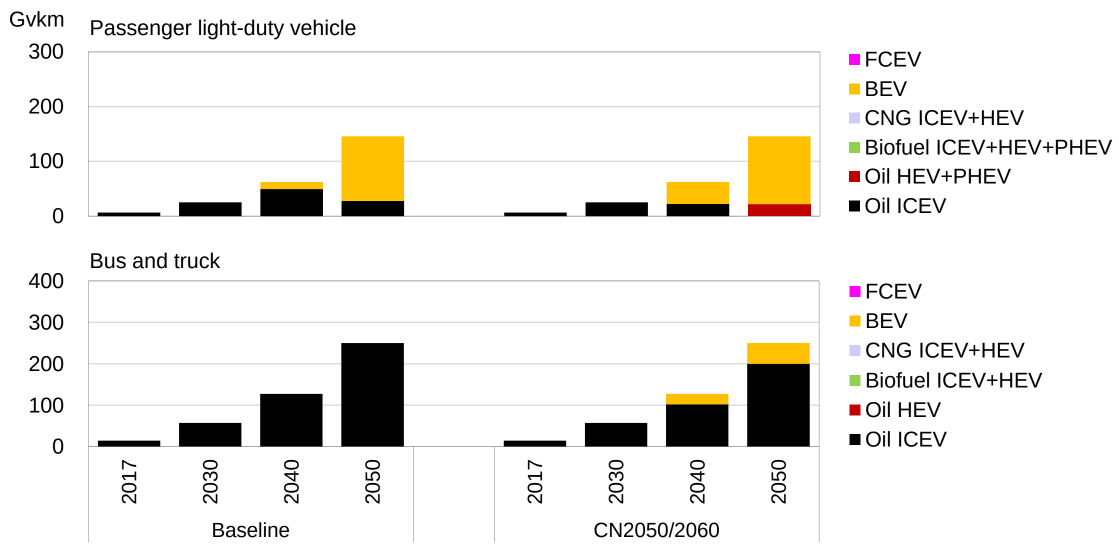
CCUS = carbon dioxide capture, utilisation, and storage; TWh = terawatt-hour; VNM = Viet Nam.
Source: Author.

Figure A.127. Variable Renewable Energy and Battery (VNM-CN2050/2060)



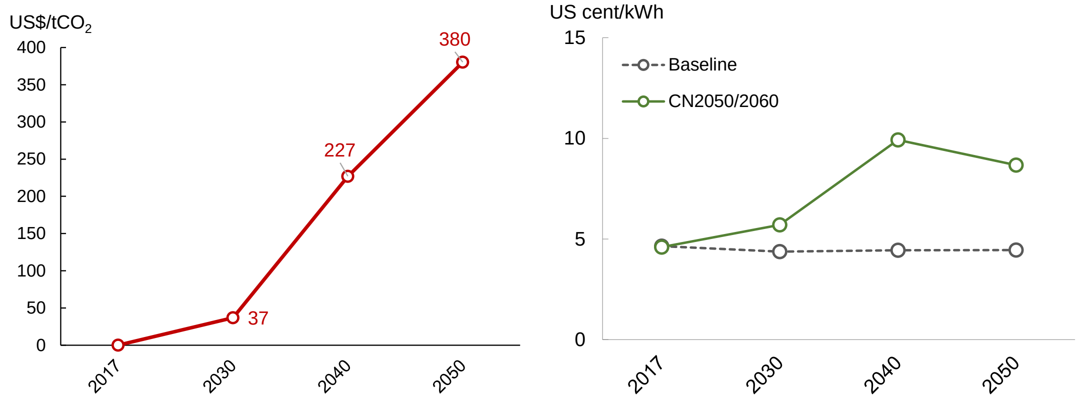
GW = gigawatt, GWh = gigawatt-hour, PV = photovoltaic, VNM = Viet Nam.
Source: Author.

Figure A.128. Travel Distance by Vehicle Technology (VNM-CN2050/2060)



BEV = battery electric vehicle, CN = carbon neutral, CNG = compressed natural gas, FCEV = fuel cell electric vehicle, HEV = hybrid electric vehicle, ICEV = internal combustion engine vehicle,, Gvkm = 10^9 vehicle-km, PHEV = plug-in hybrid electric vehicle, VNM = Viet Nam.
Source: Author.

Figure A.129. Marginal Carbon Dioxide Abatement Cost (Left), Electricity Price (Right) (VNM-CN2050/2060)



kWh = kilowatt-hour, tCO_2 = tonne of carbon dioxide, VNM = Viet Nam.
Source: Author.

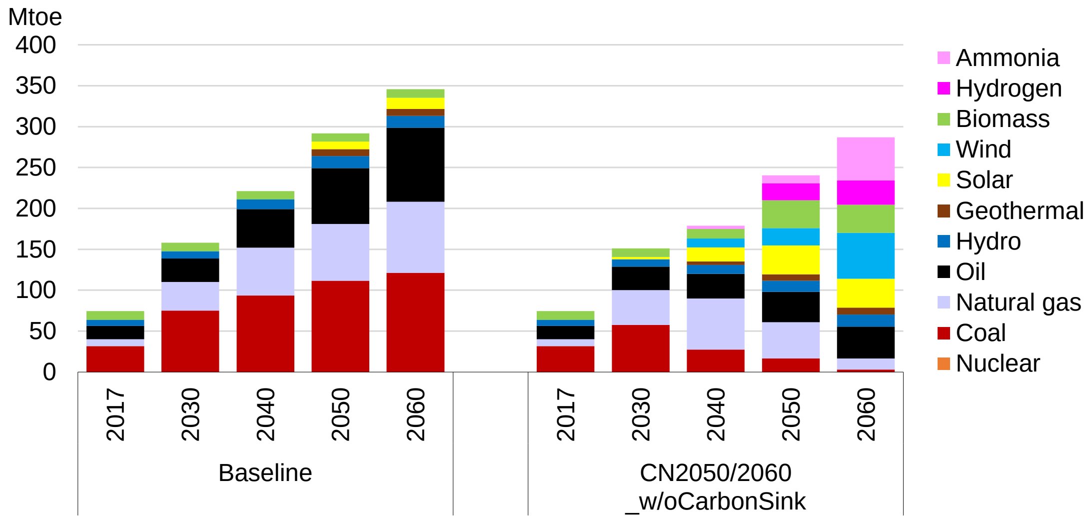
Table A.19. Carbon Dioxide Emission Baseline and with Carbon Sink Scenarios (VNM-CN2050/2060)

	Baseline ($MtCO_2$)					VNM-CN2050/2060 ($MtCO_2$)				
	2017	**2030**	**2040**	**2050**	**2060**	**2017**	**2030**	**2040**	**2050**	**2060**
Electricity	82.78	184.95	251.39	311.89	364.80	82.78	147.91	23.34	-95.01	-95.72
Industry	54.03	164.14	229.98	299.17	354.77	54.03	160.57	86.89	80.81	59.52
Transport	32.83	71.32	104.10	130.69	166.35	32.83	71.32	84.40	103.21	130.25
Other end use	12.98	29.23	42.66	42.27	38.49	12.98	20.01	26.21	30.66	32.79
Other including DACCS	12.30	18.27	26.46	35.16	44.52	12.30	15.74	15.58	-62.37	-69.55
LULUCF						-39.49	-58.50	-58.50	-58.50	-58.50
Energy-related CO_2 emissions	194.93	467.91	654.58	819.18	968.94	194.93	415.56	236.43	57.30	57.30

VNM = Viet Nam, $MtCO_2$ = Million tonne of carbon dioxide, DACCS = Direct Air Carbon Capture and Storage, LULUCF = land use, land-use change and forestry.
Source: Author.

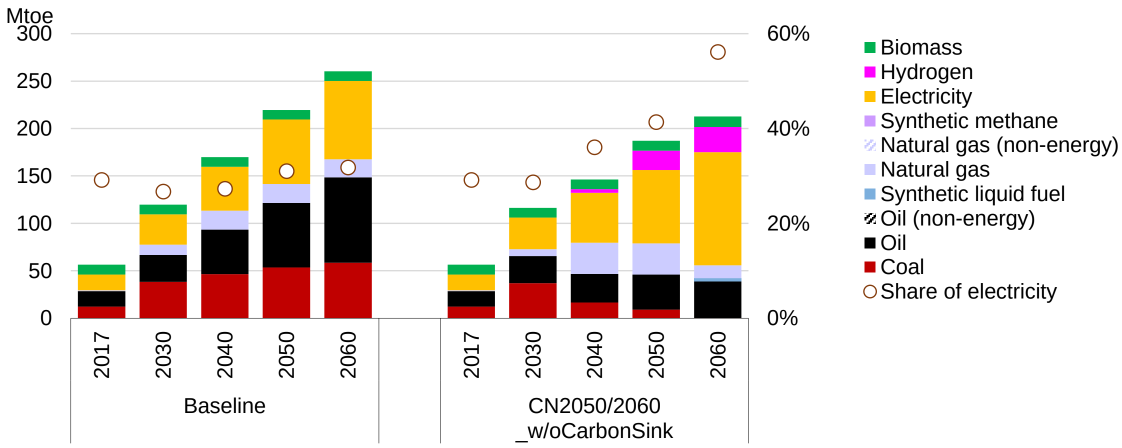
(b) CN2050/2060_w/oCarbonSink

Figure A.130. Primary Energy Supply (VNM-CN2050/2060_w/oCarbonSink)



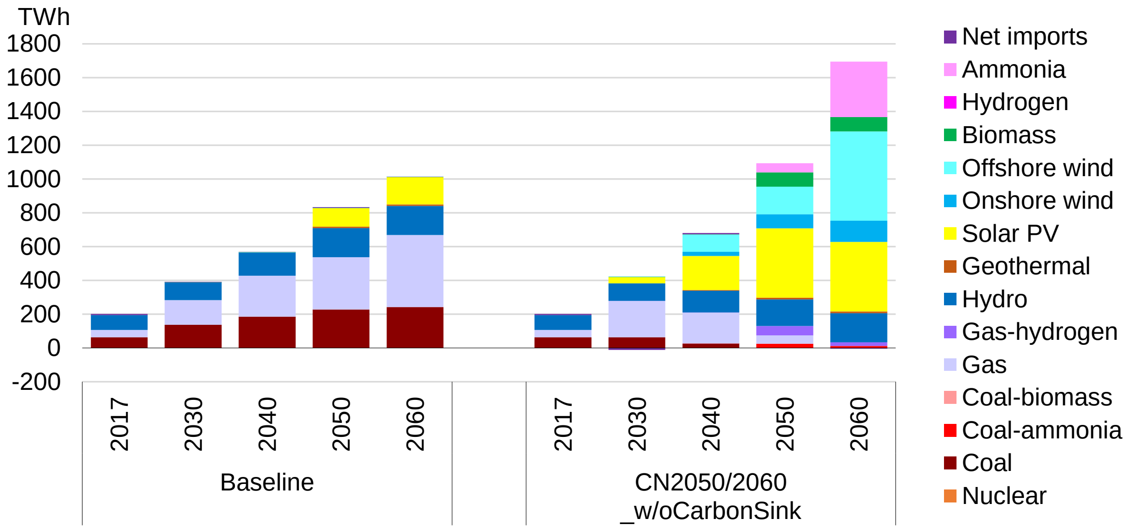
Mtoe = million tonnes of oil equivalent, VNM = Viet Nam.
Source: Author.

Figure A.131. Final Energy Consumption (VNM-CN2050/2060_w/oCarbonSink)



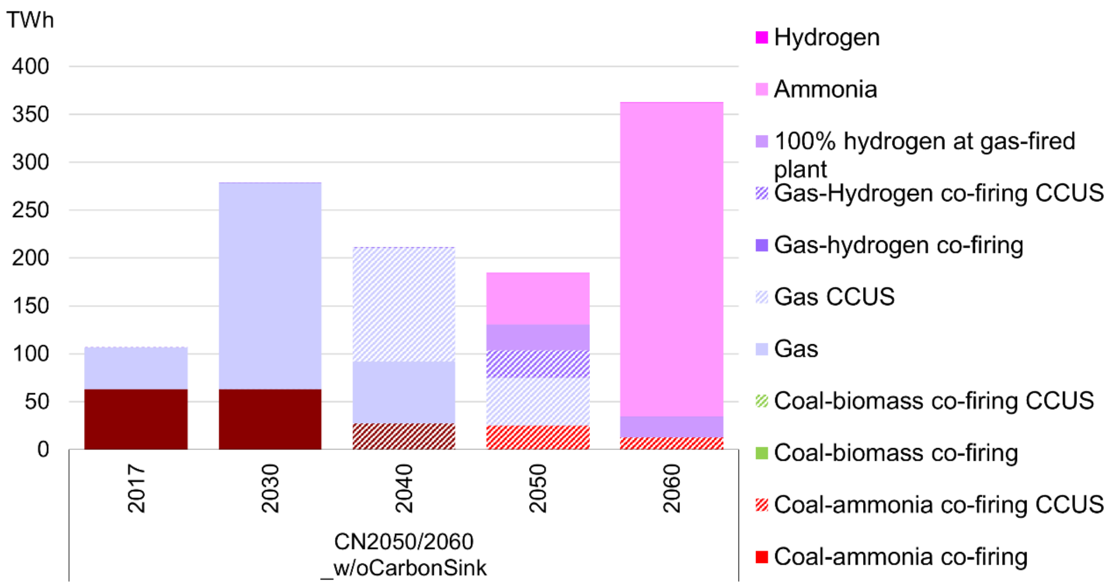
Mtoe = million tonnes of oil equivalent, VNM = Viet Nam.
Source: Author.

Figure A.132. Power Generation (VNM-CN2050/2060_w/oCarbonSink)



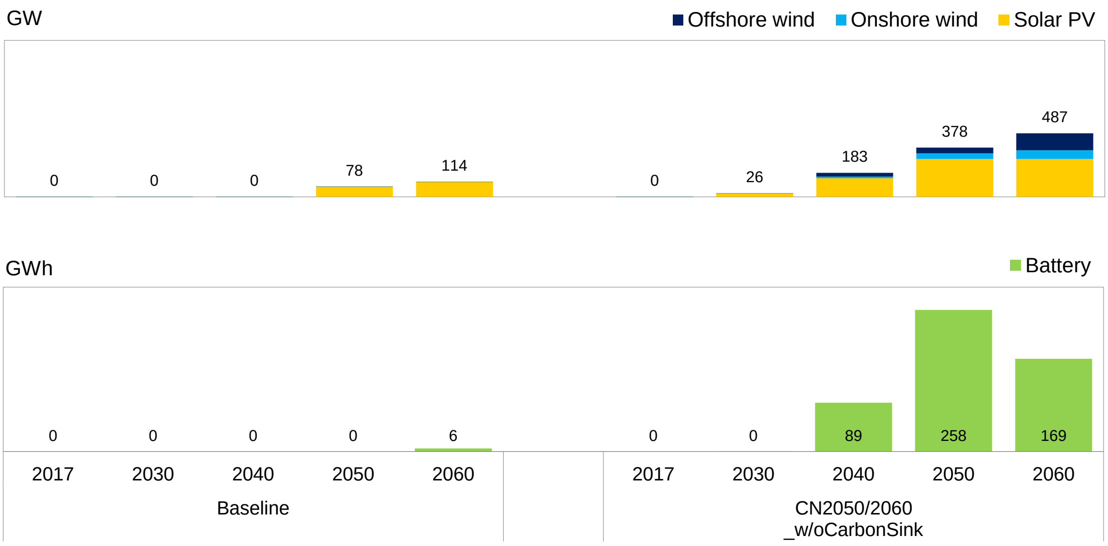
PV = photovoltaic, TWh = terawatt-hour, VNM = Viet Nam.
Source: Author.

Figure A.133. Generated Electricity from Coal, Gas, Ammonia, and Hydrogen (VNM-CN2050/2060_w/oCarbonSink)



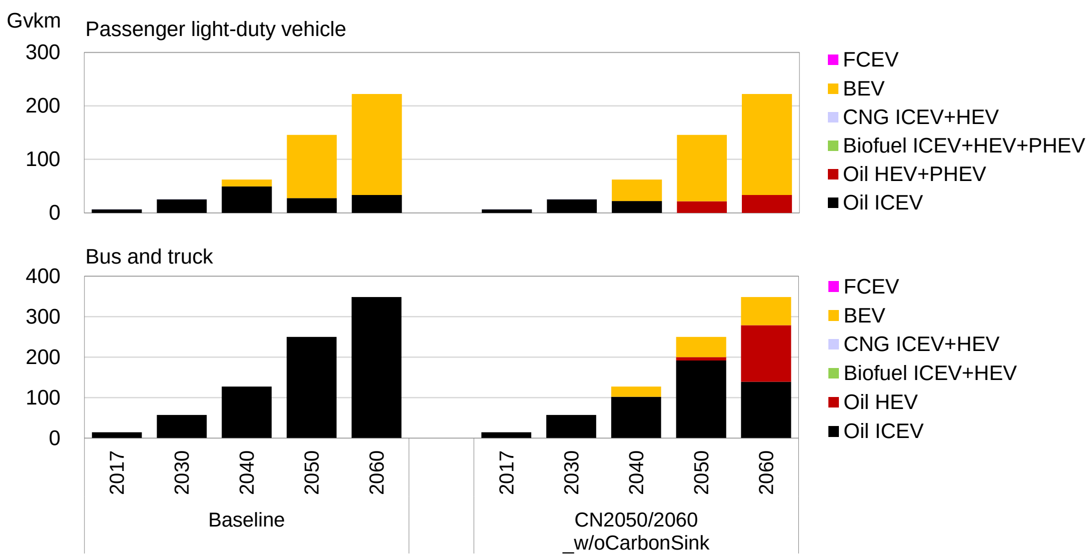
CCUS = carbon dioxide capture, utilisation, and storage; TWh = terawatt-hour; VNM = Viet Nam.
Source: Author.

Figure A.134. Variable Renewable Energy and Battery (VNM-CN2050/2060_w/oCarbonSink)



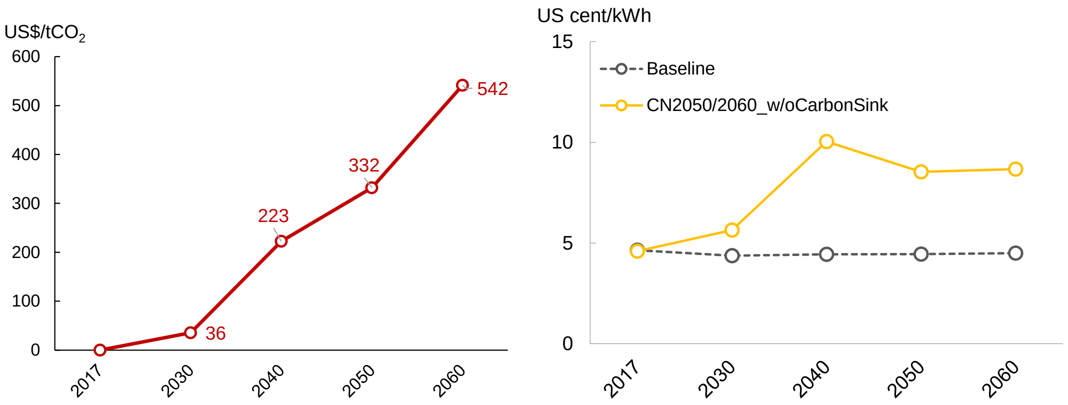
GW = gigawatt, GWh = gigawatt-hour, PV = photovoltaic, VNM = Viet Nam.
Source: Author.

Figure A.135. Travel Distance by Vehicle Technology (VNM-CN2050/2060_w/oCarbonSink)



BEV = battery electric vehicle, CN = carbon neutral, CNG = compressed natural gas, FCEV = fuel cell electric vehicle, HEV = hybrid electric vehicle, ICEV = internal combustion engine vehicle, Gvkm = 10^9 vehicle-km, PHEV = plug-in hybrid electric vehicle, VNM = Viet Nam.
Source: Author.

Figure A.136. Marginal Carbon Dioxide Abatement Cost (Left), Electricity Price (Right) (VNM-CN2050/2060_w/oCarbonSink)



kWh = kilowatt-hour, tCO_2 = tonne of carbon dioxide, VNM = Viet Nam.
Source: Author.

Table A.20. Carbon Dioxide Emission Baseline and with Carbon Sink Scenarios (VNM-CN2050/2060_w/oCarbonSink)

	Baseline ($MtCO_2$)					VNM-CN2050/2060_w/oCarbonSink ($MtCO_2$)				
	2017	**2030**	**2040**	**2050**	**2060**	**2017**	**2030**	**2040**	**2050**	**2060**
Electricity	82.78	184.95	251.39	311.89	364.80	82.78	148.83	29.10	-93.39	-97.21
Industry	54.03	164.14	229.98	299.17	354.77	54.03	159.63	121.71	98.84	31.13
Transport	32.83	71.32	104.10	130.69	166.35	32.83	71.32	84.40	102.58	116.52
Other end use	12.98	29.23	42.66	42.27	38.49	12.98	20.01	26.21	21.49	12.73
Other including DACCS	12.30	18.27	26.46	35.16	44.52	12.30	15.76	15.61	9.00	-63.17
LULUCF										
Energy-related CO_2 emissions	194.93	467.91	654.58	819.18	968.94	194.93	415.56	277.04	138.52	0.00

VNM = Viet Nam, $MtCO_2$ = Million tonne of carbon dioxide, DACCS = Direct Air Carbon Capture and Storage, LULUCF = land use, land-use change and forestry.
Source: Author.