Economics, Law, and Institutions in Asia Pacific

Han Phoumin
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Energy Sustainability and Climate Change in ASEAN

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Economics, Law, and Institutions in Asia Pacific

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ISSN 2199-8620 ISSN 2199-8639 (electronic)
Economics, Law, and Institutions in Asia Pacific
ISBN 978-981-16-1999-1 ISBN 978-981-16-2000-3 (eBook)
https://doi.org/10.1007/978-981-16-2000-3

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Acknowledgements

This study is a joint effort by the members of a working group that included outstanding researchers working to achieve energy sustainability and development in the Association of Southeast Asian Nations (ASEAN) and the East Asia region. The book results from the project titled ‘Energy Sustainability and Climate Change in ASEAN and East Asia’. We would like to acknowledge the support provided by everyone involved, including the many people whom the authors met and interviewed to obtain country data and information. Special thanks go to Hidetoshi Nishimura, President of the Economic Research Institute for ASEAN and East Asia (ERIA), who provided encouragement, support, and advice to ensure that this project addresses contemporary energy issues in ASEAN and East Asia. We are very grateful to ERIA’s publication department—Stefan Wesiak, Fadriani Trianingsih, Rachmadea Aisyah, and their team of editors—for helping to edit this book. Finally, we are very grateful to Juno Kawakami of Springer Nature for managing the publishing process on the publisher’s side.

Introduction

As of 2020, most of the world's energy investment still went to carbon-emitting sources, namely fossil fuels. On the other hand, the coronavirus disease (COVID-19) pandemic and the associated economic downturns shrank global demand for energy, including fossil fuels, resulting in a sharp drop in their prices. Low fossil fuel prices are harmful to the development of renewable energy projects—making solar, wind, and other renewable energy resources less competitive for generating electricity. This is endangering the Paris Agreement and the climate action goal of the United Nations. Given the high share of fossil fuels in the energy mix of the Association of Southeast Asian Nations (ASEAN) Member States and East Asia, these economies face tremendous challenges for their transition to cleaner energy in the post-COVID-19 world. Climate change will cause severe problems for different economic sectors such as agriculture, forestry, fisheries, and tourism, which are essential in ASEAN and East Asia.

To achieve the climate action goal set by the United Nations, the transition to cleaner energy is crucial. However, ASEAN faces tremendous challenges regarding the future energy landscape and how the energy transition will embrace a new architecture, including sound policy and technology to ensure energy access with affordability, energy security, and energy sustainability. Given the current high share of fossil fuels (almost 80% share of oil, coal, and natural gas) in ASEAN's energy mix, the clean use of fossil fuels through clean technology deployment is indispensable for decarbonising ASEAN's emissions. ASEAN needs sound policy and applicable technologies to ensure sustainable energy availability, accessibility, and affordability to reach emission reduction targets.

This book provides several up-to-date empirical policy-oriented studies on assessing the impacts of climate change on various economic sectors and the role of renewable energy resources in mitigating pollution and climate change. It provides various policy recommendations on how to increase the share of renewable energy resources in the energy baskets of ASEAN and East Asian economies and the rest of the world to ensure energy sustainability.

The book consists of 13 chapters categorised into two parts.

Part I is on the impacts of climate change and the mitigation policies and consists of six chapters.

Venkatappa et al., in Chap. 1, assessed the impact of climate change on agriculture in ASEAN by employing scientific data analysis. The recent developments in environmental technologies and scientific big data make it possible to analyse and process the information necessary for policymakers to make better informed decisions in the context of climate change. The authors applied the Google Earth Engine and analysed the climate impacts on agriculture at a regional scale in ASEAN. They found that the monsoon climate region had more droughts with higher intensity, while the equatorial climate region experienced more wet conditions with a lower intensity of drought conditions in irrigated and rain-fed agriculture land.

In Chap. 2, Sasaki assessed timber production, bioenergy generation, and emission reductions through the management of production forest for timber and bioenergy production in Southeast Asia. Apart from deforestation, emissions from logging operations were the second-highest source of emissions, indicating that attention should be paid to improve logging machinery's efficiency while reducing deforestation and forest degradation. The chapter proposes the introduction of tax exemptions or financial incentives for carbon and environmental taxes and/or energy tax to realise reduced impact logging (RIL)-based forest management.

In Chap. 3, Purwanto and Lutfiana utilised the vehicle technology impact assessment model for energy consumption and climate measurement in Indonesia. Transportation models play a crucial role in assessing the implementation schemes of carbon abatement measures. The Vehicle Technology Impact Assessment Model for Indonesia (VEIA-ID) facilitates the study of the effects of different energy, environment, and transport policies on road transport's energy consumption, greenhouse gas emissions, air pollution, and changes in welfare in Indonesia up to 2050. The model is an open-source tool that is freely available and does not require any commercial software. Governments and academics could use the model as the primary tool in developing national road transport sector energy scenarios.

In Chap. 4, Sasaki, Myint, and Venkatappa assessed the forest carbon balance resulting from deforestation and forest plantation in ASEAN. Assessment of the carbon balance resulting from changes in forest land use is needed under the Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD+) scheme of the United Nations Framework Convention on Climate Change. This chapter developed forest land use and carbon stock models to assess the carbon gains and losses in Southeast Asia during the Paris Agreement's implementation period from 2020 to 2030. The chapter suggests that plantation forests could increase wood supply to the region, but caution is needed because large-scale plantations can cause environmental destruction.

In Chap. 5, Han, Kimura, and Arima employed energy modelling to seek plausible policy scenarios for ASEAN to achieve more emission reductions and energy savings. The chapter also seeks to understand to what extent this will change the composition of the energy mix under various scenarios. The results imply policy implications for accelerating the share of renewables, adopting clean technologies, and the clean use of fossil fuels, and investing in resilient energy infrastructure.

In Chap. 6, Ali et al. present a review of high-efficiency, low-emission (HELE) technologies that are applicable to new coal-fired power plants and can easily retrofit to existing pulverised coal-fired power plants. The chapter also provides insight into global HELE deployment trends and highlights related barriers. Moreover, the authors estimated the economic costs and benefits of deploying HELE and subcritical coal-fired power plants in Southeast Asia. The chapter stresses the necessity of strengthening the carbon pricing policy for coal-fired power plants in Southeast Asia to support a quicker transition from less efficient subcritical stations towards HELE coal-fired technologies.

Part II is on policy measures for promoting renewable energy projects and consists of seven chapters.

In Chap. 7, Taghizadeh-Hesary et al. investigated the characteristics of green bonds. With increasing concern over climate change, many see green finance as a solution to fund sustainable projects. Green bonds—a type of debt instrument aimed at financing sustainable infrastructure projects—are growing in popularity. The authors found that green bonds' characteristics depend on the issuing region. Their findings prove that green bonds in Asia, including ASEAN, tend to show higher returns but higher risks and higher heterogeneity. Generally, the Asian green bonds market is dominated by the banking sector, representing 60% of all issuance. Given that the bonds issued by this sector tend to show lower than average returns, they recommended policies that could increase the rate of return of bonds issued by the banking sector through the use of tax spillover. Diversification of issuers, with higher participation from the public sector or de-risking policies, could also be considered.

In Chap. 8, Han, Kimura, and Arima analysed the potential of green hydrogen for ASEAN's clean energy future. The development of green hydrogen could be a game-changer to accelerate the increase in the share of renewables in ASEAN's energy mix. Employing policy scenario analysis of the energy outlook modelling results, this chapter examined the potential scalability of renewable hydrogen production from curtailed electricity in scenarios of a high share of variable renewable energy in the power generation mix. The study intensively reviewed the potential cost reduction of hydrogen production worldwide and its implications for changing the energy landscape. It found many social and environmental benefits, as hydrogen can help to decarbonise emissions in ASEAN.

In Chap. 9, Nepal, Han, and Khatri revisited the development and deployment of green technologies in ASEAN. The chapter suggests that carbon capture and storage (CCS) technologies will allow ASEAN to continue to use fossil fuels while achieving sustainable economic growth as coal demand increases in the region. The deployment of CCS technologies is also an enabler of hydrogen energy as a green energy solution in the region in the longer term. Short- to medium-term policies include boosting public acceptance of nuclear energy, implementing energy efficiency improvement policies, and eliminating fossil fuel consumption subsidies. Increasing both public and private sector energy investments and the development of CCS technologies in the longer term are necessary complementary policies for maximising the benefits of greater deployment of renewable energy sources in the region.

In Chap. 10, Jusoh, Ludin, and Ibrahim investigated the role of innovation management and productivity in sustainable energy in a case study of biomass fuel manufacturers in Malaysia and Thailand. The chapter examined innovations in products powered and led by biomass, introduced by three firms (two in Malaysia and one in Thailand). It argues that the firms have to employ effective innovation management to ensure sustainability in their business, which is challenged by volatility in the price of oil, their main competitor. The chapter showed that with innovation management and adaption to the market, these three biomass firms could defend their business from shocks caused by the drop in the oil price and competing demands for feedstock.

In Chap. 11, Chang and Han examined whether and how harnessing more wind energy can decrease the cost of meeting the demand for electricity and the amount of carbon emissions in the ASEAN region, using the ASEAN integrated electricity trade model. Three scenarios were considered: a counterfactual business-as-usual scenario, which assumes no wind energy is used; an actual business-as-usual scenario that uses the wind generation capacity in 2018 by employing the wind generation capacity from the *Renewable Energy Outlook for ASEAN*. Their simulation results suggest that dispatching more wind energy decreases the cost of meeting the demand for electricity and the amount of carbon emissions.

In Chap. 12, Ludin et al. evaluated the sustainability and lifetime economics of solar photovoltaic generation systems in selected ASEAN Member States. The chapter aims to provide a comprehensive assessment of the environmental and economic impacts of various solar photovoltaic systems (e.g. stand-alone, rooftop, and solar farm) by using sustainable quantitative approaches, such as life-cycle analysis and life-cycle cost analysis. Data normalisation was also conducted to compare the performance of each system. They found that the solar PV rooftop system has the lowest greenhouse gas emissions, life-cycle cost, and levelised cost of energy. This chapter then offers policy recommendations to attract sustainable green investment to the region.

In the final chapter, Han, Meas, and An, besides reviewing key regional initiatives for infrastructure investment and development in the Mekong subregion, examined energy demand and supply and forecast energy consumption in the subregion during 2017–2050 using energy modelling scenario analysis. The chapter found that to satisfy growing energy demand in the subregion, huge power generation infrastructure investment, estimated at around $190 billion–$220 billion, is necessary from 2017 to 2050. Such investment will need to be guided by appropriate policy. The authors argue that without redesigning energy policy towards high-quality energy infrastructure, it is very likely that the increasing use of coal—upon which the region greatly depends—will lead to the widespread construction of coal-fired power plants, which could result in increased greenhouse gas and carbon dioxide emissions.

The future energy landscape of ASEAN will rely on today's actions, policies, and investment to change the current dominant fossil fuel-based energy system towards a cleaner energy system. However, any decisions and energy policy measures to be rolled out during the energy transition will need to be weighed against potentially higher energy costs, affordability, and energy security risks. This book provides several empirical studies and practical policy recommendations that could help policymakers set effective energy and sustainability policies in ASEAN and other regions. It is also a valuable source for researchers and graduate students in energy, environment, and sustainability.

Han Phoumin
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About the Editors

Dr. Han Phoumin is a senior energy economist at the Economic Research Institute for ASEAN and East Asia (ERIA) (Indonesia). He has more than 20 years of experience working at various international and intergovernmental organisations and multidisciplinary research consortiums related to the energy market and technology, environment, integrated water resources management, governance, and economic development in the region of the Association of Southeast Asian Nations (ASEAN) and East Asia. He specialises in economic development and policy and applied econometrics. Over the past ten years, much of his career has involved the power sector, including sustainable hydropower development, renewable energy research, energy efficiency, clean coal technology, energy security, and energy demand and supply forecasting.

Dr. Farhad Taghizadeh-Hesary is an associate professor of Economics at Tokai University (Japan) and a visiting professor at Keio University (Japan). He is a grantee of Japan's Ministry of Education 'excellent young researcher' status. He is a founding member and vice-president in charge of academic affairs at the International Society for Energy Transition Studies. He is also a visiting professor at Chiang Mai University (Thailand) and distinguished research fellow at the University of Economics Ho Chi Minh City (Viet Nam). He serves as the editor of *Cogent Business & Management*, and an associate editor/board member of several journals, including *Singapore Economic Review*, *Frontiers in Energy Research*, *Global Finance Journal*, and *Energy Efficiency*. He has guest-edited special issues of several journals, including *Energy Policy, Energy Economics, Finance Research Letters*, and the *Journal of Environmental Management*. His research credits include authoring more than 160 academic journal papers and book chapters, and the editing of ten books. He holds Ph.D. in Economics from Keio University and was a Government of Japan Ministry of Education, Culture, Sports, Science, and Technology (MEXT) scholar.

Prof. Fukunari Kimura has been a professor at the Faculty of Economics of Keio University, Tokyo (Japan) since 2000 and was the dean of the Graduate School of Economics, Keio University, from 2015 to 2017. He has also been the chief economist at ERIA since 2008. He serves as a co-editor of the Journal of the Japanese and International Economies. He specialises in international trade and development economics. He has recently been active in writing academic and semi-academic books and articles on international production networks and economic integration in East Asia.

Prof. Jun Arima is a professor at the Graduate School of Public Policy, University of Tokyo (Japan) and Senior Policy Fellow on Energy and Environment at ERIA. He also serves as a visiting professor at the International University of Japan; distinguished senior research fellow at the Asia Pacific Institute of Research; consulting fellow at the Research Institute of Economy, Trade, and Industry; visiting researcher at the Institute of Energy Economics of Japan; and is a member of the German–Japanese Energy Transition Council. In addition, he is one of the lead authors of the forthcoming 6th Assessment Report of the Intergovernmental Panel on Climate Change. During his professional career, he held various senior positions at the International Energy Agency; he was director-general of the Japan External Trade Organisation (JETRO) London office, and was Japan's Ministry of Economy, Trade, and Industry's Special Advisor on Global Environmental Affairs. He has extensive publications on energy policy.

Part I
Impacts of Climate Change and the Mitigation Policies

Chapter 1
Impacts of Climate Change on Agriculture in South-East Asia—Drought Conditions and Crop Damage Assessment

Manjunatha Venkatappa, Nophea Sasaki, Jiachun Huang, and Han Phoumin

Abstract Climate change has had adverse impacts on agriculture, but only a handful of studies exist on this phenomenon in South-East Asia. To help provide better-informed policy interventions, in this study, the Google Earth Engine (GEE) cloud-computing platform was used to assess the temporal and spatial changes of drought conditions and related impacts on crops in the Association of Southeast Asian Nations (ASEAN) region from 1980 to 2019. To assess drought intensity and to identify its impact on irrigated and rain-fed agriculture land, 47,192 grid points with 10 × 10 km (km) resolution were created. It found that the Monsoon Climate Region had more droughts with higher intensity, while the Equatorial Climate Region experienced more wet conditions with a lower intensity of drought conditions in irrigated and rain-fed agriculture lands. Still, about 19.9 million hectares (ha) of croplands in the ASEAN region faced severe drought conditions, while 3.6 million ha of croplands faced wet conditions and possible flood damage. Accordingly, the loss of production of irrigated and rain-fed croplands in Cambodia, Indonesia, the Lao People's Democratic Republic, Myanmar, Thailand, and Viet Nam was estimated at about 21.9 million tons during 2015–2019. To address drought impacts,

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H. Phoumin et al. (eds.), *Energy Sustainability and Climate Change in ASEAN*, Economics, Law, and Institutions in Asia Pacific,
https://doi.org/10.1007/978-981-16-2000-3_1

four levels of policy interventions for ASEAN are suggested—low, medium, high, and business-as-usual—depending on the level of drought conditions in a particular country.

Keywords Google earth engine · Terra climate · PDSI · ASEAN · Climate change · Agriculture

1.1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) reported an increase in global surface air temperature by an average of 0.6 °C over the twentieth century (Othman 2011), with a global mean temperature rise of 1.1 °C, about 0.1 °C above pre-industrial levels in 2019 (WMO 2020). The Association of Southeast Nations (ASEAN) region is highly vulnerable to climate change because of its dependency on coastal areas for economic development (Asian Development Bank 2015) and agriculture for daily subsistence (Lassa et al. 2016; Chan et al. 2017).

Climate change-driven El Niño and La Niña—known as El Niño–Southern Oscillation (ENSO) events—have caused massive droughts, floods, and tropical cyclones, affecting rice production in South-East Asia (Lassa et al. 2016) most frequently in the 2010s, which was the warmest decade ever recorded (WMO 2020). The IPCC also predicted an increase of about 0.3 °C in temperature and 3% in rainfall in South-East Asia over the past decade, while positing that overall changes in land temperature may reach 1.59 °C in 2050, 1.96 °C in 2080, and 2.46 °C in 2100. (Anang et al. 2017). Other studies suggested about 11% of the region's gross domestic product (GDP) could be lost due to climate change by the end of this century, because climate change is likely to affect major sectors such as agriculture, tourism, and health (Prakash 2018; ASEAN 2020).

The agriculture sector in the ASEAN region, especially paddy cultivation, is quite vulnerable to flooding and drought events (Lassa et al. 2016). Rainfall in the ASEAN region may decrease in the Monsoon Climate Region (MCR) and increase in the Equatorial Climate Region (ECR), contributing to a decline of 50% in the rice yield and the loss of 6.7% of combined GDP in ASEAN by 2100, in addition to causing more stress on water and human health (Asian Development Bank 2009). It is very likely that as crop-growing seasons are shifted, crop cultivation suitability will be affected, and climate change-driven diseases will affect yields (Aryal et al. 2019). High variation in rainfall patterns and frequency will also affect crop productivity and even lead to crop loss (Lassa et al. 2016). Agriculture-breakthrough technologies, adaptation, and mitigation are thus essential to curb the estimated loss of about half of the rice yields from Indonesia, the Philippines, Thailand, and Viet Nam by 2100 compared to 1990 levels (Prakash 2018; ASEAN 2020).

Drought is one of the most damaging disasters environmentally and economically; hence, evaluation and monitoring are of concern globally (Liu et al. 2016). Some studies have found the increase in frequency and area of droughts to be 50% to

200% worldwide in the past 20 years alone (Zhao and Dai 2017). Indeed, drought conditions strongly affect crop production, yield, and food security over the globe (Daryanto et al. 2016), reducing cereal productivity by 9–10% globally (Lesk et al. 2016). Climate change also causes water-deficit conditions (i.e., soil water content decreases below saturated conditions), reducing yields of rice by 53–92% (Lafitteet et al. 2007). Similarly, around 40% of water deficiency could reduce rice crop yield by more than 50% (Daryanto et al. 2016). It must be noted that an increase in the production of global agriculture systems by approximately 110% (Tilman et al. 2011) is crucial to ensure food security to the estimated 870 million who will be underfed by 2050 (FAO, WFP, IFAD 2012).

The impacts of climate change on agriculture in South-East Asia have been assessed previously (e.g., Lassa et al. 2016; Bohra-Mishra et al. 2016; Chan et al. 2017), yet little research has been conducted on cropland productivity affected by climate-induced disasters such as droughts at spatial scale in the ASEAN region.

The Palmer Drought Severity Index (PDSI) has been commonly used to assess and to monitor drought intensity and to prioritise cropland areas for associated policy intervention (Abatzoglou et al. 2018). PDSI data sets help identify and monitor droughts; due to the longevity of the PDSI, there are numerous examples of its use over the years. Trends in the PDSI were characterised during 1900–2008 (Dai 2011), and a global data set of PDSI data for 1870–2002 regarding soil moisture and the effects of surface warming was developed (Aiguo et al. 2004). Several studies have also suggested that the PDSI is a suitable indicator of soil-moisture content (Szép et al. 2005), effective in identifying the severity of droughts historically (Vasiliades and Loukas 2009; Mavromatis 2010) on agriculture lands for policy interventions (Edossa et al. 2016; Liu et al. 2018) by using the Google Earth Engine (GEE) (Xulu et al. 2018).

Recent development of technologies, along with freely available big environmental data (Guo et al. 2014), now make it possible for policymakers to analyse information regarding climate change impacts (Szép et al. 2005; Narasimhan and Srinivasan 2005; Yan et al. 2013; Antofie et al. 2015; Dai and Zhao 2017). The invention of the GEE cloud-computing platform and its spatial application provides new opportunities to analyse data on a large scale and speed, with over 40 years of climate data available at every locale (Gorelick et al. 2017). With its cloud-computing machine-learning technologies, predicting past and future trends of climate anywhere—especially in the ASEAN region—is possible (Campos-Taberner et al. 2018; Kumar and Mutanga 2018; Venkatappa et al. 2019).

The GEE remote-sensing and climate data catalogue is continuously updated at a rate of nearly 6,000 scenes per day from active missions, and data are available for free for education and research purposes (Gorelick et al. 2017). The GEE provides Moderate Resolution Imaging Spectroradiometer (MODIS), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Advanced Very-High-Resolution Radiometer (AVHRR), National Land Data Assimilation System (NLDAS-2), Gridded Surface Meteorological (GridMET), and TerraClimate data sets, including precipitation, temperature, the PDSI, humidity, wind, and other variables over short periods of time (Gorelick et al. 2017). Therefore, easily available climate big data and the GEE fast cloud-computing processing platform are essential to understanding the impacts of climate change on major sectors, particularly cropland, in the ASEAN region.

One of the benefits of using the GEE is that the user is almost completely shielded from the details of working in a parallel processing environment (Gorelick et al. 2017). The system hides nearly every aspect of how computation is managed, including resource allocation, parallelism, data distribution, and retries. For explanatory purposes, the interactive computational time-limit is sufficient to complete the workflow within a single timeout at scale (Venkatappa et al. 2019).

This study aims to assess the impacts of climate change on the agriculture sector in the MCR and ECR in the ASEAN region using the GEE and available TerraClimate data during the crop-growing season from May to November in the MCR and October to April in the ECR over the last 40 years, from 1980 to 2019. Climate change has already became apparent in the ASEAN region as indicated by the rising temperature, erratic rainfall pattern, and extreme drought and flood events since the 1960s, and has continued until recently (IPCC 2018). Assessment of the impact of climate change on agriculture lands is urgently needed to support the introduction of appropriate policy interventions for sustainable agriculture practices in the region.

1.2 Materials and Methods

1.2.1 Study Area

For the purposes of this study, the ASEAN region is divided into two regions based on their primary crop-growing seasons: May to November for the MCR and October to April for the ECR (USDA 2012, 2013a, b). The MCR is composed of Cambodia, the Lao People's Democratic Republic (Lao PDR), Myanmar, Thailand, and Viet Nam, and the ECR comprises Brunei Darussalam, Indonesia, Malaysia, the Philippines, and Singapore (Fig. 1.1).

However, it must be noted that these countries do not have a single planting season. Paddy rice is the primary crop in the entire region, and it is planted at different times according to rice variety. In Cambodia, the Lao PDR, Myanmar, and Thailand, the rice-planting season is divided into the wet season (i.e., May to November), and the dry season (i.e., December to February) (USDA 2013a, b). In paddies in the Mekong River Delta, rice is planted in the winter (i.e., June to October), spring (i.e., October to April), and autumn (i.e., February to October) (USDA 2012).

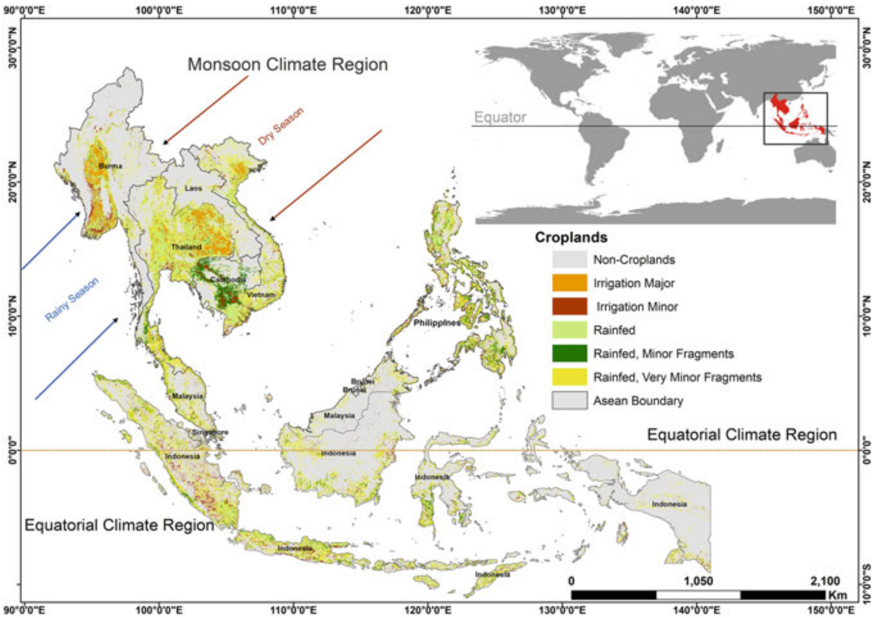

Fig. 1.1 The ASEAN monsoon climatic region and equatorial climatic region. ASEAN = Association of Southeast Asian Nations, Lao PDR = Lao People's Democratic Republic, Brunei = Brunei Darussalam.
Sources Teluguntla et al. (2016) and GEE (2020a)

1.2.2 Drought Conditions

Detection and monitoring of drought conditions on cropland can be performed by examining agriculture droughts through PDSI data that takes account of temperature and precipitation variables (Edossa et al. 2016) during a crop-growing season (Liu et al. 2012). The PDSI data set provides high spatial resolution (i.e., of about 4 kms [km]) and strongly validated monthly data for global terrestrial surfaces from 1958 to 2019.

In this study, using the GEE, PDSI data were examined over the 40-year period between 1980 and 2019. Temporal droughts were assessed during the major crop-growing seasons, May to November for the MCR and October to April for the ECR. To measure the drought condition levels, PDSI values were categorised as follows: 4.00 or more, extremely wet; 3.00–3.99, very wet; 2.00–2.99, moderately wet; 1.00–1.99, slightly wet; 0.50–0.99, incipient wet spell; 0.49 to −0.49, near normal; −0.50 to −0.99, incipient dry spell; −1.00 to −1.99, mild drought; −2.00 to −2.99, moderate drought; −3.00 to −3.99, severe drought; or −4.00 or less, extreme drought (Abatzoglou 2013; Dai and Zhao 2017; Xulu et al. 2018; GEE 2020b; Lai et al. 2020).The GEE provides gridded surface meteorological, TerraClimate data sets including those on precipitation, temperature, the PDSI, humidity, wind, and other variables over 40 years. The GEE climate data catalogue is continuously updated at a rate of nearly 6000 scenes per day from active missions, and data are available for free for education and research purposes (Gorelick et al. 2017).

JavaScript programming language was applied in the GEE to collect the PDSI monthly time-series data during the crop-growing seasons in the ASEAN region. The earth engine filter date function was applied to reduce the PDSI data set to between 1980 and 2019, and then the time-series function was applied to generate the PDSI profiles for the MCR and ECR (Fig. 1.2) (Venkatappa et al. 2019, 2020a, b). The generated PDSI profiles were exported using the export function in the GEE, and then the temporal drought conditions were computed using Microsoft Excel during the crop-growing seasons. Eventually, the temporal drought severity index was assessed by country for the MCR and ECR.

To assess the spatial drought conditions and associated impacts on agriculture lands, 47,192 spatial grid points (10 km × 10 km) were generated using ArcMap for the ASEAN region. The grid points were used to certify the frequency distribution of the PDSI and intensity of drought over the 40-year period. The spatial grid points were then imported into the GEE, and then the PDSI values were extracted into grid points using the point value extraction function by country from 2015 to 2019 in the GEE (Fig. 1.3).

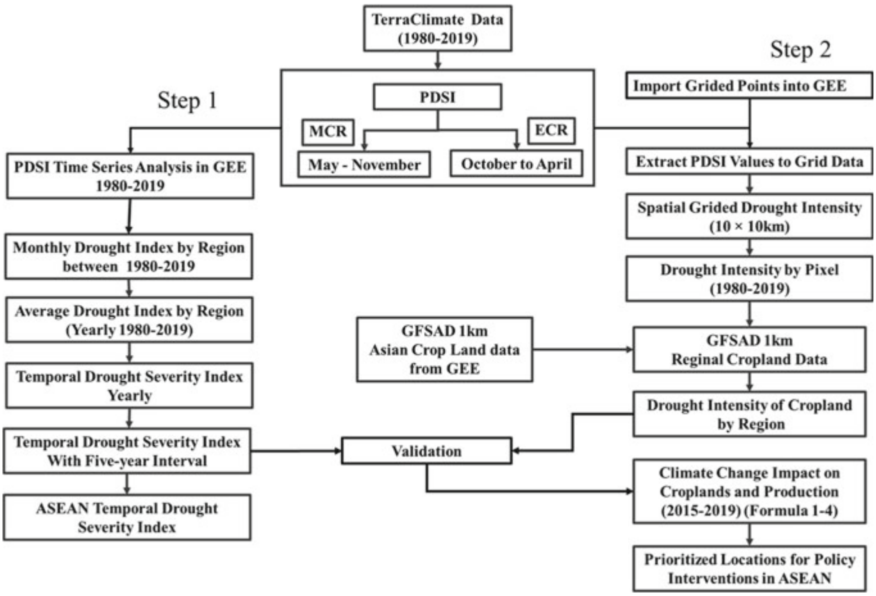

Fig. 1.2 Flowchart of assessing impacts of climate change on agriculture in the ASEAN region. ASEAN = Association of Southeast Asian Nations, ECR = Equatorial Climate Region, GEE = Google Earth Engine, GFSAD = global food security-support analysis data, km = kilometre, MCR = Monsoon Climate Region, PDSI = Palmer drought severity index.
Source Authors

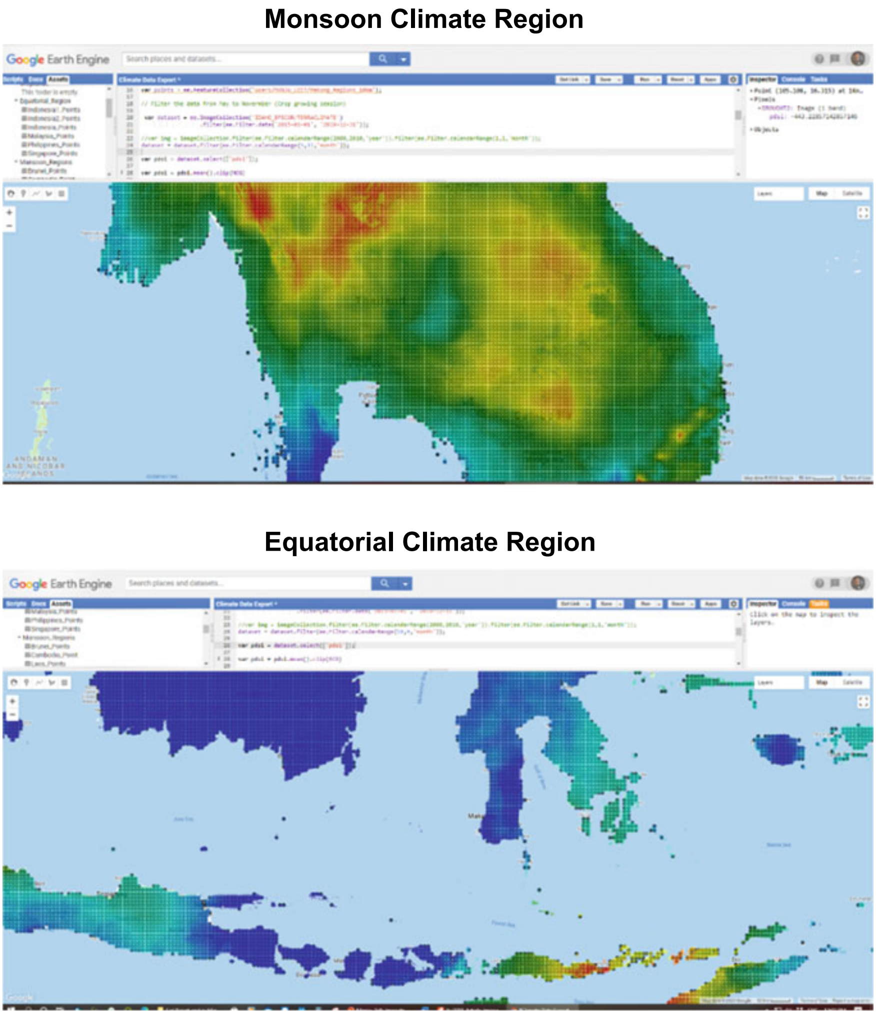

Fig. 1.3 Example of grid points imported into Google Earth engine for extraction of drought severity index values. *Note* The background is the Palmer Drought Severity Index map showing red as higher drought and blue as low drought or wet conditions.
Source Authors

Often, 'computation timed out' was encountered in the GEE while extracting the PDSI values into 47,192 grid points for the entire region; therefore, the grid points were clipped by country using the GEE clip function. The grid points were then applied by country, and the PDSI values were extracted into the grid points by using the extraction function in the GEE (Table 1.1). To assess the drought intensity spatially by country, the ArcMap geoprocessing merge tool was used to combine the

Table 1.1 Palmer drought severity categories, crop-growing seasons, and number of geographical grids point by country

Country	Climate zone	Crop-growing season	Grid points (10 × 10 kms)
Cambodia	Monsoon	May to November	1926
Lao People's Democratic Republic		May to November	5558
Myanmar		May to November	7760
Thailand		May to November	3601
Viet Nam		May to November	2572
Indonesia	Equatorial	October to April	19,255
Malaysia		October to April	3311
Philippines		October to April	3146
Brunei		October to April	59
Singapore		October to April	4
Total			47,192

Source Authors

grid points and to analyse the drought intensity by applying the drought levels during the crop-growing seasons.

1.2.3 Crop Damage Assessment

To assess crop damage from drought and wet intensity, global cropland data in the GEE was used (Fig. 1.1), which was derived from the multi-sensor remote-sensing data (e.g., AVHRR, Landsat, and MODIS); secondary data; and field-plot data at a 1-km scale (Teluguntla et al. 2016). A Global Food Security-Support Analysis Data (GFSAD) 1000 nominal 2010 product was created with data from 2007 to 2012 (Teluguntla et al. 2016).

Irrigated and rain-fed cropland were used to assess drought severity during the crop-growing seasons. PDSI values were assigned for cropland types, and drought and wet severity were then assessed from 2015 to 2019. The PDSI levels were categorised to identify the drought and wet intensity for the croplands (Abatzoglou et al. 2018) (Table 1.2).

Crop cultivation practices were divided as traditional, including rain-fed, or irrigated. The cropland in dry conditions is that facing moderate to extreme droughts (i.e., a PDSI of less than −2.00), and that in wet conditions facing moderately wet to extremely wet conditions (i.e., a PDSI of more than 2.00). Cropland drought and wet intensity were calculated based on a relative frequency of 10 × 10 km grid points that include PDSI levels.

Croplands that were affected by drought were found by selecting moderate, severe, and extreme drought for the MCR and ECR. The percentage of croplands that were

Table 1.2 Palmer drought severity levels during crop-growing seasons

PDSI level	Severity class
>4.00	Extremely wet
3.00 < PDSI ≤ 4.00	Very wet
2.00 < PDSI ≤ 3.00	Moderately wet
1.00 < PDSI ≤ 2.00	Slightly wet
0.50 < PDSI ≤ 1.00	Incipient wet spell
−0.50 ≤ PDSI ≤ 0.50	Near normal
−1.00 ≤ PDSI < −0.50	Incipient drought
−2.00 ≤ PDSI < −1.00	Mild drought
−3.00 ≤ PDSI < −2.00	Moderate drought
−4.00 ≤ PDSI < −3.00	Severe drought
<−4.00	Extreme drought

PDSI Palmer Drought Severity Index
Source Abatzoglou et al. (2018)

damaged and number of people affected by drought were then calculated in both the MCR and ECR by applying Eqs. 1.1–1.3. Eventually, policy interventions for ASEAN cropland were formulated—low, medium, high, and business-as-usual—based on the level of drought conditions on cropland during the crop-growing seasons. Wet conditions that effected croplands were not discussed in this study.

Crop production damage:

$$\mathrm{TCPD_{ij}} = \mathrm{CA_{ij}} \times \mathrm{CP_i} \times \mathrm{Dr_{ij}} \tag{1.1}$$

where:

TCPD Total crop production damage by drought (i.e., ton year^{-1}).
CA_{ij} crop area (hectares) affected by drought levels *i* of crop type *j*.
CP_i crop production by country (tons per year) (i.e., ton ha^{-1} year^{-1}).
Dr_i crops damaged by drought level *i* (%).

The loss of crop production was estimated (FAO 2020) using rice production to represent all crops in the ASEAN region (ton year^{-1}) during 2015–2019 by applying effects of drought stress on rice yield. There was a reduction of 27.8% of rice yield in the case of a moderate drought, 32.0% in the case of a severe drought, and 90.0% or almost no production under extreme drought conditions (Zhang et al. 2018).

Total damage rate (%) of crop production:

$$\mathrm{DR} = \left(\frac{TCPD_{ij}}{TCP_i}\right) \times 100 \tag{1.2}$$

where:

DR Damage rate (%)
$TCPD_{ij}$ total crop production in tons per year damage by drought from Eq. 1.1
CP_i actual crop/rice production in average tons per year 2015 to 2018 by country.

As rice is the main diet in South-East Asia, assessment of affected people can provide useful information for policymakers to prioritise appropriate interventions.

People (million) affected by crop production damage:

$$\frac{TCPD_{ij}}{FC_i} \tag{1.3}$$

where:

PC_i Per capita food consumption (0.2 ton or 200 kg of rice per person per year).

1.3 Results and Discussion

1.3.1 Drought Conditions During Crop-Growing Seasons

Between 1980 and 2019, temporal drought conditions in the MCR and ECR were assessed during the crop-growing seasons. As indicated in Table 1.2, those values fall below −0.50 are considered to be in a drought, while above 0.50 indicates wet conditions.

As shown in Fig. 1.4, the ECR faced moderate wet conditions in 1984, 1989, 1996, 1999, 2000, 2001, 2008, 2009, 2011, 2012, 2013, 2017, and 2018. Wet conditions occurred in 1999–2001, 2008–2009, 2011–2013, and 2017–2018. The MCR faced frequent dry conditions, with 1992–1993 and 2014–2016 seeing the most serious drought conditions. In the MCR, the highest intensity and duration of drought during the crop-growing season occurred in 1990–1995, 2002–2005, and 2014–2016. Indonesia shows increasing wet conditions in 2015–2019 (i.e., 2.24), while the rest of the ECR is witnessing a decrease in wet conditions.

In Fig. 1.5, the MCR shows average drying trends with incipient wet conditions during 1995–2000 and 2005–2010. The average PDSI value decreased from −0.50 in 1980–1985 to −1.34 in 2015–2019, with the driest conditions faced in 1990–1995 with a drought condition of −1.84. Amongst the five MCR countries, Cambodia has been the most affected by drought conditions, with a decrease in the average index value from 0.67 in 1980–1985 to −1.63 in 2015–2019; the most severe drought was in 1990–1995 with a PDSI value of −3.49. Thailand is the second-most drought-affected country in the MCR, followed by the Lao PDR, Viet Nam, and Myanmar. It is worth noting that the increasing trend of drought condition frequency in the MCR

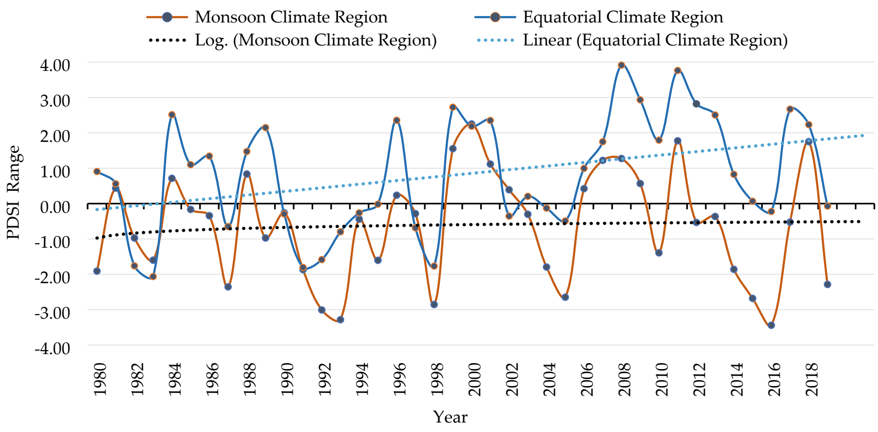

Fig. 1.4 Yearly temporal pattern of drought conditions during major crop-growing seasons, 1980–2019. PDSI = Palmer Drought Severity Index.
Note The orange graph profile represents the Monsoon Climate Region (May–November), and the blue graph profile indicates the Equatorial Climatic Region (October–April).
Source Authors

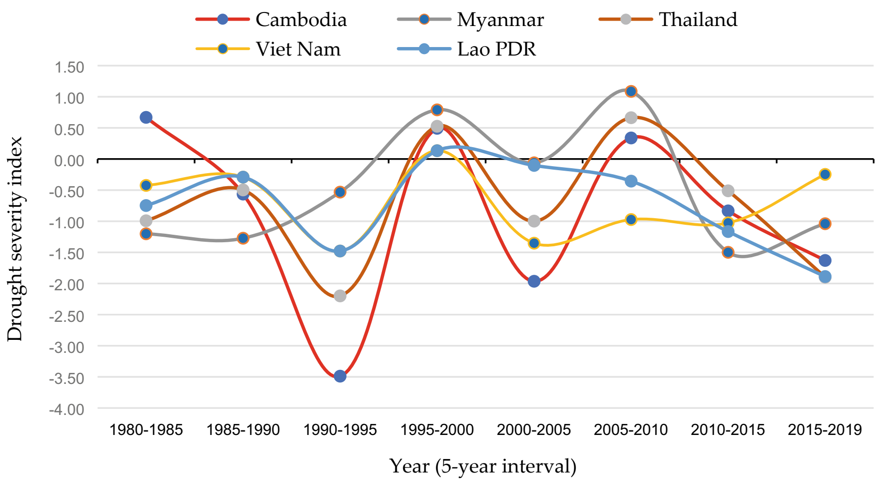

Fig. 1.5 Average drought conditions during crop-growing seasons in the monsoon climate region Lao PDR = Lao People's Democratic Republic.
Source Authors

during the crop-growing season is due to ENSO precipitation from 1980 to 2019 (UNESCAP 2019; Tangang et al. 2020; Wojtys 2020).

Trends in the ECR show an average increase in wet conditions with dipping drier conditions during 1990–1995 and 2000–2005 (Fig. 1.6). Average wet conditions increased from 0.31 in 1980–1985 to 0.96 in 2015–2019, with very wet conditions

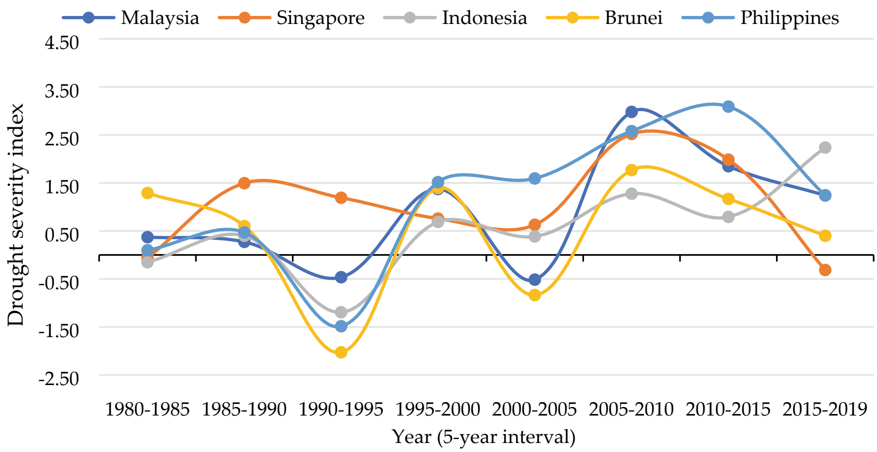

Fig. 1.6 Average drought conditions during crop-growing seasons in the equatorial climate region Brunei = Brunei Darussalam.
Source Authors

in 2005–2010 and 2010–2015. Indeed, this region is known for experiencing heavy rainfall, featuring severe storms and typhoons (Trenberth et al. 2014; Sutton et al. 2019a, b). All countries in the region followed an increasing wet conditions trend, especially Singapore, until 2010–2015. Brunei Darussalam, Indonesia, Malaysia, and the Philippines faced incipient to mild drought conditions during 1990–1995.

1.3.2 Spatial Distribution of Drought Intensity

Over the past 40 years, mild to severe drought frequently has occurred in all MCR countries (Fig. 1.7). Higher drought intensity can be observed during 1990–1995 and 2010–2019. Extremely wet and very wet conditions occurred more frequently in most of the ECR, particularly in 2005–2010 and 2010–2015. The Appendix Tables (Tables 1.5, 1.6, 1.7, 1.8, 1.9, 1.10,1.11, 1.12, 1.13 and 1.14) shows drought intensity during the crop-growing seasons by country.

In 1980–1985, the relative frequency of moderate to extreme drought intensity is seen in less than 10% of all ASEAN countries (Fig. 1.8). In the MCR, mild to moderate drought occurred in central and southern Myanmar (30%), and central and north-eastern Thailand (41%) (Fig. 1.10). In the same period, in the ECR, Sulawesi and southern Irian Jaya in Indonesia and the central Philippines witnessed mild to moderate drought conditions**.** Then, between 1985 and 1990, severe drought occurrences are noted in Myanmar, extending to several parts of the country but affecting the central portion the most. The relative frequency of mild (25%), moderate (36%), and severe droughts (4%) triggered severe dryness in Myanmar, and the drought

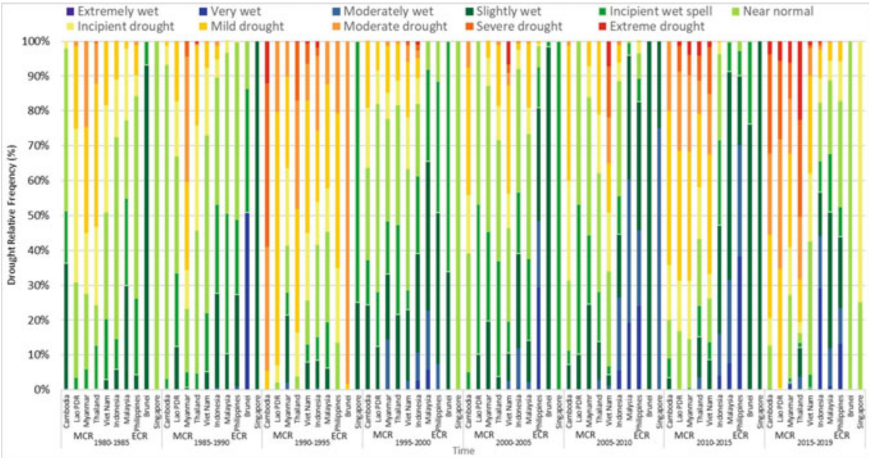

Fig. 1.7 Spatial drought intensity during crop-growing seasons km = kilometre, Brunei = Brunei Darussalam, Lao PDR = Lao People's Democratic Republic.
Note The light to darker red colour indicates mild to extreme drought intensities, the light green colour represents near normal drought conditions, and the light blue to darker blue colours indicate mild to extreme wet conditions in the ASEAN

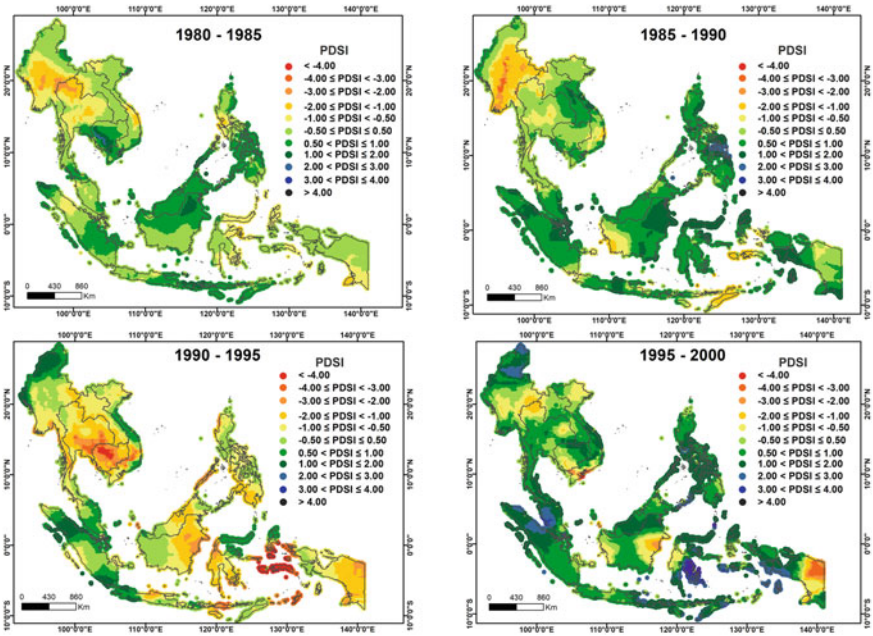

Fig. 1.8 Drought intensity levels during crop-growing seasons, 1980–2000. *Source* Authors

spread to northern and central Thailand, distinct from incipient drought (30%) and mild drought (23%).

As shown in Fig. 1.8, from 1990 to 1995, higher drought occurred in most of the ASEAN region. In the ECR, severe drought arose in eastern Kalimantan and in northern Sulawesi, Maluku, and Papua in Indonesia. The southern part of the Philippines and eastern part of Malaysia also faced drought intensity during the same period. In the MCR, severe drought occurred in Cambodia, spreading across the country, with the relative frequency of extreme drought, severe drought, and moderate drought reaching 12%, 47%, and 35%, respectively. Thailand experienced serious dry conditions during the same period, distinct from the high drought intensity in the central and north-eastern part of the region. Between 1994 and 1996, drought affected about 300,000 hectares (ha) in northern and central Cambodia (CRED 2019).

From 1995 to 2000, droughts were less frequent in the ASEAN region. However, in the ECR, drought events occurred in eastern Papua and Kalimantan in Indonesia. In the MCR, northern and southern Viet Nam saw mild and moderate drought (CRED 2019). In north-western and north-eastern Thailand, central and southern Myanmar, northern and central Lao PDR, and south-western and southern Cambodia, drought conditions ranged from incipient to moderate.

From 2005 to 2010, most ASEAN countries experienced a higher relative frequency of drought patterns. Several parts of Indonesia, including Nusa Tenggara, Papua, and Sulawesi, observed incipient drought and mild drought (Fig. 1.9).

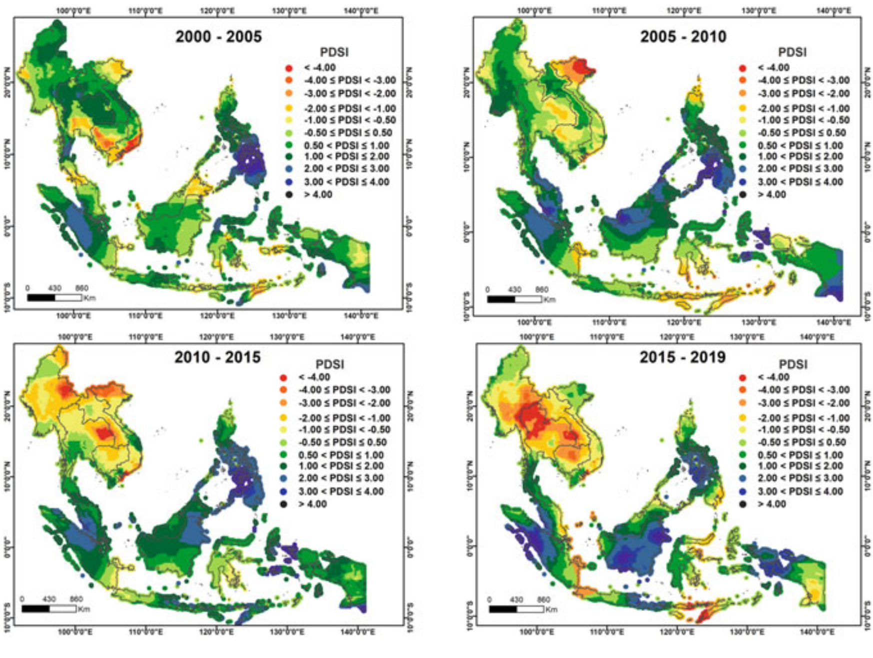

Fig. 1.9 Drought intensity levels during crop-growing seasons, 2000–2019. *Source* Authors

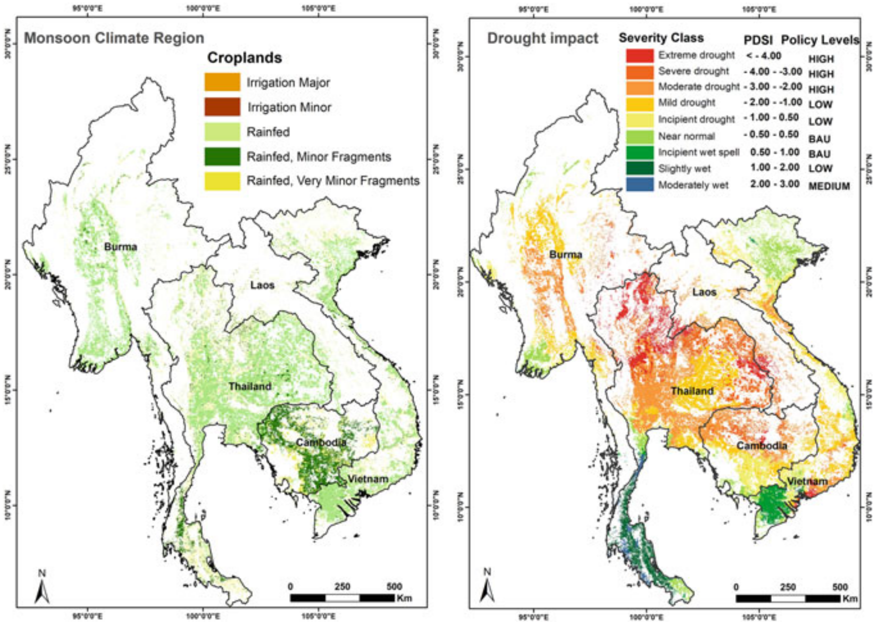

Fig. 1.10 Spatial distribution of drought impact on cropland. BAU = business as usual. *Source* Authors

At the same time, Sabah, in eastern Malaysia, experienced mild drought conditions. In the MCR, Viet Nam experienced more frequent drought levels in its southern areas in 2002 and Ben Tre Province in 2005, during crop-planting seasons (CRED 2019). Cambodia's incipient drought intensity was more than 30% and mainly occurred in Kampong Speu Province (CRED 2019). During the same period, northern and north-eastern Thailand also encountered incipient drought.

The relative frequency of drought in all five MCR countries reached 50% of drought intensity (i.e., incipient to extreme drought) during 2010–2015. This indicates that drought intensity spatially increased in the MCR during the past 20 years. Several provinces in eastern Thailand also had dry conditions, such as Loei and Nakhon Ratchasima in 2010, 2011, and 2014 (CRED 2019). In 2015–2016, over 50% of the Mekong watershed area in north-eastern Thailand experienced extreme drought conditions (UNESCAP 2020).

In recent years, mild drought, moderate drought, and severe drought frequency have been extensive in most of the MCR. Cambodia, the Lao PDR, Myanmar, and Thailand experienced moderate to severe droughts, with increasing drought intensity from 40 to 79% from 2005 to 2019. During the same time, the Lao PDR's dryness increased from 0 to 99%; Myanmar, from 7 to 59%; Thailand, from 21 to 81%; yet in Viet Nam, it decreased from 49 to 38%. In the ECR, the drought intensity was relatively high in Indonesia, Malaysia, and the Philippines, but, between 2005 and 2019, moderate to extreme wet conditions actually increased by 45–57% in

Indonesia. During the same period, drought intensity in Malaysia decreased by 96–51%, in the Philippines from 83 to 44%, Brunei Darussalam and Singapore remained as business as usual.

During 2015–2017, Thailand experienced drought that effected 42 provinces, including 28 in the north, north-east, and central plains (CRED 2019). In Myanmar, 2014–2015 was the driest. In 1980 and 2016, Mandalay underwent severe stress conditions attributed to ENSO events; in 2015, eastern parts of the country were considered drought risks. Moreover, in 2015–2016, drought events were reported in its northern and central regions, including Ayeyarwady, Magway, and Sagaing (UNESCAP 2020). At the same time, northern and southern Lao PDR were affected by drought, particularly Champasak, Luang Prabang, Savannakhet, and Vientiane provinces. In 2018–2019, drought events were also reported in its central and northern areas (UNESCAP 2020). Central and northern Cambodia were reported at drought risk, including Kampong Thom and Siem Reap provinces (UNESCAP 2020).

Drought conditions in the MCR are triggered by erratic ENSO events; the 2015–2016 drought caused serious losses to crop production in Cambodia, the Lao PDR, Myanmar, Thailand, and Viet Nam (UNESCAP 2020). The most severe El Niño-induced droughts were in 1982–1983, 1997–1998, and 2015–2016 (UNESCAP 2020). While drought conditions severely affected northern regions of the MCR, Indonesia, Malaysia, and the Philippines were also severely affected during these events. Thailand had 27 million tons of rice damaged, Vietnam had about 60% crop production damage, and around 2.5 million people were affected in Cambodia due to the loss of more than 40,000 ha of rice (UNESCAP 2020). Other studies reported that drought waves affected the ASEAN region during 1987, 1992–1994, 1998, and 2005 (Miyan 2015), which is consistent with this study's results.

1.3.3 Drought Impacts and Policy Implications

Table 1.3 describes the effects of dry and wet conditions on the ASEAN region from 2015 to 2019 based on crop cultivation practices in respective crop-growing seasons of the countries. In total, about 19.86 million ha of croplands in the ASEAN region faced drought conditions, and 3.55 million ha of croplands faced wet conditions in the 2015–2019 period (Table 1.3). The estimated loss of crop production, primarily rice, due to moderate to extreme drought conditions, amounted to about 2.5 million tons per year in Cambodia, about 1.2 million tons per year in the Lao PDR, about 4.4 million tons per year in Myanmar, about 12.0 million tons per year in Thailand, about 1.5 million tons per year in Viet Nam, and about 3,936.0 million tons per year in Indonesia (Table 1.4). These losses of crop production affected 13.00 million people in Cambodia, 6.02 million in the Lao PDR, 22.41 million in Myanmar, 60.05 million in Thailand, and 7.87 million in Viet Nam.

As shown in Fig. 1.10, irrigated and rain-fed croplands in the MCR were most affected by drought during 2015–2019. In addition, the ECR was most affected by

Table 1.3 Drought effect on croplands in the ASEAN region

	Dry conditions (PDSI < −2.00)					Wet conditions (PDSI > 2.00)				
	Effect on croplands (ha)			Effect on croplands (%)		Effect on croplands (ha)			Effect on croplands (%)	
	Irrigated	Rain-fed	Total	Irrigated	Rain-fed	Irrigated	Rain-fed	Total	Irrigated	Rain-fed
Cambodia	645,687	2,215,277	2,860,964	23	77	–	–	–	–	–
Lao PDR	255,196	611,113	866,310	29	71	–	–	–	–	–
Myanmar	2,899,793	2,242,799	5,142,593	56	44	–	–	–	–	–
Thailand	5,470,677	4,792,150	10,262,827	53	47	–	–	–	–	–
Viet Nam	152,652	563,926	716,578	21	79	–	–	–	–	–
Indonesia	1,611	1,219	2,831	57	43	977,265	543,314	1,520,580	64	36
Malaysia	12,404	651	13,056	95	5	127,415	272,271	399,686	32	68
Philippines	–	–	–	–	–	861,909	772,842	1,634,751	53	47
Brunei	–	–	–	–	–	–	–	–	–	–
Singapore	–	–	–	–	–	–	–	–	–	–
Total	9,438,025	10,427,138	19,865,163			1,966,590	1,588,427	3,555,017		

ha = hectare, *Lao PDR* = Lao People's Democratic Republic, *Brunei* = Brunei Darussalam, *PDSI* = Palmer Drought Severity Index
Source Authors

Table 1.4 Crop production loss due to drought, 2015–2019 (ton/year)

Country	Moderate drought (crop production loss of 27.80%)	Severe drought (crop production loss of 32.00%)	Extreme drought (crop production loss of 90.00%)	Total crop production loss
Cambodia	1,444,212	1,045,008	110,008	2,599,230
Lao PDR	132,313	463,397	607,380	1,203,091
Myanmar	3,744,614	565,831	170,748	4,481,194
Thailand	2,595,157	5,457,908	3,957,675	12,010,742
Viet Nam	966,443	73,678	533,532	1,573,654
Indonesia	3,936	–	–	3,936
Malaysia	145	–	–	–
Philippines	–	–	–	–
Brunei	–	–	–	–
Singapore	–	–	–	–

Lao PDR = Lao People's Democratic Republic, Brunei = Brunei Darussalam
Source Authors

wet conditions and flooding. Brunei Darussalam and Singapore, small nations with little cropland, do not show significant areas affected by drought or floods.

From 2015 to 2019, Thailand faced drought conditions in 10.26 million ha of cropland during May to November, out of which 47% (i.e., about 4.79 million ha) were traditional (i.e., rain-fed) cropland and 53% (i.e., about 5.47 million ha) were managed (i.e., irrigated) cropland. Figure 1.10 shows that the rain-fed croplands of northern Thailand, as well as both rain-fed and irrigated croplands of north-eastern Thailand, were most affected by drought conditions these 5 years. This calls for national and provincial attention in these regions towards high-level policy to adapt to and to mitigate the effects of drought.

In Myanmar, 5.14 million ha of cropland were affected by drought conditions in the same period. Irrigated and rain-fed cropland of central Myanmar were affected by moderate to extreme drought conditions, also calling for high-level policy interventions to combat losses in crop production and yield.

Table 1.3 shows a loss of 2.86 million ha of cropland in Cambodia, 77% of which were affected rain-fed cropland and 23% irrigated cropland. The north-eastern and north-central irrigated and rain-fed croplands were most affected by drought conditions, which call for high-level policy to curb further crop damage in the country. About 0.86 million ha of cropland in the Lao PDR were affected by drought, 70% of which were rain-fed cropland in the south. This rain-fed cropland area is close to the north-eastern cropland in Thailand, the most affected areas in Savannakhet Province, which calls for medium- to high-level policy interventions to prevent further losses in crop production and yield.

Regarding Viet Nam, 0.71 million ha of cropland were affected by drought conditions during 2015–2019. The parts most affected were the rain-fed and irrigated cropland in the Mekong River Delta.

In the ECR, Indonesia is one of the most vulnerable nations, with 1.52 million ha of cropland facing flood conditions and about 0.003 million ha of cropland facing drought conditions in 2015–2019. The flooded conditions affected 64% of irrigated areas and about 36% of rain-fed areas (Fig. 1.11).

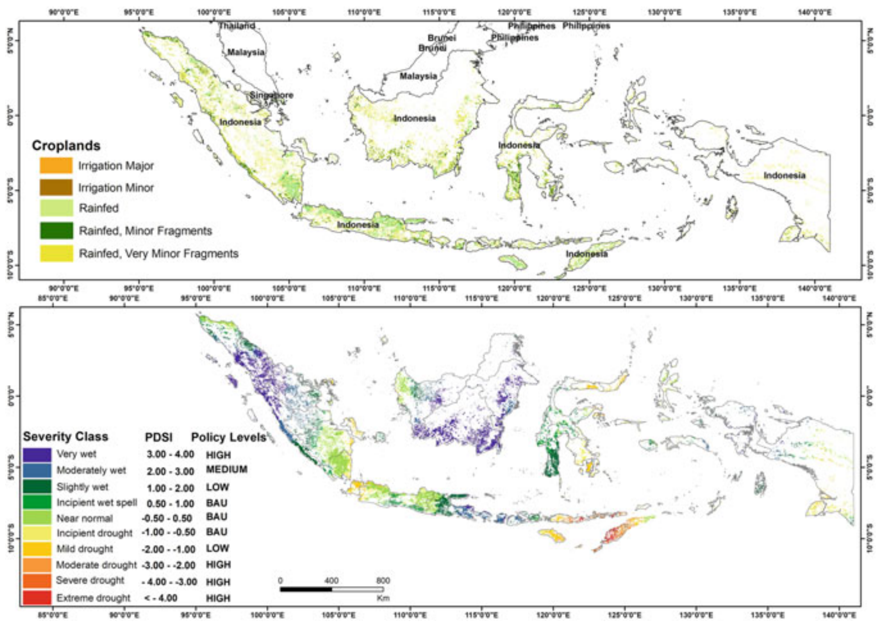

Fig. 1.11 Flood impact on croplands and level of policy implication needed in Indonesia. BAU = business as usual.
Source Authors

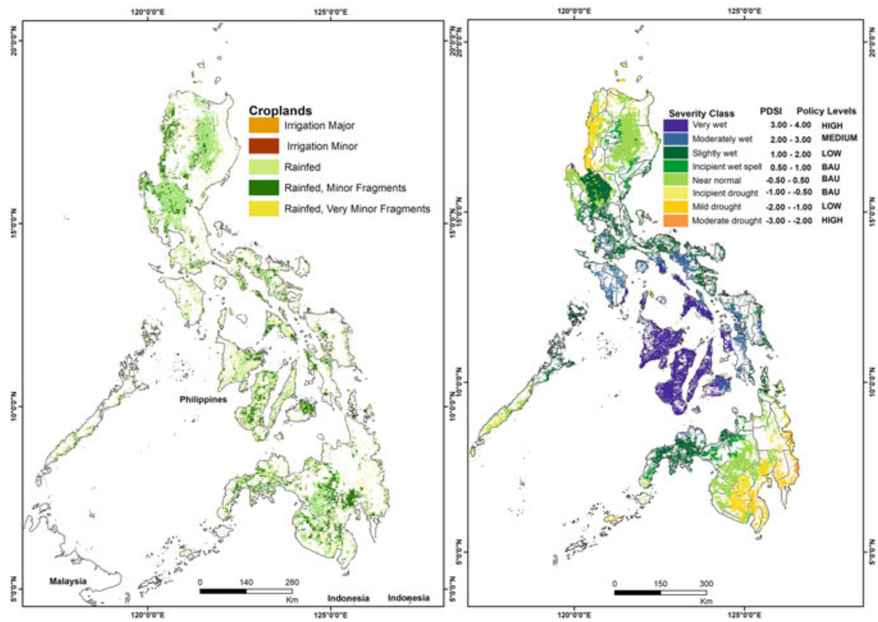

Fig. 1.12 Flood impact on cropland and level of policy implication needed in the Philippines. BAU = business as usual.
Source Authors

The second-most vulnerable country in the ECR is the Philippines, with 1.63 million ha of cropland facing flooded conditions in 2015–2019 (Fig. 1.12). Wet conditions affected 53% of irrigated and 47% of rain-fed areas. Similarly, Malaysia faced flooded conditions in 0.39 million ha of cropland, the majority (68%) of which hit rain-fed croplands with moderate to very wet conditions in the south-west (Fig. 1.13).

The study results are generally consistent with previous studies showing that the agriculture sectors of the MCR and ECR are severely affected by extreme climatic events, primarily governed by ENSO warming and cooling events. Myanmar and Cambodia faced eight severe El Niño events in 1980–2015, with the 2014–2016 event being the worst in the recorded history of these countries. El Niño drought conditions impacted 15.0 million people in Myanmar and 2.5 million in Cambodia, destroying rice and other crops (Sutton et al. 2019a, b). In Myanmar, for instance, the average rice yield losses during El Niño were 6%, and in Cambodia, 10% (Sutton et al. 2019a, b). Some studies have shown that yield losses during El Niño events are somewhat covered by yield gains in La Niña events, however.

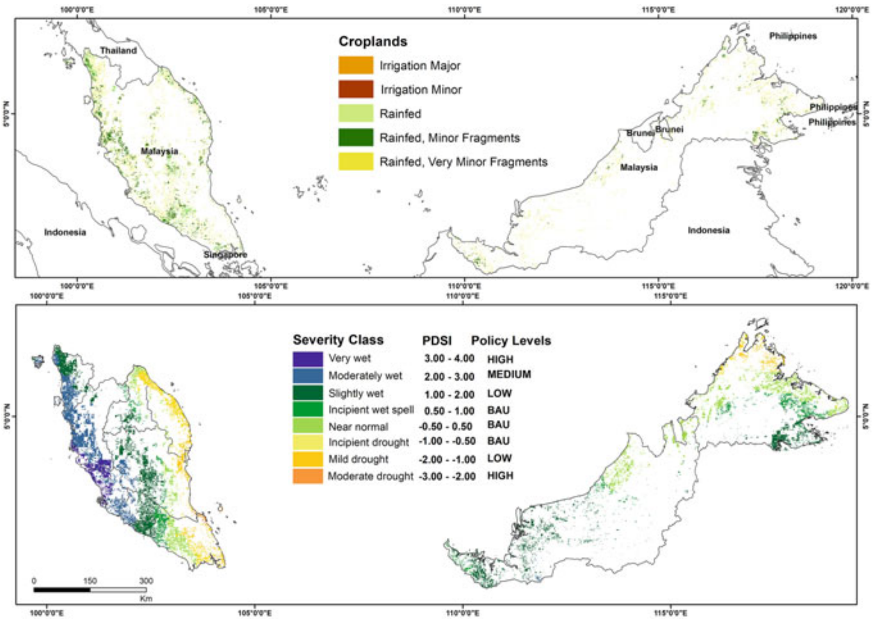

Fig. 1.13 Flood impact on cropland and level of policy implication needed in Malaysia BAU = business as usual.
Source Authors

Average rainfall also decreases during El Niño, with a 30% decline in the Lao PDR from 1980 to 2015 (Sutton et al. 2019a, b). During this period, the Lao PDR faced 38 extreme climatic events, a total loss of $625 million. The areas most severely affected by drought conditions were in the south, such as Savannakhet Province (Sutton et al. 2019a, b). Similarly, in Viet Nam, the most vulnerable places are the south-central coast, central highlands, and Mekong River Delta, with damages totalling nearly $3.6 billion especially due to the 2014–2016 El Niño event (FAO 2016; Sutton et al. 2019a, b).

In the ECR, ENSO events also hit adversely, with severe flooding and droughts. The most severe ENSO events include the 1997–1998 drought that affected two-thirds of the Philippines and wildfires that burnt down almost 10,000 ha of forests (OCHA 2015; Sutton et al. 2019a, b). Flooding during the La Niña conditions generally impacted low-lying cropland and resulted in pest and disease outbreaks in the farmlands. La Niña also brought about the significant increase of—while El Niño a significant decrease in—the average rainfall in the ECR (Roberts et al. 2009).

The study was limited in identifying the drought conditions on various crop types in small farming areas. The main bias could be the total area of cropland affected by drought conditions and their production loss, as 1 km scale global cropland data were used and may mix with other land cover categories. One possible solution would be to produce crop-type maps using high-resolution remote sensing data Sentinel 2 with 10 m resolution, planet imagery QuickBird, WorldView-4 GeoEye-2, and the Pleiades, with 0.5 m or finer spatial resolution (Venkatappa et al. 2020a). By having higher-resolution cropland data, governments can better prepare for droughts by developing strategies on specific crop-type areas based on crop tolerance of climate change.

Another source of error could be the level of drought severity on cropland, as results were not validated with weather station data. Therefore, future studies may need to validate PDSI and metrological data for better interventions (Yan et al. 2013; Liu et al. 2016).

1.4 Conclusions and Policy Recommendations

This study shows that droughts have become more intense over the past 40 years in the ASEAN region, and that mild to severe droughts frequently occurred in the MCR. Higher drought intensity was observed during 1990–1995 and 2010–2019. At the same time, extremely moderate wet and very wet conditions occurred more frequently in most of the ECR countries, particularly in 2005–2010 and 2010–2015. About 19.86 million ha of cropland in the ASEAN region faced drought conditions, and 3.55 million ha of cropland faced wet conditions in 2015–2019.

Due to the increase of drought intensity, Cambodia lost crop productivity of about 2.5 million tons per year; Lao PDR, about 1.2 million tons per year; Myanmar, about 4.4 million tons per year; Thailand, about 12.0 million tons per year; Viet Nam, about 1.5 million tons per year; and Indonesia, about 3,936.0 million tons per year.

Drought is a hazard that occurs in both dry and wet regions, and it is expected to become more intense in the region. Therefore, policymakers should prepare by developing and implementing strategies and plans that reduce associated impacts on both irrigated and rain-fed agriculture lands.

The GEE is a useful tool for assessing cropland drought conditions and severity using PDSI data in any region of the world speedily and free of cost. However, using high-resolution cropland data could provide a deeper understanding of crop drought tolerance, and it is important to compare meteorological data.

Policy interventions in drought-affected cropland should include:

- introducing drought-tolerant—targeted for the MCR—or stress-resistant—for both MCR and ECR—seed/crop varieties, as well as promoting crop diversification with a focus on crops that consume less water than rice varieties in drought-prone areas;
- financing irrigation to raise crop yields during normal years, including exploring opportunities for using groundwater for irrigation in the MCR;
- introducing water-use efficiency techniques, small-scale irrigation, and water harvesting in irrigation ponds in drought-prone cropland, especially rain-fed agriculture lands;
- designating national and regional taskforces for ENSO events, with coordination from local focal points composed of nongovernmental stakeholders;
- strengthening and expanding hydrological and meteorological stations in the MCR and ECR for better forecasting; and
- developing early-warning systems in both the MCR and ECR, as forecasting and disseminating information about upcoming ENSO events are essential for ensuring adaptation practices at the farm level. The forecasting and warning systems must prioritise vulnerable areas by developing agriculture risk maps that point out high-intervention areas. Information sharing and communication should be accessible through web portals, news, and other telecommunications for better decision making as well.

Acknowledgements This study was carried out under funding from the Economic Research Institute for ASEAN and East Asia (ERIA).

Appendix A

Table 1.5 Drought Intensities during the Crop-Growing Season by Country (Tables 1.6, 1.7, 1.8, 1.9, 1.10, 1.11, 1.12, 1.13 and 1.14).

Table 1.5 Cambodia

Drought Intensity	1980–1985	Rf (%)	1985–1990	Rf (%)	1990–1995	Rf (%)	1995–2000	Rf (%)	2000–2005	Rf (%)	2005–2010	Rf (%)	2010–2015	Rf (%)	2015–2019	Rf (%)
Extremely wet	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Very wet	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Moderately wet	11	1	0	0	0	0	0	0	0	0	7	0	0	0	0	0
Slightly wet	687	36	4	0	0	0	469	24	0	0	132	7	67	3	0	0
Incipient wet spell	291	15	60	3	0	0	250	13	99	5	82	4	109	6	12	1
Near normal	897	47	1731	90	0	0	508	26	654	34	383	20	211	11	231	12
Incipient drought	40	2	107	6	0	0	332	17	322	17	553	29	302	16	153	8
Mild drought	0	0	24	1	108	6	365	19	708	37	744	39	852	44	461	24
Moderate drought	0	0	0	0	683	35	2	0	143	7	25	1	385	20	450	23
Severe drought	0	0	0	0	904	47	0	0	0	0	0	0	0	0	549	29
Extreme drought	0	0	0	0	231	12	0	0	0	0	0	0	0	0	70	4
Total	1926	100	1926	100	1926	100	1926	100	1926	100	1926	100	1926	100	1926	100

Rf = Drought intensity relative frequency
Source Authors

Table 1.6 Thailand

Drought intensity	1980–1985	Rf	1985–1990	Rf	1990–1995	Rf	1995–2000	Rf	2000–2005	Rf	2005–2010	Rf	2010–2015	Rf	2015–2019	Rf
Extremely wet	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Very wet	0	0	0	0	0	0	0	0	0	0	12	0	1	0	0	0
Moderately wet	0	0	0	0	0	0	25	0	0	0	155	3	201	4	211	4
Slightly wet	15	0	0	0	7	0	1175	21	211	4	606	11	643	12	459	8
Incipient wet spell	694	12	270	5	13	0	1435	26	1847	33	796	14	500	9	90	2
Near normal	638	11	2264	41	190	3	1902	34	1921	35	1885	34	1054	19	143	3
Incipient drought	1249	22	1681	30	707	13	390	7	545	10	934	17	826	15	172	3
Mild drought	2281	41	1271	23	1966	35	592	11	974	18	1158	21	1173	21	697	13
Moderate drought	653	12	28	1	1727	31	39	1	60	1	12	0	536	10	989	18
Severe drought	28	1	2	0	934	17	0	0	0	0	0	0	404	7	1542	28
Extreme drought	0	0	42	1	14	0	0	0	0	0	0	0	220	4	1255	23
Total	5558	100	5558	100	5558	100	5558	100	5558	100	5558	100	5558	100	5558	100

Rf = Drought intensity relative frequency
Source Authors

Table 1.7 Myanmar

Drought intensity	1980–1985	Rf	1985–1990	Rf	1990–1995	Rf	1995–2000	Rf	2000–2005	Rf	2005–2010	Rf	2010–2015	Rf	2015–2019	Rf
Extremely wet	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Very wet	0	0	0	0	0	0	0	0	0	0	0	0	0	0	113	1
Moderately wet	0	0	0	0	160	2	1128	15	7	0	32	0	0	0	44	1
Slightly wet	17	0	57	1	1508	19	1443	19	1526	20	1880	24	4	0	0	0
Incipient wet spell	459	6	347	4	503	6	1180	15	1994	26	1537	20	46	1	112	1
Near normal	1661	21	1401	18	1032	13	2274	29	3235	42	3065	39	1072	14	1837	24
Incipient drought	1356	17	861	11	1737	22	589	8	625	8	696	9	1305	17	1057	14
Mild drought	2356	30	1967	25	2031	26	1048	14	363	5	550	7	2873	37	2091	27
Moderate drought	1891	24	2785	36	772	10	98	1	10	0	0	0	1710	22	1231	16
Severe drought	20	0	323	4	17	0	0	0	0	0	0	0	453	6	799	10
Extreme drought	0	0	19	0	0	0	0	0	0	0	0	0	297	4	476	6
Total	7760	100	7760	100	7760	100	7760	100	7760	100	7760	100	7760	100	7760	100

Rf = Drought intensity relative frequency
Source Authors

Table 1.8 Viet Nam

Drought intensity	1980–1985	Rf	1985–1990	Rf	1990–1995	Rf	1995–2000	Rf	2000–2005	Rf	2005–2010	Rf	2010–2015	Rf	2015–2019	Rf
Extremely wet	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Very wet	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Moderately wet	0	0	0	0	0	0	91	3	95	3	45	1	7	0	0	0
Slightly wet	105	3	190	5	287	8	738	20	285	8	112	3	302	8	20	1
Incipient wet spell	629	17	606	17	188	5	205	6	333	9	91	3	189	5	142	4
Near normal	1098	30	1829	51	444	12	1248	35	957	27	971	27	443	12	1369	38
Incipient drought	1109	31	698	19	699	19	530	15	353	10	614	17	254	7	707	20
Mild drought	652	18	263	7	1373	38	575	16	1120	31	507	14	1240	34	1008	28
Moderate drought	8	0	15	0	375	10	171	5	133	4	475	13	624	17	287	8
Severe drought	0	0	0	0	212	6	26	1	86	2	527	15	486	13	30	1
Extreme drought	0	0	0	0	23	1	17	0	239	7	259	7	56	2	38	1
Total	3601	100	3601	100	3601	100	3601	100	3601	100	3601	100	3601	100	3601	100

Rf = Drought intensity relative frequency
Source Authors

Table 1.9 Lao People's Democratic Republic

Drought intensity	1980–1985	Rf	1985–1990	Rf	1990–1995	Rf	1995–2000	Rf	2000–2005	Rf	2005–2010	Rf	2010–2015	Rf	2015–2019	Rf
Extremely wet	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Very wet	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Moderately wet	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Slightly wet	0	0	321	12	0	0	322	13	261	10	261	10	0	0	0	0
Incipient wet spell	92	4	544	21	0	0	405	16	1111	43	1110	43	4	0	0	0
Near normal	702	27	857	33	54	2	1382	54	1200	47	1201	47	428	17	0	0
Incipient drought	1131	44	409	16	128	5	248	10	0	0	0	0	372	14	13	1
Mild drought	610	24	437	17	1866	73	215	8	0	0	0	0	963	37	881	34
Moderate drought	37	1	4	0	519	20	0	0	0	0	0	0	580	23	954	37
Severe drought	0	0	0	0	5	0	0	0	0	0	0	0	191	7	578	22
Extreme drought	0	0	0	0	0	0	0	0	0	0	0	0	34	1	146	6
Total	2572	100	2572	100	2572	100	2572	100	2572	100	2572	100	2572	100	2572	100

Rf = Drought intensity relative frequency in percentage (%)
Source Authors

Table 1.10 Indonesia

Drought intensity	1980–1985	Rf	1985–1990	Rf	1990–1995	Rf	1995–2000	Rf	2000–2005	Rf	2005–2010	Rf	2010–2015	Rf	2015–2019	Rf
Extremely wet	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Very wet	0	0	0	0	7	0	498	3	80	0	1068	6	759	4	5594	29
Moderately wet	0	0	142	1	121	1	1553	8	2232	12	4014	21	2351	12	2897	15
Slightly wet	1143	6	5171	27	1507	8	5477	28	5230	27	3519	18	5991	31	2426	13
Incipient wet spell	1700	9	4938	26	1292	7	4280	22	3365	17	2136	11	4711	24	1735	9
Near normal	11094	58	7003	36	5073	26	3971	21	6815	35	6297	33	4745	25	3179	17
Incipient drought	3219	17	992	5	2386	12	1427	7	1055	5	1048	5	605	3	1367	7
Mild drought	2079	11	779	4	3933	20	1105	6	377	2	947	5	93	0	1582	8
Moderate drought	20	0	230	1	4111	21	420	2	67	0	194	1	0	0	213	1
Severe drought	0	0	0	0	469	2	331	2	35	0	32	0	0	0	170	1
Extreme drought	0	0	0	0	356	2	193	1	0	0	0	0	0	0	92	0
Total	19,255	100	19,255	100	19,255	100	19,255	100	19,256	100	19,255	100	19,255	100	19,255	100

Rf = Drought intensity relative frequency
Source Authors

Table 1.11 Malaysia

Drought intensity	1980–1985	Rf	1985–1990	Rf	1990–1995	Rf	1995–2000	Rf	2000–2005	Rf	2005–2010	Rf	2010–2015	Rf	2015–2019	Rf
Extremely wet	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Very wet	0	0	0	0	0	0	189	6	1	0	637	19	252	8	37	1
Moderately wet	0	0	0	0	0	0	568	17	74	2	1364	41	798	24	359	11
Slightly wet	989	30	343	10	206	6	1412	43	395	12	1176	36	1974	60	1295	39
Incipient wet spell	830	25	1337	40	442	13	874	26	779	24	123	4	279	8	553	17
Near normal	741	22	1522	46	852	26	268	8	1176	36	11	0	8	0	690	21
Incipient drought	680	21	106	3	415	13	0	0	252	8	0	0	0	0	193	6
Mild drought	71	2	3	0	985	30	0	0	614	19	0	0	0	0	171	5
Moderate drought	0	0	0	0	411	12	0	0	20	1	0	0	0	0	13	0
Severe drought	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Extreme drought	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	3311	100	3311	100	3311	100	3311	100	3311	100	3311	100	3311	100	3311	100

Rf = Drought intensity relative frequency \
Source Authors

Table 1.12 Philippines

Drought intensities	1980–1985	DRF	1985–1990	Rf	1990–1995	Rf	1995–2000	Rf	2000–2005	Rf	2005–2010	Rf	2010–2015	Rf	2015–2019	Rf
Extremely wet	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Very wet	1	0	1	0	0	0	0	0	926	29	755	24	1201	38	415	13
Moderately wet	0	0	34	1	0	0	233	7	597	19	686	22	1008	32	327	10
Slightly wet	137	4	826	26	0	0	1364	43	1021	32	1158	37	626	20	639	20
Incipient wet spell	690	22	676	21	1	0	1186	38	369	12	212	7	225	7	272	9
Near normal	1820	58	1598	51	424	13	363	12	187	6	226	7	86	3	955	30
Incipient drought	191	6	11	0	672	21	0	0	24	1	100	3	0	0	359	11
Mild drought	274	9	0	0	1399	44	0	0	22	1	8	0	0	0	173	5
Moderate drought	33	1	0	0	642	20	0	0	0	0	1	0	0	0	6	0
Severe drought	0	0	0	0	8	0	0	0	0	0	0	0	0	0	0	0
Extreme drought	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total locations	3146	100	3146	100	3146	100	3146	100	3146	100	3146	100	3146	100	3146	100

Rf = Drought intensity relative frequency in percentage ()
Source Authors

Table 1.13 Brunei Darussalam

Drought Intensity	1980–1985	Rf	1985–1990	Rf	1990–1995	Rf	1995–2000	Rf	2000–2005	Rf	2005–2010	Rf	2010–2015	Rf	2015–2019	Rf
Extremely wet	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Very wet	0	0	30	51	0	0	0	0	0	0	0	0	0	0	0	0
Moderately wet	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Slightly wet	55	93	0	0	0	0	20	34	58	98	59	100	45	76	0	0
Incipient wet spell	4	7	21	36	0	0	39	66	1	2	0	0	14	24	0	0
Near normal	0	0	8	14	0	0	0	0	0	0	0	0	0	0	59	100
Incipient drought	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mild drought	0	0	0	0	1	2	0	0	0	0	0	0	0	0	0	0
Moderate drought	0	0	0	0	58	98	0	0	0	0	0	0	0	0	0	0
Severe drought	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Extreme drought	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total locations	59	100	59	100	59	100	59	100	59	100	59	100	59	100	59	100

Rf = Drought intensity relative frequency
Source Authors

Table 1.14 Singapore

Drought intensity	1980–1985	Rf	1985–1990	Rf	1990–1995	Rf	1995–2000	Rf	2000–2005	Rf	2005–2010	Rf	2010–2015	Rf	2015–2019	Rf
Extremely wet	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Very wet	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Moderately wet	0	0	0	0	0	0	0	0	0	0	3	75	0	0	0	0
Slightly wet	0	0	4	100	1	25	0	0	0	0	1	25	4	100	0	0
Incipient wet spell	0	0	0	0	3	75	0	0	4	100	0	0	0	0	0	0
Near normal	4	100	0	0	0	0	4	100	0	0	0	0	0	0	1	25
Incipient drought	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	75
Mild drought	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Moderate drought	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Severe drought	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Extreme drought	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	4	100	4	100	4	100	4	100	4	100	4	100	4	100	4	100

Rf = Drought intensity relative frequency
Source Authors

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Chapter 2
Management of Natural Forests for Carbon Emission Reductions Through Improved Logging Practices and Wood Bioenergy Use

Nophea Sasaki

Abstract The management of tropical forests can achieve multiple purposes. Here, we assessed timber production, bioenergy generation, and emission reductions through the management of production forest for timber and bioenergy production in Southeast Asia between 2000 and 2060 through a comparative study between the conventional and reduced impact logging (RIL) systems. Whilst producing an average of 35.1 million cubic metres per year (m^3 $year^{-1}$) of wood products, the adoption of the RIL can result in emission reductions of 96.6 teragrams of carbon dioxide ($TgCO_2$) over a 60-year period. Apart from deforestation, emissions from logging operations were the second-highest source of emissions, indicating that attention should be made to improve the efficiency of logging machinery whilst reducing deforestation and forest degradation. When combining all emissions together, total emission reductions were estimated at 229.9 $TgCO_2$, 215.4 $TgCO_2$, and 207.9 $TgCO_2$ annually during the Paris Agreement between 2020 and 2030 if compared to coal, diesel, and natural gas, respectively. Southeast Asia could generate about US$2.1 billion–US$2.3 billion $year^{-1}$ under the result-based payment of the REDD+ scheme at a carbon price of US$10. Introducing tax exemptions or financial incentives for carbon and environmental taxes and/or energy tax could materialise the RIL-based forest management.

Keywords Selective logging · Emission reductions · Wood bioenergy · Carbon tax · Environmental tax

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H. Phoumin et al. (eds.), *Energy Sustainability and Climate Change in ASEAN*, Economics, Law, and Institutions in Asia Pacific,
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2.1 Introduction

Forests are the most important resource of food, fresh water, clean air, and countless ecosystem services and feed the world's population whilst regulating the climate for human existence. However, the clearing of forests for different, yet avoidable, expansion of agriculture (Hansen et al. 2008; Tyukavina et al. 2018), hydro dam construction, land economy concession (Neef et al. 2013; Nomura et al. 2019; Wheeler et al. 2013), and urban expansion; the overexploitation of timber; illegal hunting of wildlife; and illegal logging (Alemagi and Kozak 2010; Santos de Lima et al. 2018) have caused the huge loss and degradation of tropical forests worldwide. Based on the most recent forest assessment report of the Food and Agriculture Organization of the United Nations (FAO), the world lost about 420 million hectares (ha) since 1990 (FAO 2020). To reduce future deforestation and forest degradation, the sustainable management of forests has become the only option that would ensure the long-term sustainability of forest resources.

In 2007 at the 11th Conference of the Parties to the United Nations Convention on Climate Change (UNFCCC) in Bali, Indonesia, the Bali Action Plan was adopted, in which the REDD+ scheme for reducing emissions from deforestation and forest degradation, conservation of forests, sustainable management of forests, and enhancement of carbon stocks in developing countries was agreed as one of the climate change mitigation measures (UNFCCC 2008). Therefore, the sustainable management of forest (SMF) plays an important role in the REDD+ scheme for achieving the Paris Agreement, whose implementation period is set for between 2020 and 2030 (Bottazzi et al. 2013). The process of SMF has been defined by different organisations. The FAO (2013) defines SMF as the process of applying forest management practices to sustain a constant carbon stock level over time (Zimmerman and Kormos 2012). According to United Nations General Assembly in 2007, the concept of SMF covers both natural and planted forests under conservation, production, and multiple purposes, and it is applicable to both the national and international levels (United Nations 2008). According to Piponiot et al. (2018), SMF can maintain wood supply, reduce forest fires, and retain carbon stocks, and it can reduce emissions (Sasaki et al. 2016) and conserve biodiversity (Lindenmayer et al. 2000).

The International Tropical Timber Organization defines SFM as managing forests to achieve specified management objectives with respect to the sustainable production of desired goods and services without affecting undesirable effects on future productivity as well as the environment (Noraida et al. 2017). The Intergovernmental Panel on Climate Change (IPCC) (2007) indicated that land use changes, including deforestation and forest degradation, account for approximately 20% of greenhouse gas (GHG) emissions (Brown et al. 2011). In this regard, minimising the impacts of wood waste (logging waste) due to unsustainable and uncontrolled selective logging practices on emissions of carbon dioxide (CO_2) from forest degradation should be considered as an issue of SFM.

Defined as the process of removing or cutting, processing, and moving trees to a location for transport, logging in the tropics produces huge amounts of wood waste throughout the logging and processing phases (Ellis et al. 2019). According to Griscom et al. (2019), selective logging emits about 0.85 gigatons of carbon dioxide ($GtCO_2$) per year from tropical and subtropical natural forests, which is equivalent to a quarter of the mean annual CO_2 emissions from the loss of tropical forests since 2001. Carbon losses from the degradation of tropical forests account for 27–69% of the total emissions from tropical forests, of which about 50% of the forest degradation emissions come from selective logging of world's tropical forests (Ellis et al. 2019). Since logging is a major cause of forest degradation, the application of improved logging practices and the implementation of an approach for the efficient utilisation of wood waste are important factors for the sustainable management of forests under the REDD+ scheme.

In the tropics, two types of selective logging practices are applied: conventional logging (CVL) and reduced-impact logging (RIL) (Sasaki et al. 2016). CVL is an unplanned timber harvesting practice applied by logging companies/concessions to fell selected trees in forests by using untrained machinery and building roads and skid trails (Rivero et al. 2008; Sasaki et al. 2016). This logging practice causes wood waste and severe damage to natural regeneration and non-selected trees that are not necessary to be felled, and when those trees are left to decompose, they produce carbon emissions (Boltz et al. 2003; Rivero et al. 2008). On the other hand, RIL is a well-controlled and planned forest management practice that minimises logging damage as well as wood waste to sustain the timber yield compared to CVL. This practice is applied through extensive pre-harvest planning, which includes the inventory and mapping of trees, well-trained logging machinery, and well-planned roads and skid trails that promote natural regeneration and reduce ground disturbance and carbon emissions (Ellis et al. 2019; Rivero et al. 2008; Sasaki et al. 2016). Previous studies have suggested that RIL minimises 30%–50% of emissions from logging in tropical forests (Griscom et al. 2019).

In terms of logging waste and forest biomass recovery after CVL and RIL, a study was conducted in Amazonian Brazil by West et al. (2014). The study observed post-logging biomass recovery in the 25.4 ha control plots subjected to CVL and RIL over a 16-year period, and over 25-cm trees were monitored. Whilst RIL produced 38.9 cubic metres per hectare (m^3 ha^{-1}) of commercial timber volume and 38.6 m^3 ha^{-1} of extracted timber volume, the commercial volume of CVL was about 37.4 m^3 ha^{-1}; however, its extracted timber volume was only about 29.7 m^3 ha^{-1}. Moreover, the study found that RIL lost 17% of aboveground biomass, whereas CVL lost about 26% after logging. After 16 years of logging, the mean annual increment of aboveground biomass in the RIL plot was estimated at 2.8 megagrams per hectare per year (Mg ha^{-1} $year^{-1}$) and that of the CVL plot was at 0.5 Mg ha^{-1} $year^{-1}$. Over 16 years after logging, the control plot subject to RIL had a forest biomass recovery of 100%, whilst the CVL plot recovered only 77%. These findings support the implementation of the approach to convert CVL to RIL to sustain timber yield and carbon stocks for SMF.

In the phase of wood processing after the logging phase, the proportion of wood waste from the conversion of standing timber to lumber depends on the regions and their technologies. One study found that only 48% of the standing timber volume can be used as merchantable timber, and the remaining portion goes into wood waste (Aina 2006). Another study found that the portion of merchantable timber is estimated at 49.3% (Jenkins 1933). In tropical countries, the wood processing efficiency is between 35 and 55%. One of the approaches to reducing the waste of woody biomass is the consumption of logging waste for the production of bioenergy, which can replace fossil fuels and contribute to SMF by reducing carbon emissions (Lima et al. 2020; Sasaki et al. 2009) since energy derived from the sources of woody biomass plays a significant role in GHG emission reductions through the provision of an alternative energy source (Lu and El Hanandeh 2017; Mangoyana 2011).

Study of the bioenergy production from wood waste and emission reductions could provide useful information for managing tropical forests beyond timber production alone. However, in Southeast Asia, only a few studies have been done on the assessment of the contribution of the sustainable management of forests to sustainable timber production and carbon emission reductions by the consumption of wood waste for bioenergy production. Therefore, this study attempts to assess the carbon emission reductions through sustainable forest management for timber and bioenergy production in Southeast Asia between 2000 and 2060 by comparing two logging systems (CVL and RIL) over the course of 60 years, or two management cycles of 30 years each.

This chapter is structured as follows: study methods and materials, then results and discussions on harvested timber and wood products, carbon stock changes, emission reductions, biomass, bioenergy, emission reductions, and emission reductions through forest management for timber and bioenergy are provided before closing with a conclusion.

2.2 Study Methods and Materials

2.2.1 Commercial Logging and Wood Waste

Selective logging is commonly applied for managing production forests in the tropics because only mature trees reaching the minimum size requirements for harvest can be harvested for each logging permit. Until recently, two types of selective logging practices have been widely recognised. They are conventional logging (CVL) and reduced impact logging (RIL). For more information on specific practices of the two logging systems, please refer to Boltz et al. (2003) and West et al. (2014). In this study, CVL is used as the base practice for selective logging in Southeast Asia's production, whose area was estimated at 7,778,000 ha in 2020 (Table 2.1). RIL is the logging practice in favour of long-term sustainable development because of its ability to avoid illegal logging, early-entry logging, logging damages, and wood waste onsite and offsite (Ellis et al. 2019; Goodman et al. 2019). As shown in Table 2.2, CVL and RIL create different levels of logging damages and wood waste, which collectively are referred to as wood residues. These wood residues are used for bioenergy production

Table 2.1 Area of natural forests in southeast Asia, 2000–2020

Land use type	2000 (ha)	2010 (ha)	2015 (ha)	2020 (ha)	2000–2030	
					Area (ha)	Change (%)
PdF (this study)	96,305,820	91,734,790	85,902,100	84,402,540	−595,164	−0.29
PrF	87,031,300	90,516,360	94,435,800	93,531,000	324,985	0.16
MpF	40,162,810	36,960,050	32,222,660	29,542,810	−531,000	−0.26
Total	223,501,930	219,213,210	212,562,575	207,478,370	−801,178	−0.39

Ha hectare, *MpF* multi-purpose forests, *PdF* production forests, *PrF* protected forests
Source FAO (2020)

to replace three scenarios of fossil fuel combustion (i.e., natural gas, oil, and coal) for the same amount of energy generation.

Overall, carbon emission reductions were calculated as follows: first, the study observed the emission reductions through sustainable forest management for timber production by switching from CVL to RIL. Second, bioenergy production from both CVL and RIL were compared, and the respective emissions for generating the bioenergy from the wood residues were estimated. Third, discussions on emission reductions through the adoption of RIL for managing production forests in Southeast Asia were made in line with the REDD+ scheme of the UNFCCC. In the context of the REDD+ scheme, in this study, baseline emissions were assumed to be the overall emissions from CVL, whilst the project emissions were assumed to be from RIL. The differences in emissions between CVL and RIL are the emission reductions, for which result-based payment is possible under the REDD+ scheme.

2.2.2 Production Forests in Southeast Asia

From the Forest Resource Assessment of the FAO, three major types of forest land use can be considered for this study, namely production, protection, and multi-purpose forests. Since selective logging is allowed only in production forests, the remaining forest land use types are not considered in this study. Production forest is where commercial logging is allowed for the exploitation of the wood within an agreed period, usually between 60 and 90 years depending on the countries in question. Harvested timber is commonly used to supply the growing needs of populations and even for export earnings. Table 2.1 shows a rapid decline of production forests (0.29%) compared to 0.26% in multi-purpose forests (MpF), whilst the area of protected forests (PrF) increased about 0.16% over the same period. For this study, a linear regression was performed to generate the parameter value and initial value for predicting (Eq. (2.1)) the change of PdF over a 30-year period of the modelling timeframe, starting from 2020 through 2050.

Table 2.2 Initial values, parameters, and variables for Eqs. (2.2)–(2.11)

Short	Description	Values	
		CVL	RIL
CS(t0)*	Initial carbon stocks ($MgC\ ha^{-1}$) (aboveground only)	73.8 (FAO 2020)	
$CS_i(t)$	Aboveground carbon stocks under logging *i* (CVL or RIL) at time *t* (year)		
MAI	Mean annual increment ($MgC\ ha^{-1}\ year^{-1}$)	0.66	
$LM_i(t)$	Loss of carbon or mortality caused by logging operations ($MgC\ ha^{-1}$). $LMi(t) = \alpha * H(t)$		
A	Proportion of trees killed by logging and log skidding	0.40	0.14
Hi(t)	Carbon in the harvested log ($MgC\ ha^{-1}$)		
BEF	Biomass expansion factor to include carbon in other wood components	1.74	
f_M	Proportion of mature trees	0.43	
f_H	Legal rate of harvesting	0.30	
r	Illegal logging	0.50	
Tc	Cutting cycle (years)	30	
$TCS_i(t)$	Total carbon stocks under CVL or RIL (TgC)		
$TWH_i(t)$	Total wood harvest (million $m^3\ year^{-1}$)		
44/12	Molecular weight of carbon over CO_2		
WD	Wood density in drywood in the tropics ($Mg\ m^{-3}$)	0.57	
CT	Carbon content in drywood ($MgC\ Mg^{-1}$) as per IPCC guidelines	0.47	
$TE_{def}(t)$	Total emissions due to deforestation and logging ($MgCO_2\ year^{-1}$)		
$ER_{def}(t)$	Emission reductions from deforestation under CVL and RIL ($MgCO_2\ year^{-1}$)		
$ER_{logging}(t)$	Emission reductions by switching logging ($MgCO_2\ year^{-1}$)		
$TLE_i(t)$	Total emissions from logging operations ($TgCO_2\ year^{-1}$)		
	$TLE_i(t) = TWH_i(t) * LEF$		
LEF	Logging emission factor ($MgCO_2\ m^{-3}$) (based on six cases reported in Pearson et al. (2014), average emissions for extracting timber were 0.34 MgC or 1.24 $MgCO_2$)	1.24	
TER(t)	Total emission reductions		
$CR_{REDD+}(t)$	Carbon revenues from result-based payment under the REDD+ scheme (million US\$ $year^{-1}$)		

(continued)

Table 2.2 (continued)

Short	Description	Values	
		CVL	RIL
CP	Carbon price	US$10 (WorldBank 2020)	

Note *is the weight of carbon stocks in aboveground and belowground carbon pools as reported in FAO (2020)
Source Adopted from Sasaki et al. (2012) or otherwise stated

Changes in the area of the production forests in Southeast Asia can be estimated by the following equation:

$$\frac{\mathrm{dPdF}(t)}{dt} = \mathrm{k} \times \mathrm{PdF}(t) \quad (2.1)$$

where PdF(t) is the production forests at time t (ha) and k is the rate of change of the production forest (%). k was obtained by performing linear regressions using data in 2000, 2010, 2015, and 2020 (FAO 2020).

2.2.3 Logging, Carbon Stocks, Emission Reductions, and Carbon Revenues

Two logging systems were implemented in our study, the CVL and RIL. Carbon stocks, timber production, emission reductions, and carbon revenues can be estimated by the following equations (modified from Sasaki et al. 2016).

$$\frac{dCS_i(t)}{dt} = \mathrm{MAI} - LM_i(t) - \mathrm{H}(t) \times \mathrm{BEF} \quad (2.2)$$

$$H(t) = \frac{f_M \times f_H}{1 - r} \times \frac{CS_i(t)}{T_c \times BEF} \quad (2.3)$$

$$TCS_i(t) = \mathrm{PdF(t)} \times \mathrm{CS}_i(t) \quad (2.4)$$

$$TWH_i(t) = PdF(t) \times \frac{H(t)}{WD \times BEF \times CT} \quad (2.5)$$

$$TE_i(t) = \frac{[TCS_i(t2) - TCS_i(t1)}{t2 - t1} \times \mathrm{CS}_i\mathrm{(t)} \times \frac{44}{12} + TLE_i(t) \quad (2.6)$$

$$ER_{def}(t) = \left\{ \frac{[TCS_{CVL}(t2) - TCS_{CVL}(t1)}{t2 - t1} \times \mathrm{CS}_{CVL}\mathrm{(t)}\} \right\}$$

$$-\{\frac{[TCS_{CVL}(t2) - TCS_{CVL}(t1)}{t2 - t1} \times \text{CS}_{RIL}(\text{t})\} \times \frac{44}{12} \tag{2.7}$$

$$ER_{logging}(t) = [\text{TLE}_{CVL}(t) - \text{TLE}_{RIL}(t)] \tag{2.8}$$

$$ER_{deg}(t) = \{[\text{TCS}_{CVL}(t) - \text{TCS}_{RIL}(t)] \times \frac{44}{12}\} - ER_{def}(t) \tag{2.9}$$

$$TER(t) = ER_{def}(t) + ER_{logging}(t) + ER_{deg}(t) \tag{2.10}$$

$$CR_{REDD+}(t) = TER_{logging}(t) \times \text{CP} \tag{2.11}$$

2.2.4 Wood Biomass, Bioenergy, and Emission Reductions

One of the principles of SMF adopted by the Forest Stewardship Council is to strengthen the efficient use of forest products and services for the viability of social, economic, and environmental benefits, and the reduction of logging waste/wood waste is one of the criteria for SMF (Sari and Ariyanto 2018). Therefore, accounting for and utilising wood waste is considered as renewable energy to replace the heavy dependency on fossil fuels for energy generation. Wood waste can be used as a woody biomass source for bioenergy and it also plays an essential role in reducing GHG emissions (Kinoshita et al. 2009). Bioenergy generation through the combustion of woody biomass and the carbon emission reduction potential under the two logging systems can be obtained through the following steps.

Total wood biomasses for bioenergy production can be estimated by:

$$TWB_i(t) = TLWA_i(t) + TWWA_i(t) + TBR(t) \tag{2.12}$$

$$TWWA_i(t) = [TWH_i(t) - TLWA_i(t)] \times a \tag{2.13}$$

where the total logging wastes (TLWA) are the wood wastes caused by logging damages onsite (leaves, branches, broken trunks, stumps, top-logs).

$$TLWA_i(t) = \frac{TWH_i(t)}{0.47} \times s \tag{2.14}$$

where s is the proportion of unusable wood after deducting losses due to logging, skidding, and damage during transportation; s = 0.30 for CVL and s = 0.10 for RIL.

The total wood wastes at the factory affected by wood processing efficiency (in TgC year^{-1}), $\text{TWWA}_\text{i}(\text{t})$, can be obtained by:

$$TWWA_i(t) = [\frac{TWH_i(t)}{0.47} - TLWA_i(t)] \times a \quad (2.15)$$

The proportion of wood loss at the processing factory is a = 0.50 for CVL and a = 0.40 for RIL. 0.47 is the carbon content in the dry wood as per IPCC Guidelines.

Note, [TWHi(t) – TLWAi(t)] * (1 − a) is the end-use wood products for end consumers; that is, the wood sold at markets.

$TBR_i(t)$ is the wood biomass in branches (including branches, leaves, twigs, toplogs, etc.)

$$TBR_i(t) = \frac{TWH_i(t)}{0.47} \times (BEF - 1) \quad (2.16)$$

Accordingly, the bioenergy generated from selective logging can be calculated by:

$$TBE_i(t) = TWB_i(t) \times EC \quad (2.17)$$

Carbon emissions for replacing the use of fossil fuels for generating the same amount of bioenergy can be estimated by:

$$ES_i(t) = [TBE(t) \times d_i - TWB(t) \times FE_{wood}] + [TWB(t) \times DW_{CH4} \times 21] \quad (2.18)$$

where TBE(t) is the total bioenergy from using woody biomass (in petajoules, or PJ), and EC, the energy content in 1 Tg of woody biomass, is 20 PJ (Hall 1997). ES_i is the emissions from burning fossil fuels (coal, diesel, gas) (in $TgCO_2$). The initial values for estimating ES_i are given in Table 2.3.

Table 2.3 Initial values and parameters for Eq. (2.18)

Description	Values	Sources
FE_{wood}: CO_2 emissions from wood combustion	1.6 $TgCO_2$ per Tg of drywood	Bhattacharya and Salam (2002)
d_i: emissions from fossil fuel burning for generating 1 PJ of energy	Coal: 0.265 $TgCO_2$ Diesel: 0.248 $TgCO_2$ Natural gas: 0.166 $TgCO_2$	Fridleifsson et al. (2008)
DW_{CH4}: methane emissions from the decay of wood	0.09 CH_4 Tg^{-1}	Covey and Megonigal, (2019)
Global warming effects of CH_4 compared to CO_2	21	
TLWAi(t): total logging waste caused by logging operations (TgC)		
$TWWA_i(t)$: total wood waste at the factory affected by wood processing efficiency (TgC $year^{-1}$)		
Proportion of wood loss at the processing factory	a = 0.50 for CVL and a = 0.40 for RIL	

2.3 Results and Discussions

2.3.1 Harvested Timber and Wood Products

Maintaining wood production is important for ensuring the long-term success of forest management. Both logging practices greatly affect the amount of the harvested timber volume and respective wood products that are used by the end consumers (refer to Sasaki et al. (2016)). As more wood is wasted and more timber is damaged, CVL needs to harvest more wood than that RIL. Our models indicate that CVL needed to harvest about 131.7 m^3 in 2000, whilst RIL needed to harvest only 85.4 million m^3 in order to secure the same amount of wood supplied to the market at 46.1 million m^3. Other studies have found similar amounts of wood harvested from the tropical forests in Southeast Asia, ranging from 85.56 million m^3 in 2012 (Chan 2016). On average, between 2000 and 2060, CVL and RIL need to harvest about 70.2 million m^3 and 58.5 m^3 million, respectively (Fig. 2.1) to produce 35.1 million m^3 for end-use wood products (i.e., wood products sold in markets). Because RIL harvests less wood than CVL, RIL can also result in less wood damage to the residual forest stands. Thereby, more carbon is stored in the production forest where the RIL system is adopted for timber harvesting.

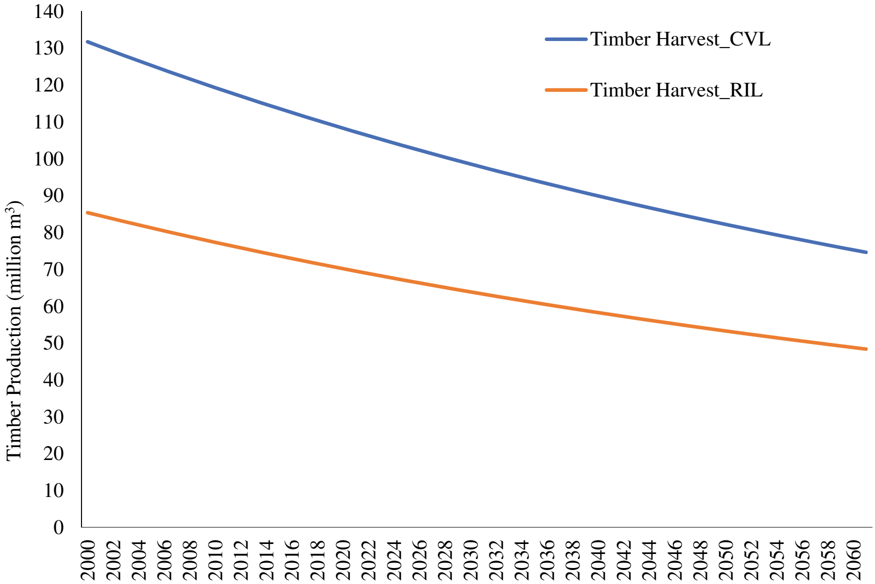

Fig. 2.1 Total timber volume harvested under CVL (upper) and RIL (lower) in southeast Asia, 2000–2060. CVL = conventional logging, RIL = reduced-impact logging.
Source Author's own calculation

2.3.2 Carbon Stock Changes and Emission Reductions

Under the two logging practices, carbon stocks in production forests in Southeast Asia decline from the same value of 7,140.2 TgC in 2000 to 4,080.6 TgC and 4,959.6 TgC in 2060 under the CVL and RIL, respectively, representing a decline of about 44.7 TgC and 34.6 TgC annually over the same period. During the Paris Agreement's implementation period (2020–2030), carbon loss under the two logging systems is 52.8 TgC and 37.2 TgC, respectively (Fig. 2.2).

With our models, it was possible to calculate the emission reductions from deforestation, forest degradation (i.e. logging-induced loss of big trees), and emissions from logging operations separately. Over the modelling timeframe (2000–2060), CVL emits about 163.2 $TgCO_2$ $year^{-1}$, of which 124.8 $TgCO_2$ are from deforestation and the rest are from logging-induced forest degradation. If emissions from logging operations are included, total emissions are 275.0 $TgCO_2$ $year^{-1}$, of which 40.7% are from logging emissions, 45.4% are from deforestation, and 14.0% are from forest degradation caused by logging. Under the RIL, emissions were estimated at

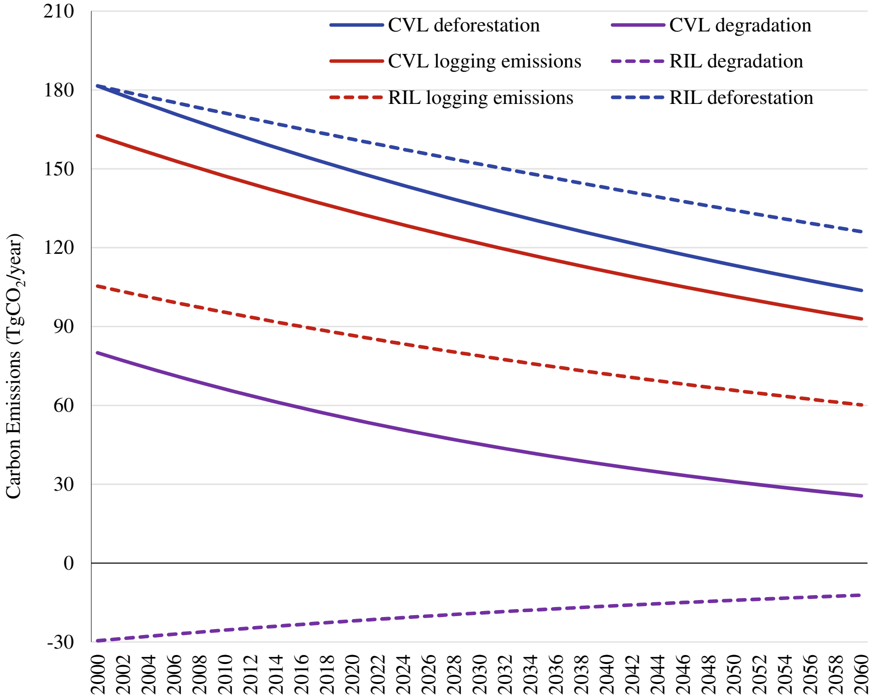

Fig. 2.2 Carbon emissions from deforestation and logging-induced degradation under CVL and RIL in southeast Asia. CVL = conventional logging, RIL = reduced-impact logging.
Source Author's own calculation

215.6 $TgCO_2$, of which 66.4% and 33.6% are from deforestation and logging operations, respectively, over the same modelling period. Unlike CVL, RIL can avoid emissions due to a lower harvest and lower damages to the existing carbon stocks. Over the same period and if compared to RIL, the production forest under the RIL emits higher emissions than that of CVL's emissions (emitting 16.6 $TgCO_2$ $year^{-1}$). During the implementation of the Paris Climate Agreement (2020–2030), logging in production forests in Southeast Asia is likely to release about 319.9 $TgCO_2$ $year^{-1}$ under the CVL or about 281.9 $TgCO_2$ under the RIL. These emissions accounted for about 33.8–38.4% of the emissions from tropical selective logging in 2015 (Ellis et al. 2019). Although generally, RIL could potentially reduce emissions, the continuous loss of production forests under RIL can release higher carbon emissions because the carbon stocks per unit area are higher than those in the CVL forest.

Of particular interest in our findings, emissions from logging operations account for a large proportion of the total emissions because they are very dependent on the harvested volume of the timber and emission factors from the use of logging machinery. However, emissions from logging operations are commonly ignored in the study of carbon emissions from deforestation in the tropics (Harris et al. 2012; Kindermann et al. 2008), suggesting that scientists may have underestimated the emissions from tropical deforestation and forest degradation. Pearson et al. (2017a) came to a similar conclusion, stating that emissions from forest degradation (i.e. caused by the loss of mature trees and emissions from logging operations) could be higher than previously thought. Therefore, future studies need to incorporate such emissions and address the energy efficiency of the logging operations.

By subtracting carbon emissions under CVL from those under RIL, the emission reductions can be estimated. If Southeast Asia switches its current logging practices from CVL to RIL for implementing its REDD+ activities during the Paris Agreement between 2020 and 2030, about 115.2 $TgCO_2$ $year^{-1}$ of emission reductions can be achieved, of which 61% and 39% are from reducing deforestation and logging emissions, respectively. Since emissions from deforestation continue to occur, this results in carbon emissions of 14.1 $TgCO_2$ over the modelling period. Therefore, the net reductions are 101.1 $TgCO_2$ $year^{-1}$ (Fig. 2.3).

2.3.3 Biomass, Bioenergy, and Emission Reductions

Apart from reducing emissions from deforestation, forest degradation, and logging operations, waste from logging damages and wood waste in the tropics are also important sources for bioenergy production. Our findings indicate that CVL and RIL can create total biomasses and bioenergy of 3,408.2 PJ and 2,209.0 PJ, respectively, between 2000 and 2060. If this bioenergy is used to replace the use of coal, diesel, and natural gas combustion, 94.6 $TgCO_2$ $year^{-1}$, 72.9 $TgCO_2$ $year^{-1}$, and 61.5 $TgCO_2$ $year^{-1}$ could be reduced under CVL. For the same purpose, RIL can reduce about 61.3, 47.2 $TgCO_2$ $year^{-1}$ and 39.9 $TgCO_2$ $year^{-1}$ if its wood wastes are used to replace coal, diesel, and natural gas for energy production between 2000

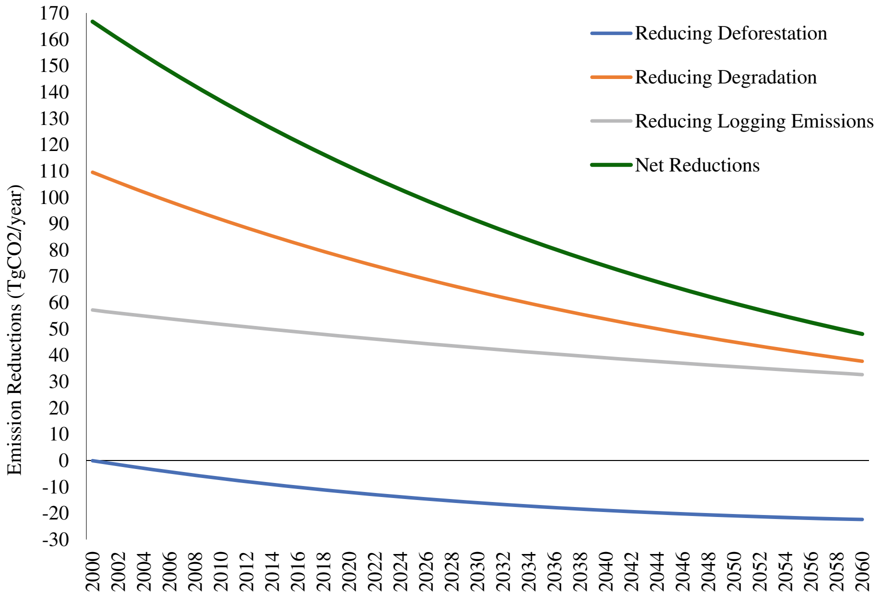

Fig. 2.3 Carbon emission reductions from deforestation, logging-induced forest degradation, and logging emissions under the CVL and RIL *Source* Author's own calculation

and 2060 (Fig. 2.4). During the Paris Agreement, annual emission reductions from the management of production forests in Southeast Asia for bioenergy production are 97.5, 75.1 $TgCO_2$ $year^{-1}$, and 63.4 $TgCO_2$ $year^{-1}$ under the CVL or 63.2, 48.7, and 41.1 $TgCO_2$ $year^{-1}$ under the RIL if wood wastes of all forms are used to replace the burning of coal, diesel, or natural gas for energy generation. Our findings indicate that CVL is attractive for bioenergy potential if other factors, such as the loss of carbon due to logging damage to the residual stands and other environmental damages, are not considered because CVL can create more biomasses as a source of raw material. However, since CVL is found to be environmentally destructive and it is currently managed for achieving short-term goals (Sasaki et al. 2016), CVL could not be eligible under the REDD+ scheme, which encourages the long-term sustainable management of forests for multiple ecosystem services.

2.3.4 *Total Emission Reductions Through Forest Management for Timber and Bioenergy*

Over the 60 years of the modelling period between 2000 and 2060, if RIL is adopted for the management of Southeast Asia's production forests, large carbon emission reductions could be achieved. Our models show that Southeast Asia could achieve the total emission reductions of 228.1 $TgCO_2$ $year^{-1}$, 214.0 $TgCO_2$ $year^{-1}$, or 206.6

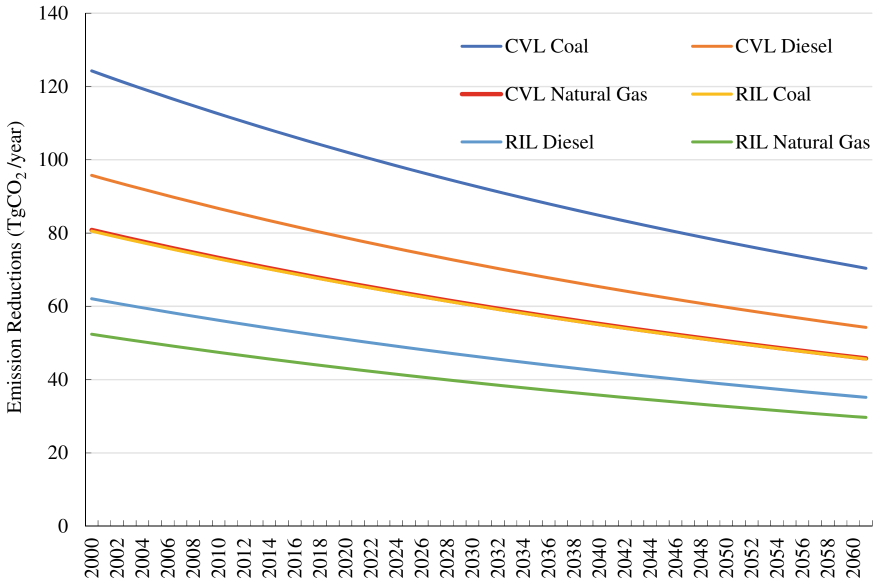

Fig. 2.4 Carbon emission reductions through the substitution of fossil fuels (coal, diesel, and natural gas) with wood biomass under CVL and RIL in southeast Asia. CVL = conventional logging, RIL = reduced-impact logging.
Source Author's own calculation

$TgCO_2$ $year^{-1}$ if wood biomasses from the logging wastes and wastes at the wood processing factories are used to substitute the use of coal, diesel, or natural gas for generating bioenergy (Table 2.4). These reductions amount to about 10% of the global emissions from the loss of tropical forests over the last 10 years (Pearson et al. 2017a; b).

Although the costs for switching from CVL to RIL have been amongst the major concerns, recent studies have indicated that the long-term revenue from RIL is higher than that of CVL. Based on Boltz et al. (2003), the net revenue from CVL was

Table 2.4 Total emission reductions through the management of production forests for timber and bioenergy production ($TgCO_2$ $year^{-1}$)

Intervals	Reductions under RIL	Reductions through biomass for bioenergy			Total reductions		
		Coal	Diesel	Natural gas	Coal	Diesel	Natural gas
2000–2060	96.6	61.3	47.2	39.9	228.1	214.0	206.6
2000–2020	137.6	73.1	56.3	47.5	239.9	223.1	214.3
2020–2030	101.1	63.2	48.7	41.1	229.9	215.4	207.9
2020–2060	76.0	55.4	42.7	36.0	222.1	209.4	202.8

RIL reduced-impact logging
Source Author's calculation

US$9.84 but US$12.66 from RIL, representing about US$1.84 in net profit for one management cycle. The costs for biomass collection and processing for bioenergy production are also another important factor for turning wood waste to bioenergy. Apart from the returns in terms of timber production, there are other benefits from managing forests for bioenergy production. For example, if a carbon tax (Benavides et al. 2015), environmental tax (Hao et al. 2021) and energy tax (Wang and Zhan 2019) are introduced for clean energy consumption, wood-based bioenergy would become an attractive option for responsible businesses. These responsible businesses could also benefit from the increasing market opportunities under the United Nations Sustainable Development Goals, which were estimated at about US$12 trillion by 2030.

As tropical forests are home to various flora and fauna species, and important sources of daily subsistence for about 2 billion people around the world, the sustainable management of tropical forests can achieve far beyond emission reductions.

2.4 Conclusion and Policy Recommendations

Carbon emission reductions through forest management for timber and bioenergy production in Southeast Asia's production forest were studied under two logging practices, CVL and RIL, over a 60-year period corresponding to two management cycles of 30 years. The emission sources were from deforestation, forest degradation, and logging operations under both logging systems. Emission reductions through the substitution of the use of fossil fuels with woody biomass were achieved by comparing the emissions to those of coal, diesel, and natural gas combustion for bioenergy production.

Over the modelling period, carbon stocks in production forests declined at the rates of 51 TgC year-1 and 36.3 TgC $year^{-1}$, resulting in total annual carbon emissions of 309.8 $TgCO_2$ $year^{-1}$ and 232.7 $TgCO_2$ $year^{-1}$ under the CVL and RIL, respectively between 2000 and 2060. These emissions are about 10% of the global emissions from tropical deforestation. Under CVL, the emissions were 42.8, 18.9, and 38.3% from deforestation, logging-induced forest degradation, and logging operations. Emissions under RIL were 63.3% from deforestation and 36.7% from logging operations, but emissions from degradation were not observed. Emissions from deforestation were higher because of the high carbon stock per unit area.

Because both CVL and RIL produce large amounts of wood waste onsite and offsite, the use of such waste as material for energy production can generate about 3,408.2 PJ and 2,209.0 PJ between 2000 and 2060 under the two systems, respectively. When coal, diesel, and natural gas are replaced by woody biomass for bioenergy production, about 39.9–61.3 $TgCO_2$ $year^{-1}$ emissions can be reduced over the same period of 60 years. By combining emission reductions from the management of forests for timber and bioenergy production, Southeast Asia can achieve emission reductions of 206.6–228.1 $TgCO_2$ $year^{-1}$ for 60 years, depending on the chosen scenario. During the implementation period of the Paris Agreement (2020–2030). Southeast Asia is likely to achieve 207.9–229.9 $TgCO_2$ $year^{-1}$. With a carbon price of US$10, the region can generate carbon revenues of US$2.1 billion–US$2.3 billion annually for 10 years by managing its production forests.

We can conclude that with the management of production forests through appropriate logging practices and with the right incentives for carbon neutrality, it is possible to manage forests for climate change mitigation and clean energy production. To materialise the adoption of RIL whilst reducing the practice of devastating CVL, it important that governments in Southeast Asia provide incentives for the adoption of RIL and introduce carbon taxes, environmental taxes, and energy taxes as has been done in Europe because having these policies will make RIL adoption financially attractive, socially acceptable, and environmentally friendly.

Acknowledgements This research was carried out under funding from the Economic Research Institute for ASEAN and East Asia. I thank Ms. Yadanar Ye Myint of the Natural Resources Management at the Asian Institute of Technology for assisting the data collection and draft chapter preparation.

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Chapter 3
Vehicle Technology Impact Assessment Model for Indonesia (VEIA-ID): Concept and First Results

Alloysius Joko Purwanto and Dian Lutfiana

Abstract Energy use and carbon dioxide (CO_2) emissions, key impacts of transport sector activities in Indonesia, need to be accurately estimated, as they influence energy security, Indonesia's commitment to mitigate climate change, and policy development. The Vehicle Technology Impact Assessment Model for Indonesia (VEIA-ID) has the capacity to create a long-term outlook of transport demand, vehicle stock, energy use, and CO_2 emissions of two transport modes (i.e., cars and road freight vehicles) and to measure the impacts of various transport and energy policies. Using economic and demographic assumptions, it endogenously projects transport demand and is able to split it into different transport modes. It uses existing data to project fleet dynamics, fuel consumption, and CO_2 emissions up to 2050. In the baseline scenario, energy consumption from cars and road freight vehicles would grow 4 times from 33 million tons of oil equivalent (Mtoe) in 2020 to 132 Mtoe in 2050, and CO_2 emissions would rise from 95 million tons to 380 million tons during that same period. Policies such as carbon taxing, motorway tolls, and improvement of road freight logistics have the ability to reduce fuel consumption and CO_2 emissions.

Keywords Policy assessment · Road transport · Energy economic modelling · Climate change · Cars · Road freight

3.1 Introduction

Due to rapidly growing populations and economies, the Association of Southeast Asian Nations (ASEAN) region's rising greenhouse gas (GHG) emissions—as well as energy demand—are concerning. In general, transport was the most energy-consuming sector after industry in 2019 within the region (ASEAN 2019a). During that same year, road transport (i.e., cars, motorcycles, and trucks) accounted for 28% of total energy-related carbon dioxide (CO_2) emissions and about 90% of transport-related CO_2 emissions in the region. Sales of passenger cars are also estimated to

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H. Phoumin et al. (eds.), *Energy Sustainability and Climate Change in ASEAN*, Economics, Law, and Institutions in Asia Pacific,
https://doi.org/10.1007/978-981-16-2000-3_3

grow to around 3.0 million cars per year by 2025, from about 1.5 million in 2015, as income and urbanisation continue to increase. These upward trends are in accordance with the estimated increase of energy consumption in the region's transport sector, from 188 million tons of oil equivalent (Mtoe) in 2013 to 309 Mtoe in 2035.

Fossil fuels, especially oil, remain the dominant fuel source in the transport sector. As such, this sector is responsible for around 24% of direct CO_2 emissions from fuel combustion, and road vehicles account for nearly 75% of transport CO_2 emissions (Teter et al. 2020).

Sandu et al. (2019) analysed the growth of energy-related CO_2 emissions in the ASEAN region from 1971 to 2016. Indonesia, with the largest area and population in the region, emitted the most CO_2 emissions, with its annual energy-related CO_2 emissions increasing from 25 million tons in 1971 to 455 million tons in 2016. Within about 10 years, the country's consumption has increased around 24.0%, from 226.58 million barrels of oil equivalent in 2009 to 414.98 million barrels of oil equivalent in 2019, accounting for 41% of total energy consumption by its transport sector in 2019 (GOI 2010, 2019). In addition, a presidential regulation estimated that energy consumption in the transport sector in 2050 will be 26.3% (GOI 2017).

In 2015, through the Paris Agreement, each ASEAN member state committed to increasing its long-term environmental goals, tackling climate change impacts, fostering climate resilience, and lowering GHG emissions under nationally determined contribution targets. If Indonesia wants to achieve its nationally determined contribution targets of reducing unconditional CO_2 up to 29% and conditional CO_2 up to 41% below business as usual by 2030, policymakers must maximise their efforts to scale up existing regulations to transform Indonesia's energy sector, particularly regarding its transport sector.

As recommended by the ASEAN Secretariat (2019b), introducing fuel economy targets into light-duty vehicle markets should be carried out through policy initiatives, and fuel efficiency should be further increased through an ambitious policy framework, including fuel economy standards, labels, and tax schemes. Unfortunately, a lack of specific regulations on transport hinders the pace of infrastructure development, specifically renewable energy use, and fails to curtail oil consumption.

Indonesia must develop an integrated policy that covers transport, economy, energy, and environment perspectives. Many—such as Sieber et al. (2013), Nilsson et al. (2008); and McIntosh et al. (2011)—have emphasised the importance of impact assessment tools as decision-support instruments for policymaking, which allow policymakers to analyse complex relationships between the different interrelated constituent parts in a system and to reach decisions based on quantitative information. The Vehicle Technology Impact Assessment Model for Indonesia (VEIA-ID) has been developed by the Economic Research Institute for ASEAN and East Asia (ERIA) to project different transport sector scenarios in Indonesia, estimate transport demand and CO_2 emissions, as well as forecast the impacts of policy and technological measures in transport-related sectors. At this phase of model development, an advanced state of calibration has been achieved in the car and road freight vehicle modes, including transport demand, fleet dynamics, and the environment, comprising energy use and CO_2 emissions.

This chapter first shows the concept of modelling that is based on demand projection, fleet dynamics simulation, and energy use and emissions calculation. The next section elaborates the results of baseline projections as well as several simple impact assessment exercises of policy and technological measures.

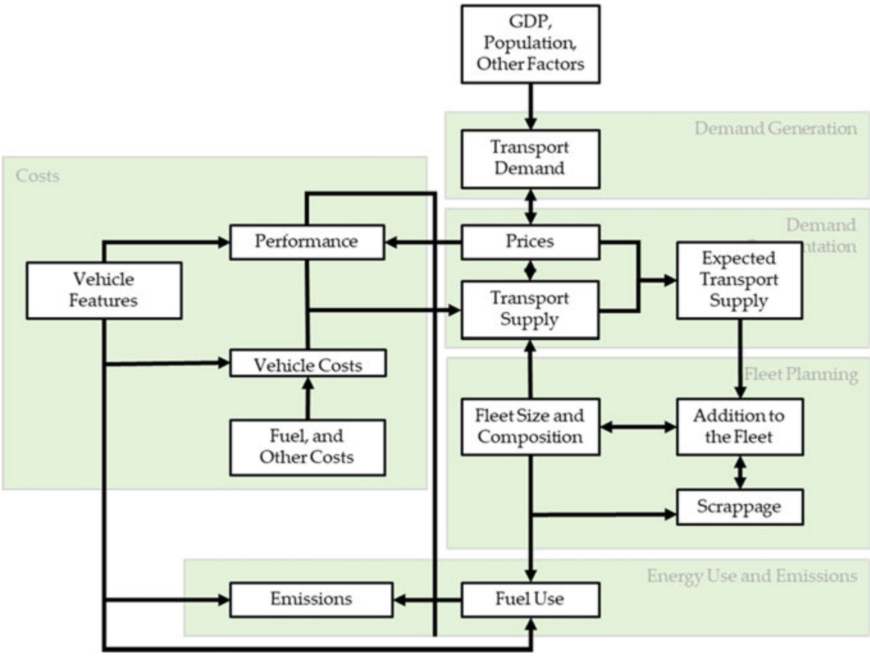
3.2 Modelling Concept

Various analytical tools are used to estimate energy demand and CO_2 emissions from transport sector activities, including.

- **POLES**. The Prospective Outlook on Long-Term Energy System (POLES) model is the European Commission's tool for global, long-term analysis of GHG mitigation policies (Despres et al. 2018). It examines the evolution of markets where transport, together with industry, are considered energy-intensive sectors of 57 world regions to 2050. In its transport module, POLES projects vehicle stocks per engine type, related energy use, and GHG emissions with a detailed representation of vehicle stock and propulsion technologies for road transport, especially passenger cars (Christidis et al. 2003).
- **ASTRA**. The Assessment of Transport Strategies (ASTRA) model focuses on strategic policy assessment in the transport and energy fields (Schade et al. 2018). It covers 27 countries in the European Union plus Great Britain, Norway, and Switzerland. Vehicle fleet, transport, and emission models are amongst its integrated nine modules.
- **ForFITS**. The For Future Inland Transport System (ForFITS) model is a software tool capable of estimating emissions in transport and evaluating transport policies for CO_2 emission mitigation, applied to seven pilot countries—Chile, Ethiopia, France, Hungary, Montenegro, Thailand, and Tunisia (Bhandari 2013).
- **MoMo**. The Mobility Model (MoMo) of the International Energy Agency (IEA), covering 27 countries and regions, is a technical economic database spreadsheet and simulation model that enables detailed projections of transport activity, vehicle activity, energy demand, and well-to-wheel GHG and pollutant emissions according to user-defined policy scenarios to 2060 (IEA 2020).
- **MOVEET**. The Mobility, Vehicle Fleet, Energy Use and Emissions Forecast Tool (MOVEET) covers the same 57 world regions as POLES to 2050 (Purwanto et al. 2016).

As shown in Fig. 3.1, the modular methodology implemented in the VEIA-ID model follows the first three steps of the classical four-step approach in Bonnel (2004) and Ortúzar and Willumsen (2011).

Using gross domestic product (GDP), trade, population, transport prices, and other relevant driving factors, the VEIA-ID model projects transport demand endogenously. This causal relationship between economic development and transport demand varies across regions and countries (Brida et al. 2016; Aguirre et al. 2018;



GDP = gross domestic product.

Fig. 3.1 VEIA-ID module structure. GDP = grossVEIA-ID module structure. *Source* Authors

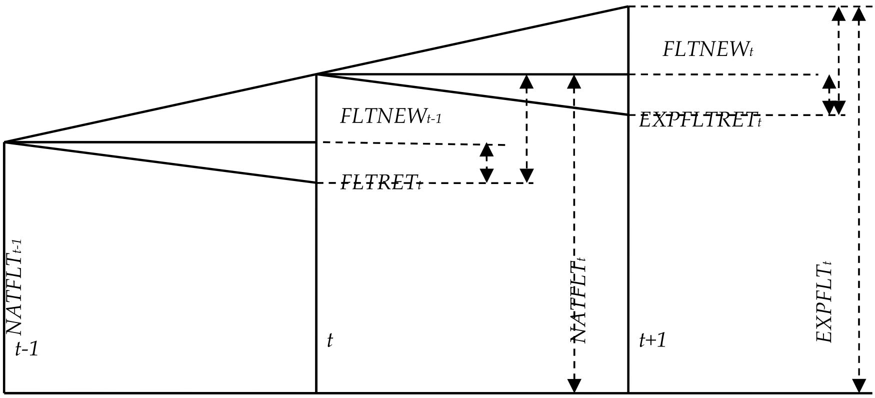


Fig. 3.2 Capacity planning. *Source* Purwanto et al. (2016)

Maparu and Mazumder 2017; Baker et al. 2015). It further disaggregates the generated demand into the required level of segmentation based on a specific set of variables and parameters, with generalised transport costs being the most important. The model is therefore partial equilibrium in the sense that transport demand would increase or decrease solely in the function of generalised costs and increased competition between modes and links but not in function of changes in the whole economy (Bergkvist 2001).

Second, in the fleet module, the VEIA-ID model projects figures of the fleet dynamics in detail. Through a vintage model, which considers past additions to the fleet and the survival rate of each vehicle type, the model establishes the number of vehicles in service. The current fleet by region is then calculated from the balance of added, retired, and remaining vehicles. Expected changes in the transport supply are used to determine the requirements of new vehicles in a simulation period. The methodology underlying this module is that used in the transport modules of the POLES model, TREMOVE model, and MOVEET.

Finally, in the environmental module, using assumptions on vehicle technology-based emissions and fuel consumption factors, the model calculates energy use and emissions for each vehicle type, considering the number and technological composition produced by the fleet module. Fleet composition, together with the technical features of the vehicles, are used to determine the amount of energy consumed. There is no transport emissions inventory model for Indonesia, but the emissions and fuel consumption factors have already been disaggregated into vehicle technology and age levels. Having those disaggregated variables, the VEIA-ID model could be linked to a transport emissions inventory model, like that between the COPERT emissions model and TREMOVE model, as described in Breemersch et al. (2010).

The base is the neoclassical microeconomic theory of user choice. Its application in transport was pioneered by Domencich and McFadden (1975), Ben-Akiva and Lerman (1979), and Manheim (1984). Utility maximisation as an element of neoclassical microeconomic theory (Brémond 1990) is the main principle used in breaking down transport demand into modes and network types, and vehicle fleets into the technologies whose choices are limited by user income and prices formed in the market (Renaud and Tabourin 1998).

Finally, the tool can simulate the impacts of at least four different policies related to:

- Vehicle technologies, such as the introduction of new emissions standards, penetration of new technologies, and implementation of supplementary measures to increase fuel efficiency or to accelerate fleet renewal;
- Fuel quality (i.e., regulatory aspects in terms of costs and environmental benefits obtained), like maximum sulphur limits;
- Fiscal instruments in the transport sector, such as freight taxation, vehicle taxation, incentives for low-emissions cars, and internalisation of external costs via Pigovian taxes; and
- Traffic management, such as logistics in passenger and freight transport and changes in the speed-flow curves.

The VEIA-ID model is the first open-access transport policy impact assessment tool for Indonesia and Southeast Asia. In addition, most of the non-based vehicle fleet models, as in Deendarlianto et al. (2019), Suehiro and Purwanto (2019), and IESR (2020), do not consider competition between transport modes—they only consider their focused mode as a closed system. The vehicle fleet stock could only be estimated regarding the relationship between the vehicle ownership rate with per capita GDP or per capita represented in the Gompertz function as pioneered in the work of Dargay et al. (2007). In the VEIA-ID model, however, total demand is split into the different transport modes based on generalised costs and other parameters. The model preserves not only competition between modes but also between the different types of demand such as purpose, cargo type, and distant bands. Finally, it breaks down emissions and fuel consumption factors not only into technology types but into age or vehicle vintages; previous studies used average emissions and fuel consumption factors of each technology, mixing all vehicle ages. Differentiation by vehicle age allows more a detailed analysis of new technology impacts.

In the following subsections, each module is explained in detail. The VEIA-ID model's innovative character lies in the endogenous transport demand generation and split, based on macro and micro circumstances, inclusion of congestion effects, detailed levels of vehicle fleets' techno-economic features, and calculation of energy use and CO_2 emissions.

3.2.1 Transport Demand Module

The VEIA-ID model distinguishes transport demand between continental (i.e., national) and intercontinental (i.e., international), each having its own specific, independent generation procedure. It generates the motorised continental transport demand endogenously. It splits this demand into geography (i.e., national versus international), distance (i.e., long versus short), purpose, and period (i.e., peak versus off-peak) dimensions. Using a macro context, the model ensures that this split is not determined by individual (i.e., transport user) decisions; rather, it uses mathematical equations that depend on a set of policy-sensitive variables from exogenous data such as population, trade, and GDP, or from other parts of the model (e.g., the motorisation rate). The model then classifies demand further according to micro decisions, transport modes, and road types. In the second step, a discrete choice algorithm is used, based on the generalised costs of transport for each alternative.

Total motorised passenger demand generated by zone is estimated in three steps: (i) demand at the base year is estimated, (ii) the estimated trend is applied to reproduce the development over the simulation period (i.e., until 2050), and (iii) a multiplier parameter is applied for splitting demand depending on the purpose.

The overall process for the generation of total demand by purpose over the simulation period is based on two main drivers, GDP per capita and the motorisation rate (Eq. 3.1).

$$Pdem_{zm}^{T} = \left(\alpha_1 \cdot \frac{GDP_z^{T0}}{POP_z^{T0}} + \alpha_2 \cdot \frac{Car_z^{T0}}{POP_z^{T0}} + \gamma_1\right) \cdot \left(\alpha_3 \cdot \frac{\frac{GDP_z^{T}}{POP_z^{T}}}{\frac{GDP_z^{T0}}{POP_z^{T0}}} + \alpha_4 \cdot \ln\left(\frac{\frac{Car_z^{T}}{POP_z^{T}}}{\frac{Car_z^{T0}}{POP_z^{T0}}}\right) + \gamma_2\right) \cdot \beta_{zm} \tag{3.1}$$

where:

$Pdem_{zm}{}^{T}$ = number of passenger-kilometres (km) at the year T from zone z (i.e., Indonesia) for the purpose m

$GDP_z{}^{T0}/POP_z{}^{T0}$ = GDP per capita at base year in region z

Car/POP = car ownership (i.e., number of cars per 1000 inhabitants)

T = year

T_0 = initial (i.e., base) year of the simulation

z = region or zone (i.e., Indonesia)

m = purpose

α_i, γ_i = parameters to be calibrated

β_{zm} = multiplier parameter for splitting demand by purpose m (differentiated by zone z).

After generating total demand for a particular zone and purpose, the module splits demand between national and international demand. One of the most significant drivers of this split is the trend of the generalised cost of long-distance modes (i.e., train and air). If national travel becomes cheaper compared to the baseline, a larger share of total demand is expected to be international. A similar approach, in which the travel generalised cost is the endogenous element used, is applied further for the segmentation of national demand into the distance travelled (i.e., between a short distance and long distance).

Finally, the module splits demand into urban and rural passenger-kilometres (km) and into peak and off-peak periods. Demand belonging to the urban context is supposed to be influenced by changes in travel costs as well as in the motorisation rate, because car ownership gives rise to sprawling—and therefore a larger share of—rural trips. Traffic in peak and off-peak times does not depend on the variables simulated in the model; it is not expected that the kind of policy measures that the tool is designed to simulate can change it significantly. Therefore, a simple fixed share is implemented.

Freight transport demand generation applies the same approach described for passenger demand, although other variables are considered as drivers of the ton-km calculation. The upper-level freight demand is the result of a multiplicative model based on the value of external trade, GDP, and the generalised cost of transport. Still, the total motorised demand is estimated first at the base year, and then the estimated trend is applied to reproduce the development over the simulation period. Finally, a multiplier parameter is applied to split demand depending on cargo type (Eq. 3.2).

$$Fdem_{zc}^{T} = \left(\alpha_{1_z} \cdot GDP_z^{T0} + \alpha_{2_z} \cdot Trade_z^{T0} + \gamma_{1_z}\right)$$

$$\cdot \left(\alpha_{3_z} \cdot \frac{GDP_z^T}{GDP_z^{T0}} + \alpha_{4_z} \cdot \left(\frac{Trade_z^T}{Trade_z^{T0}} \right) + \gamma_{2_z} \right) \cdot \beta_{zc} \quad (3.2)$$

where:

$Fdem_{zc}{}^{T}$ = number of ton-km at year T from zone z for cargo type c

$GDP_z{}^{T}$ = GDP in region z at year T

$Trade_z{}^{T}$ = trade within the same macro region (in terms of export in value) at year T

T = year

T_0 = initial (i.e., base) year of the simulation

z = region

c = cargo type

α_{Nz}, γ_{Nz} = parameters to be calibrated, by region z

β_{zc} = multiplier parameter for splitting demand by cargo type c (differentiated by zone z).

Demand is further split into national and international demand, considering the influence of the generalised cost trend. Like passenger trip generation, for freight, the demand module also calculates shares of short- and long-distance demand at the national level. The same methods are used to estimate the amount of urban and rural demand at short distances as well as a breakdown according to peak and off-peak periods. After demand has been generated according to the aggregate dimensions, those aspects that can be interpreted as a result of individual decisions (i.e., the choice of transport mode and of network type) are modelled based on a random utility approach where the consumer's preference of an alternative with the highest utility over the others (i.e., utility maximisation) is assumed.

A nested logit algorithm is used to compute mode shares. The value of the parameters in the algorithm for the various segments comes from the literature, mostly compiled in the MOVEET, which are the result of a calibration process. The deterministic part of the utility function consists mainly of the generalised cost (i.e., transport cost plus time weighted with value of time).

As the VEIA-ID model is not network-based, further assumptions are made in relation to the representation of the transport infrastructure network. To represent network capacity constraints, proxies are made of network capacity of various transport modes to estimate congestion effects that, in turn, affect the mode or network attractiveness impacting user choice.

For road modes, travel time is affected by the level of demand to capture the impact of congestion, although in an aggregated manner. Yet, congestion is a local effect, and a network model is required to simulate it properly, but the prototype can represent if road demand is growing more than road supply. The average travel time then tends to deteriorate, and the attractiveness of the road modes is reduced. This impact is considered by means of speed-flow functions (Government of the US 1964) as shown in Eq. 3.3.

$$\begin{cases} T = T_{base} \cdot \left[1 + \alpha \cdot \left(\frac{D}{C}\right)^{\beta}\right] if \left(\frac{D}{C}\right) \leq 1 \\ T = T_{base} \cdot \left[1 + \alpha + \chi \cdot \left(1 - \frac{1}{\left(\frac{D}{C}\right)^{\delta}}\right)\right] if \left(\frac{D}{C}\right) > 1 \end{cases} \tag{3.3}$$

where:

T = travel time

T_{base} = base travel time on the road type considered

D = total demand on the road type in vehicle-km

C = total capacity of the road type in vehicle-km

α, β, χ, δ = parameters.

The same form of function is implemented and calibrated for diverse road types—urban roads, motorways, and other roads—and congestion time variables are calculated based on the equation above. Furthermore, the congestion effect influences the travel time of each private road mode as the multiplier of the base time of the correspondent mode. At the same time, the congestion effect directly influences the running time part of the travel time of the public transport road mode (e.g., buses and trams) and indirectly the waiting time part.

3.2.2 Fleet Module

The fleet module receives the following inputs from the transport demand module: passenger-km at zone (i.e., national level), purpose, region, distance, urban level, time of the day, mode and network, ton-km at zone distinguished by vehicle type, region, distance, urban level, time of day, mode and network, and average load factor by demand segment.

In return, this module sends back the following information to the demand module: total amount of fleet per mode and zone, total vehicle-km by demand segment, vehicle-km per vehicle type and demand segment, and operating cost per vehicle type, which feeds the environmental module with vehicle-km by vehicle type and demand segment, fleet structure by vehicle type and technology (i.e., emissions standards), and use by vehicle type and technology.

The main goal of the fleet module is to convert aggregate estimations of transport demand, in terms of passenger-km, ton-km, and/or vehicle-km, into more detailed vehicle classification, which directly relates to technology in terms of vehicle performance and characteristics, fuel use, and emissions.

Figure 3.2 shows how the capacity planning procedure works. In any year ***t***, $NATFLT_{v,t-1}$, the fleet existing in ***t-1***, minus $FLTRET_{v,t}$, the fleet retired in ***t***, equals the fleet in ***t*** ($NATFLT_{v,t}$) minus the new fleet planned in ***t-1*** (to be added in ***t***), (i.e., $FLTNEW_{v,t-1}$) as shown in Eq. 3.4.

$$NATFLT_{v,t-1} - FLTRET_{v,t} = NATFLT_{v,t} - FLTNEW_{v,t-1} \tag{3.4}$$

In $\boldsymbol{t}$, the existing fleet ($NATFLT_{v,t}$) minus the fleet to be retired in $\boldsymbol{t+1}$($EXPFLTRET_{v,t}$) equals the expected fleet in $\boldsymbol{t+1}$($EXPFLT_{v,t}$) minus $FLTNEW_{v,t}$, (i.e., the new fleet planned in $\boldsymbol{t}$). Note that all expected values are calculated in $\boldsymbol{t}$ as shown in Eq. 3.5.

$$NATFLT_{v,t} - EXPFLTRET_{v,t} = EXPFLT_{v,t} - FLTNEW_{v,t} \tag{3.5}$$

To study the effects of different transport and environment policies on transport sector emissions, transport modes in the model are distinguished into seven vehicle categories, which are further split into types: road passenger or car category (26 vehicle technology types), road freight (13), rail passenger (6), rail freight (5), air passenger (7), air freight (3), and maritime freight (22). Vehicle technology types of road passenger and road freight modes are given in Appendix 1 and 2.

In the VEIA-ID model, vehicle types split when new vehicles enter the market. The split is performed by logit models representing the choice of vehicle based on user utility maximisation. User utility is represented by vehicle utilisation costs, which are the total sum of fixed and variable vehicle utilisation costs.

For cars, the discounted fixed cost is calculated considering the average new car price, maintenance costs, mileage, and average scrapping age. For road freight vehicles, the annual fixed cost per ton-km performed is obtained by adding up the following 12 exogenously estimated yearly cost components: insurance, labour, labour taxes, purchase, repair, congestion, fuel tax, insurance tax, network tax, ownership tax, registration tax, and other expenses.

The main fleet data used are the new (i.e., wholesale) vehicle fleet statistics of the Association of Indonesia Automotive Industries or GAIKINDO (2020) from 2010 to 2017. Historical vehicle stock data per vehicle vintage have been calculated based on those data and stock data of BPS Statistics Indonesia (2017). Vehicle cost data are based on the data used in the MOVEET, which includes Indonesia as one of the 57 modelled world regions from which cost data have been collected.

3.2.3 Environmental Module

In the environmental module, fuel consumption from car activities in million litres distinguished by car type ($TFCBYCAR_{car}$) is calculated by multiplying four disaggregated variables: vehicle-km ($KMYEAR_{car,user,age}$), fuel economy in litres per 100 km ($PKFCCUSTAGE_{car,user,age}$), percentage of consumer types ($CUSTSH_{user}$), and the existing fleet ($FLTAGE_{car,age}$) as shown in Eq. 3.6.

$$TFCBYCAR_{car} = 10^{-6} \sum_{user,age} (KMYEAR_{car,user,age}.PKFCCUSTAGE_{car,user,age}.CUSTSH_{user}.FLTAGE_{car,age}.10^{-2}) \tag{3.6}$$

where:

car = car types

$user$ = user types

age = age of car

An almost similar energy use from road freight vehicles is calculated in Eq. 3.7.

$$TFCBYDV_{dv} = 10^{-6} \sum_{age} (KMYEAR_{dv,age}.LTPERKHMAGE_{dv,age}.FLTAGE_{dv,age}.10^{-2}) \quad (3.7)$$

where:

dv = light- and heavy-duty vehicle types

The two fuel economy variables (i.e., $PKFCCUSTAGE_{car,user,age}$ and $LTPERKHMAGE_{dv,age}$) contain fuel efficiency information regarding car technology, vehicle vintage, and user characteristics for cars. The fuel economy data were adopted from the literature, which has investigated the fuel consumption of motorcycles, passenger cars, buses, and trucks in Indonesia, specifically in the cities of Yogyakarta, Semarang, and Surakarta (Sandra 2012). It has also created business-as-usual road transport scenarios for Indonesia (Sinaga et al. 2010). As no fuel economy regulation has been put in place, limited improvement is assumed in the fuel economy of both car and road freight transport vehicles in Indonesia, which is in line with Purwanto et al. (2010) and Purwanto et al. (2016). The average fuel economy for each vehicle type is given in the following two tables (Tables 3.1 and 3.2).

The VEIA-ID model has been calibrated with the statistics of road transport fuel consumption as produced by the Government of Indonesia (2019) and Government of the United States (2020). The model shows some consistency with historical data, in that it can replicate the statistics with less than 5% error in the base year 2019 despite fluctuations in road transport energy consumption as shown in the statistics (Table 3.3).

CO_2 emissions are calculated by multiplying the above fuel use with the carbon content of each fuel type (Table 3.4) and the ratio of the molecular weight of CO_2 to that of carbon, which is 44/12.

3.2.4 Software Development

A software tool is being developed to implement the VEIA-ID model. Its main purpose is to allow energy and transport experts, as well as non-expert users, to create relevant scenarios under various modules—transport demand, fleet, environmental, and welfare—as inputs for further policy measurement. The tool is expected to help.

- Implement economic, energy, and/or environmental scenarios that may represent policy packages through several defined interfaces;
- Process calculations following the model concept developed by ERIA;

Table 3.1 Fuel economy of aggregated car types (kilometre per litre)

Aggregated car types	2020–2025		2026–2030		2031–2035		2036–2040		2041–2045		2046–2050	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Light diesel	12.4	12.1	12.4	12.1	12.5	12.3	12.6	12.4	12.6	12.6	12.6	12.6
Medium diesel	11.1	7.7	11.1	7.7	11.1	7.7	11.1	7.8	11.2	7.7	11.2	7.7
Heavy diesel	9.3	8.5	9.4	8.5	9.5	8.8	9.5	9.0	9.5	9.1	9.5	9.2
Light gasoline	12.3	11.3	12.3	11.3	12.5	11.5	12.6	11.7	12.6	11.7	12.6	11.7
Medium gasoline	9.6	9.1	9.6	9.1	9.6	9.3	9.6	9.3	9.6	9.4	9.5	9.5
Heavy gasoline	8.6	8.3	8.6	8.3	8.5	8.3	8.5	8.4	8.5	8.4	8.5	8.4
CNG cars	8.2	8.0	8.2	8.0	8.4	8.2	8.4	8.4	8.5	8.4	8.6	8.5

CNG compressed natural gas
Source Authors

Table 3.2 Fuel economy of road freight vehicles (kilometre per litre)

Road freight vehicles	2020–2025		2026–2030		2031–2035		2036–2040		2041–2045		2046–2050	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Light diesel truck	4.3	4.1	4.4	4.3	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4
Medium diesel truck	3.9	3.6	3.9	3.6	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
Heavy diesel truck	3.2	3.0	3.2	3.0	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2
Medium gasoline truck	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8
Heavy CNG truck	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1
Diesel pick-up	5.2	4.7	5.2	4.7	5.4	5.2	5.4	5.4	5.5	5.5	5.5	5.5
Gasoline pick-up	6.4	6.3	6.4	6.3	6.7	6.5	6.7	6.7	6.8	6.7	6.8	6.8
Diesel double-cabin	7.5	5.0	7.5	5.0	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Gasoline double-cabin	9.3	9.3	9.3	9.3	9.3	9.3	9.3	9.3	9.3	9.3	9.3	9.3

CNG compressed natural gas
Source Authors

Table 3.3 Road transport fuel consumption model calibration results (million litres)

	2014	2015	2016	2017	2018	2019
Diesel fuel statistics	27,220	25,433	25,372	27,843	28,785	29,621
Diesel fuel model	26,966	27,766	27,873	27,856	26,861	28,229
Error (%)	−0.93	9.17	9.86	0.05	−6.68	−4.70
Gasoline fuel statistics	30,925	31,528	31,986	33,548	34,353	35,246
Gasoline fuel model	33,102	34,002	34,867	35,692	36,376	36,755
Error (%)	7.04	7.85	9.01	6.39	5.89	4.28

Sources Government of Indonesia (2019), Government of the United States (2020), and authors

Table 3.4 Carbon content values in the VEIA-ID

Fuel type	Carbon Content (tons of carbon/ton of oil equivalent)	Sources
Gasoline	0.79	Eggleston et al. (2006)
Diesel	0.82	Eggleston et al. (2006)
CNG	0.61	Eggleston et al. (2006)
Electricity from grid	2.40 (2020) 1.94 (2030) 1.80 (2040) 1.61 (2050)	2020 value: Climate Transparency (2018) Growth rate: Purwanto et al. (2016)

CNG compressed natural gas

- Produce the calculation results yearly up to 2050;
- Store data, coefficients, intermediate calculation results, and final outputs in a
- Well-structured database; and
- Present calculation results in several defined report templates by level of detail.

This tool is written in the Python programming language. Users can easily download the tool, install it, and run it, as it can be used without purchasing any license, apart from Microsoft Office. Interested users will still, however, need ERIA's permission to run the tool so that they can have full access to the VEIA-ID model. They will have to register as experts or common users, and experts will be able to import data so that the tool will help create a new scenario.

New scenarios can be developed by clicking on the 'Scenario' button. All new scenarios will be created under the reference scenario, the 2020 base year, to calibrate the model's data and parameters and to validate the model results. In the new scenario, a user can modify each parameter under each module according to the data that he/she owns or wants to assess. Once the new scenario has been set up, the user can run it to view the results, and return to his/her modified scenario until expected results are obtained.

All scenarios will be saved automatically in the application. However, a user can also download it in.xls or.csv format for further offline analysis. In addition, the tool has a feature in which a user can export only created scenarios or both scenarios and its results. The results will also appear as tables and graphs.

In the long run, the tool is expected to be managed by ERIA and Indonesian stakeholders to develop Indonesia's road transport sector as well as to provide insights for implementing related policies in Indonesia.

3.3 Economic and Energy Market Assumptions

The most important assumptions in the VEIA-ID model relate to how societal behaviour in relation to the transport system is represented, and especially in the demand module. The demand module is a schematic representation of reality that relies on certain assumptions of how people and firms behave on average. The key underlying assumption in this module is the distinction between macro and micro circumstances, as explained previously.

The baseline scenario was developed using exogenous demographic and economic assumptions that are in line with World Bank (2020) and United Nations (2020b) data, while trade data were calculated based on United Nations (2020a). Based on these resources, Indonesia's population is expected to grow steadily from 273.5 million people in 2020 to nearly 310.0 million in 2050. Expressed in constant rate of the 2020 Indonesian rupee, the total GDP would rise from nearly Rp 9600 trillion ($0.66 trillion) in 2020 to Rp 39,100 trillion ($2.68 trillion) in 2050.

An economic growth situation is assumed where the current COVID-19 pandemic and oil crisis have impacts on 2020, leading to a GDP growth rate of −5% for 2020. Economic growth gets back on track gradually, reaching 0% by 2021, and 5% by 2022 onwards (Table 3.5).

Assumptions regarding oil prices (Table 3.6) are based on EIA (2020a, b); on

Table 3.5 Economic assumptions in the VEIA-ID model

	Unit	2018	2020	2025	2030	2035	2040	2045	2050
GDP	Rp trillion (2020)	10,425	9591	11,547	14,738	18,809	24,006	30,638	39,100
	$ trillion (2020)	0.71	0.66	0.79	1.01	1.29	1.65	2.10	2.68
Trade	Rp billion (2020)	939	864	1008	1104	1219	1346	1501	1654
	$ trillion (2020)	0.06	0.06	0.07	0.08	0.08	0.09	0.10	0.11

GDP gross domestic product
Source World Bank (2020), United Nations (2020a), and authors

Table 3.6 World crude oil price assumption in the VEIA-ID model ($ per barrel)

2018	2020	2025	2030	2035	2040	2045	2050
71	41	55	61	67	73	79	85

Source EIA (2020a, b)

average, the North Sea Brent crude oil price fell from $71.19 per barrel in 2018 to $64.37 per barrel in 2019, and further to $40.50 per barrel in 2020. The baseline scenario's world oil prices are assumed to follow those of the reference scenario in EIA (2020a).

These assumptions affect the evolution of future average gasoline and diesel prices in Indonesia. Transport fuel prices in Indonesia are more reactive to price changes in global oil. Future average gasoline and diesel prices are estimated in a linear function of the North Sea Brent crude oil price.

The Government of Indonesia is assumed to want to improve the environmental performance of fuel; therefore, it would ban premium (i.e., octane number 88) and pertalite (i.e., octane number 90) gasoline fuels from the market in 2022 and 2023, respectively, in the framework of progressing towards Euro 4 fuel standards (GOI 2019). This elimination would result in a 17% increase of the average gasoline price between 2022 and 2023.

For diesel fuel, cetane 48 fuel is assumed to disappear from the market in 2025. The elimination of cetane diesel fuels should result in an increase of 28% of the average diesel fuel price between 2024 and 2025, a stronger shock than that caused by the disappearance of premium and pertalite gasoline.

The effects of the fuel quality improvement due to the use of higher-octane and cetane-numbered fuels are unknown and need further empirical research.

3.4 Results

Baseline scenario results were produced by conducting a model run using economic and energy market assumptions as described in the previous section. Four alternative scenarios were run based on the implementation of four different policy measures: fuel quality improvement, emissions trading, application of additional motorway toll roads, and improved carrying capacity of heavy-duty trucks.

3.4.1 Baseline Scenario

3.4.1.1 Transport Demand

As shown in Fig. 3.3, the total passenger transport demand should increase from 8600 billion passenger-km in 2020 to around 14,000 billion passenger-km in 2050, about a 1.6% annual growth rate. Road transport modes, including cars, buses, and motorcycles, comprised around 96% of the total passenger transport demand in 2020 and will decrease slightly to 94% in 2050. The air transport share should almost double from 2.7% in 2020 to 5.2% in 2050, while the rail mode share would drop from 1.6 to 0.9% in 2050.

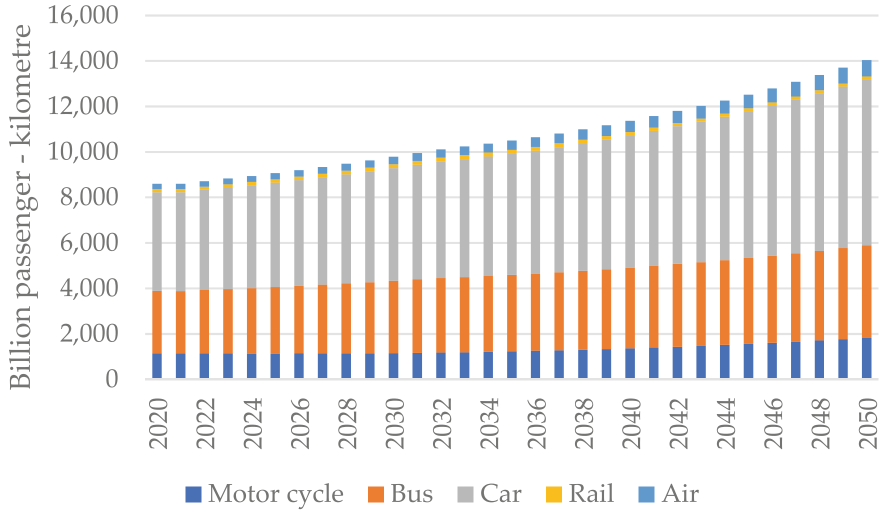


Fig. 3.3 Total passenger transport demand. *Source* Authors

For road transport modes, the car share would increase slightly from around 53% in 2020 to around 55% in 2050. Buses, on the other hand, should fall from 33% in 2020 to 31% in 2050, while the share of motorcycles will remain at a constant 14% during the whole period.

Figure 3.4 shows that the car transport demand will increase by an average annual

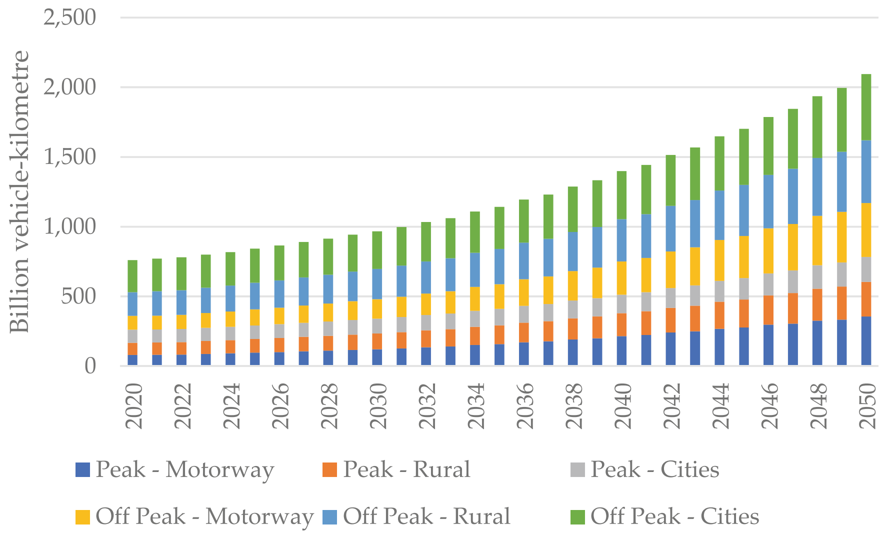


Fig. 3.4 Car transport demand. *Source* Authors

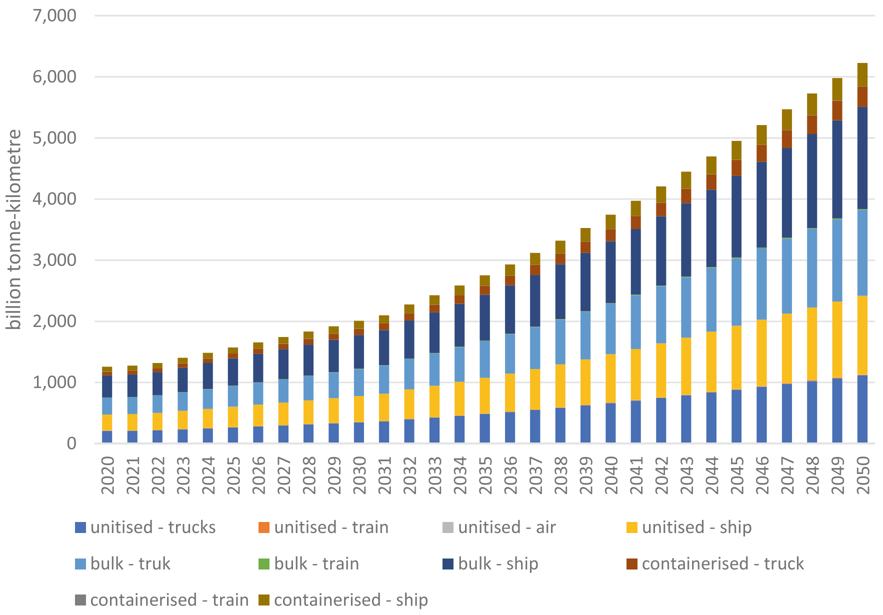


Fig. 3.5 Total freight transport demand. *Source* Authors

rate of 3.3% between 2020 and 2050 from around 760 billion vehicle-km to nearly 2,100 billion vehicle-km. Around two-thirds of the demand is expected to happen during the off-peak period. Demand is equally shared between the three types of road networks: urban, motorways, and rural.

The total national freight demand should increase by an average annual growth rate of 5% from 1250 billion ton-km in 2020 to around 6230 ton-km in 2050 (Fig. 3.5). The growth between 2020 and 2030 would only be around 3.3% per year, as freight transport is expected to experience pandemic effects in slower economic growth at least until 2023.

Around 57% of freight is currently transported by sea, while around 43% is transported by land. Trucks' share would grow to reach almost 46% by 2050, while that of ships would fall to around 54%. The shares of goods transported by train and air modes would remain almost negligible during the whole simulation period.

The share of transported goods in bulk would remain at around half of the total demand, while unitised goods' share and containerised goods' share would remain at around 39% and 11%, respectively.

As shown in Fig. 3.6, road freight transport demand is also expected to grow remarkably, increasing from around 94 billion vehicle-km in 2020 to around 490 billion vehicle-km in 2050, an almost five-fold increase or an annual growth rate of 5.2%. The share of very long-distance trips creates around 60% of all road freight transport demand, while at the same time, long-distance and very short-distance trips each comprise around 18% of the share.

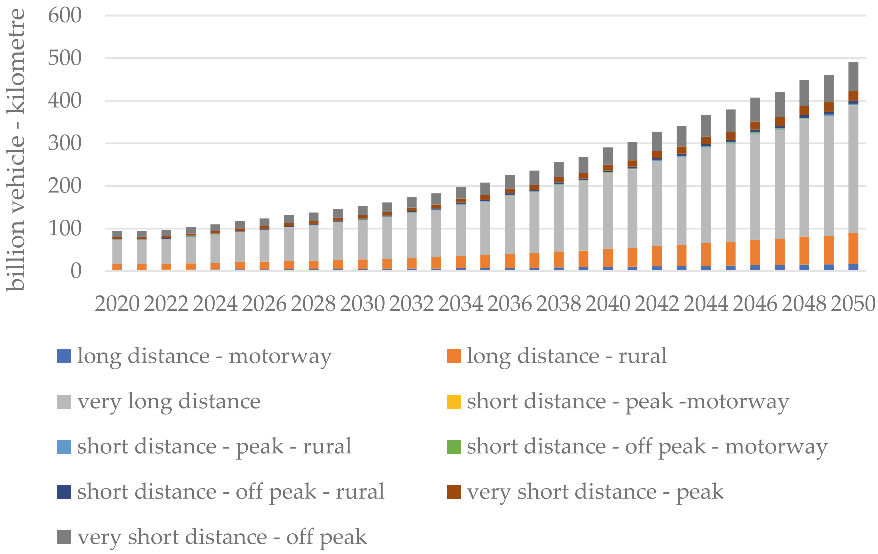


Fig. 3.6 Road freight transport demand. *Source* Authors

The phasing out of low-octane gasoline fuels and cetane-48 diesel fuel between 2022 and 2025 would trigger an increase of 17% and 28%, respectively, of the average gasoline and diesel fuel prices. This fuel price increase grows generalised transport costs by around 4% and 7%, respectively, for gasoline- and diesel-fuelled road vehicles, which, in turn, drop the total transport demand of cars and road freight vehicle by around 1.2% compared to the situation without a fuel price increase.

3.4.1.2 Car and Road Freight Fleet

The fleet of passenger cars will triple, from around 12.9 million units in 2020 to nearly 37.5 million units in 2050. Most of them, around 80%, will be light-engine gasoline cars followed by medium-sized diesel and gasoline cars whose shares measure around 9% each. As no policy interventions are assumed to facilitate electric vehicle penetration by 2050, the share of electric vehicles will only reach less than 1%, about the same share as light-diesel and medium gasoline cars (Fig. 3.7).

For road freight vehicles, the model foresees growth in the fleet from 4.4 million in 2020 to 12.6 million vehicles in 2050. The annual growth rate increases from 1.3% between 2020 and 2030 to 5.0% between 2040 and 2050. Diesel-fuelled, light-duty vehicles, such as light diesel trucks and pick-ups, make up about 50% of the total road freight fleet during the whole simulation period. Gasoline-fuelled pick-up and double-cabin trucks comprise around 40%, while diesel-fuelled, medium and heavy trucks make up around 8% of the total fleet (Fig. 3.8).

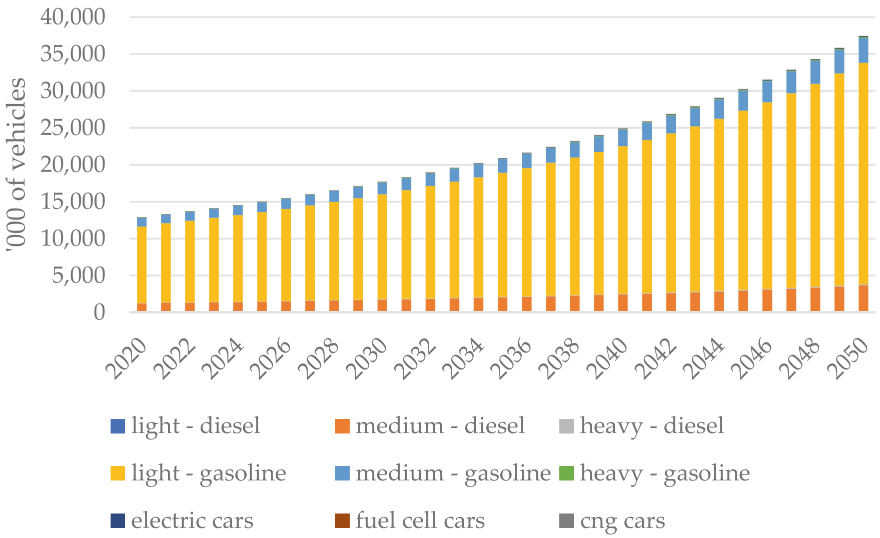
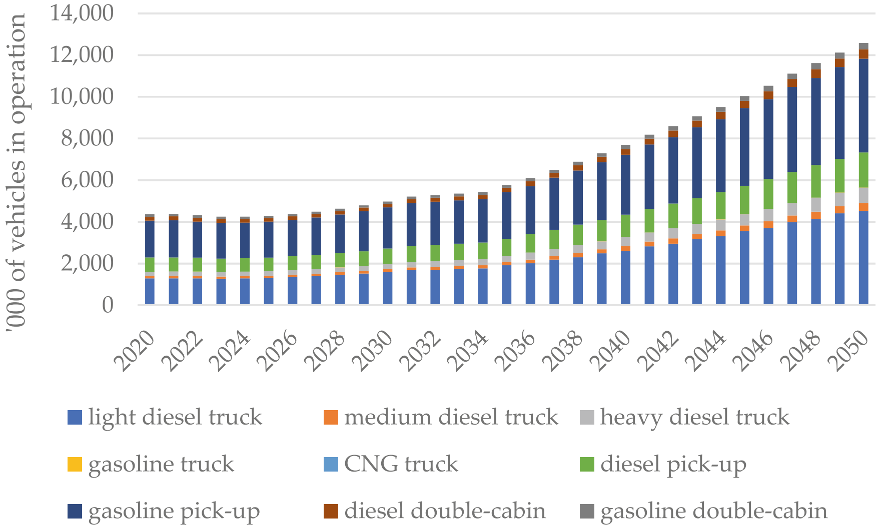


Fig. 3.7 Car fleet in operation. *Source* Authors



CNG = compressed natural gas.

Fig. 3.8 Road freight fleets in operation. *Source* Authors

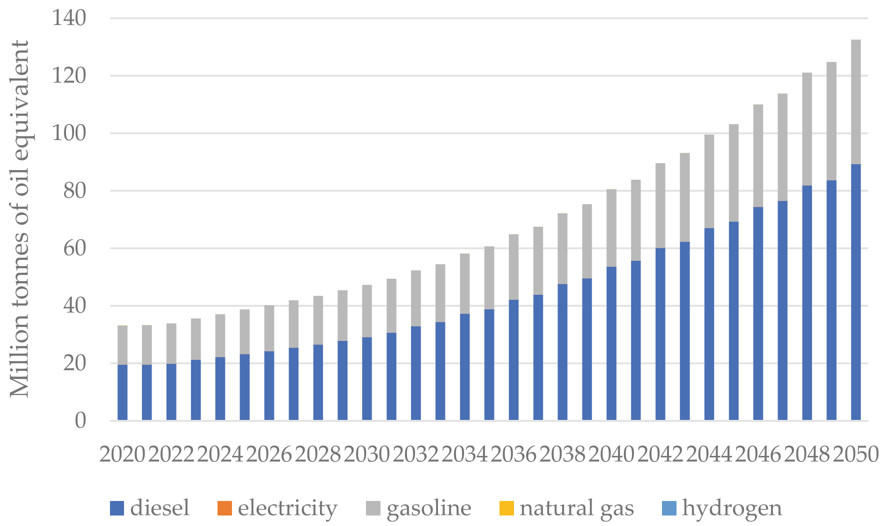


Fig. 3.9 Total energy use from cars and road freight vehicles. *Source* Authors

3.4.1.3 Energy Use from Car and Road Freight Modes

Total energy use from car and road freight modes would increase from around 33 Mtoe in 2020 to around 132 Mtoe in 2050 (Fig. 3.9), an average annual growth rate of 4.7%. The diesel fuel share should increase from nearly 60% in 2020 to 67% in 2050, while that of gasoline decreases from 41 to 33%. This development may be triggered by the fact that the car share, in terms of fuel consumption, would drop from 38 to 30% during the same period, while that of road vehicle freight would increase from around 62 to 70%.

In terms of volume, diesel fuel consumption would grow from around 26 million kilolitres in 2020 to 105 million kilolitres in 2050, while gasoline grows from 17.5 million kilolitres in 2020 to 55 million kilolitres in 2050.

A 30% mandatory biodiesel blend in diesel fuel, the B30 program, has been in place since December 2019 as a sequel to the previous B20 program. If the B30 program continues until 2050 and no further increase in the blending rate takes place, the biodiesel consumption from cars and road freight vehicles will increase from 7.8 million kilolitres to around 8.2 million kilolitres by 2025, 10.3 million kilolitres in 2030, 19.0 million kilolitres in 2040, and finally 31.6 million kilolitres by 2050.

3.4.1.4 Carbon Dioxide Emissions from Car and Road Freight Modes

CO_2 emissions from car and road freight modes would increase from around 95 million tons of CO_2 in 2020 to 380 million tons of CO_2 in 2050. The road freight vehicle share of CO_2 emissions is bigger than that of cars; the car share would

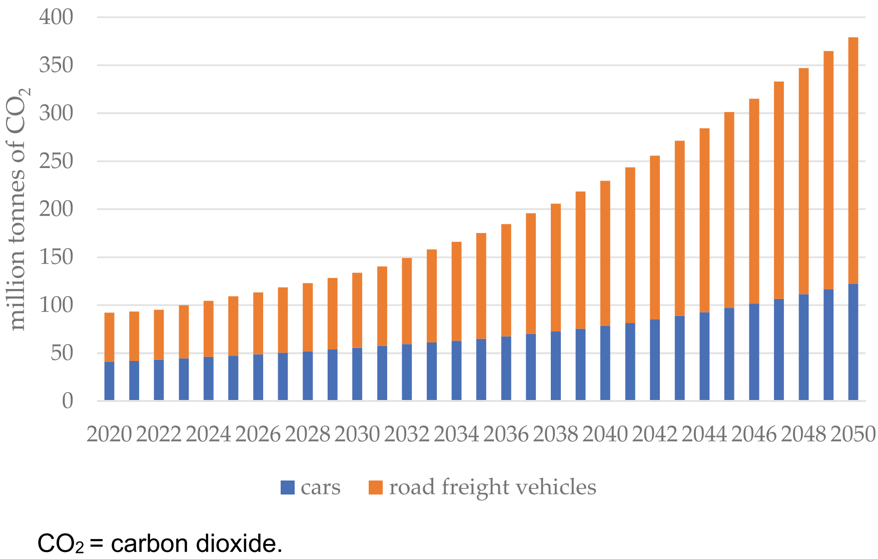


Fig. 3.10 Direct carbon dioxide emissions. CO_2 carbonDirect carbon dioxide. *Source* Authors

decrease from 37% in 2020 to around 30% in 2050, while the road freight vehicle share would increase from 63 to 70% (Fig. 3.10).

The direct life-cycle analysis of CO_2 emission factors from Posada et al. (2012) was used for crude palm oil-based biodiesel, 0.6051 ton-carbon per ton of oil equivalent. This emissions factor means that pure biodiesel (i.e., B100) fuel contains 30% less carbon than pure diesel fuel. Depending on the year-to-year fluctuation of diesel and gasoline consumption, a 30-percent blend from the crude palm oil-based biodiesel mandatory programme would reduce CO_2 emissions by 2–5%.

These direct emissions intensities assume no carbon loss from the field in which biofuels are grown or planted. Direct life-cycle analysis emissions factors from biofuel production concern mostly agriculture processing and are dependent on the pathways. The emissions factors vary in function of the carbon intensity of the electricity used and factors such as fertiliser application rate.

3.4.2 Alternative Scenarios

3.4.2.1 Example 1: Improvement of Fuel Quality

As mentioned in Sect. 1, the Government of Indonesia intends to improve fuel quality by shifting away from low-octane gasoline and low-cetane diesel fuel between 2022 and 2025. This measure should induce a 17% and 28% increase, respectively, in average gasoline and fuel prices, increase transport costs, and decrease the total transport demand of cars and road freight vehicles by around 1.2% compared to the situation without a fuel price increase. This drop in car and road freight vehicle transport demand should decrease fuel consumption and CO_2 emissions from the two modes by around 1.6%. Should the fuel quality improvement also affect fuel efficiency and therefore CO_2 emissions, then the impacts on fuel consumption and CO_2 emissions would be greater.

3.4.2.2 Example 2: Carbon Tax

A carbon tax policy from 2020 has been implemented by setting the carbon value to Rp 300,000 per ton of CO_2 or around \$20.60 per ton of CO_2 in 2020 up to 2050. As fuel's carbon contents are assumed to be constant during the whole simulation period, for gasoline and diesel fuel, there will be a fixed annual tax surcharge of around Rp 870,000 (\$59.60) per ton of oil equivalent and Rp 902,000 (\$61.80) per ton of oil equivalent, respectively. For gasoline, this tax surcharge equivalent is around 9.4% of the fuel price increase in 2020 that will decrease to around 6.9% of the fuel price increase in 2050. For diesel fuel, this increase drops from 11.60% in 2020 to 7.45% in 2050. Significant effects can be observed in Table 3.7 regarding air passenger transport demand, which drops by around 2%. In freight, road and air modes will shift to rail and ship (Tables 3.8, 3.9 and 3.10).

Table 3.7 Effects of carbon tax scenario on passenger transport demand (%)

Passenger transport mode	2020	2030	2040	2050
Air	−2.0	−2.5	−2.1	−2.3
Rail	1.1	1.2	0.9	1.1
Bus	0.8	0.9	0.8	0.8
Car	0.0	0.0	−0.1	−0.1
Motorcycle	−1.0	−1.0	−0.8	−0.9
Total	0.0	0.0	0.0	0.0

Source Authors

Table 3.8 Effects of carbon tax scenario on freight transport demand (%)

Freight Transport Mode	2020	2030	2040	2050
Road	−1.0	−1.0	−1.0	−1.0
Rail	0.8	0.9	1.0	1.0
Air	−1.1	−1.0	−1.0	−1.0
Ship	0.9	0.9	0.8	0.8
Total	0.1	0.1	0.0	0.0

Source Authors

Table 3.9 Effect of increase in toll roads on car and rail transport demand, fuel consumption, and carbon dioxide emissions (%)

Car mode	2020	2030	2040	2050
Car trip demand, motorway	−0.4	−0.8	−0.6	−0.6
Car trip demand, rural road	0.0	0.1	0.2	0.2
Car trip demand, city road	0.0	0.0	0.0	0.0
Rail trip demand	0.1	0.1	0.1	0.1
Car fuel consumption and CO_2 emissions	−0.3	−0.4	−0.3	−0.3

Source Authors

Cars and road freight fuel consumption and CO_2 emissions should drop by around 1.5%. Shifting to smaller-engine vehicles should lead to a fuel consumption and CO_2 emissions drop of around 1% in cars and around 2% in road freight vehicles.

The carbon tax has a small effect, because carbon contents in fuels are assumed to remain constant during the whole simulation period, making the final % age of the tax on the final fuel price shrink with time. To maintain the importance of a fuel tax component during a certain period, the value of the carbon tax needs to thus increase at least at the same growth rate as fuel price growth.

3.4.2.3 Example 3: Application of Additional Motorway Road Tolls

Two simulations were created to test the model's elasticity with respect to tolls on motorways: one toll for passengers and another for trucks.

For passengers, an additional toll of Rp 1000 ($0.07) per vehicle-km is implemented on motorways for cars from 2020 to 2050. As a result, car trip demand in the motorway network drops by 0.4–0.6%, which is compensated by increased demand on rural roads and rail. Car fuel consumption and CO_2 emissions drop by around 0.3–0.4% (Table 3.9).

For freight, the same additional toll is implemented on motorways from 2020 to 2050. As a result, truck transport demand on motorways drops by around 0.3–0.5% while those of rural and city roads increase. Some demand shift from road to rail and maritime can also be expected. The toll implementation should decrease the total road freight fuel consumption and CO_2 emissions by around 0.2–0.4% (Table 3.10).

3.4.2.4 Example 4: Improvement of Carrying Capacity of Heavy-Duty Vehicles

Improving freight logistics efficiency can also be simulated by the VEIA-ID model. One measure is to assume an increase in the ratio of load factor to the carrying capacity of heavy-duty trucks. As an example, a 60% increase of the ratio starting

Table 3.10 Effect of increase in toll roads on freight transport demand, fuel consumption, and carbon dioxide emissions (%)

	2020	2030	2040	2050
Road freight demand, motorway	–0.5	–0.5	–0.4	–0.3
Road freight demand, rural road	0.1	0.1	0.1	0.1
Road freight demand, city road	0.0	0.1	0.0	0.0
Rail freight demand	0.1	0.1	0.1	0.1
Maritime freight demand	0.0	0.1	0.2	0.2
Road freight fuel consumption and CO_2 emissions	–0.4	–0.4	–0.2	–0.2

CO_2 = Carbon dioxide
Source Authors

Table 3.11 Effects of a 60% increase in the ratio between load factor and carrying capacity of heavy trucks (%)

	2020	2030	2040	2050
Road freight transport demand	0.0	7.3	6.5	4.6
Rail freight transport demand	0.0	−0.5	−1.2	−3.1
Maritime freight transport demand	0.0	0.1	−0.8	−2.7
Air freight transport demand	0.0	−1.9	−1.9	−2.1
Total freight transport demand	0.0	3.3	2.5	0.7
Fuel consumption and CO_2 emissions of road freight transport	−24.8	−19.5	−19.8	−21.1

Source Authors

from 2020 is implemented, signifying that the ratio between load factor and carrying capacity heavy-duty trucks increases from 0.45 to 0.72.

Increasing the ratio of the carrying capacity of heavy-duty trucks by 60% seems to be effective in decreasing fuel consumption and CO_2 emissions of road freight transport, as these drop by 19–24% (Table 3.11). In practice, this ratio increase means that each truck is loaded more, resulting in fewer empty running trucks. This should bring down the total amount of road freight vehicle transport volume (i.e., vehicle-km) by 20% on average during the whole simulation period, which, in turn, induces a drop in fuel consumption and CO_2 emissions.

3.5 Conclusions and Policy Recommendations

The VEIA-ID model can be used to project Indonesia transport demand and its impacts in term of energy use and CO_2 emissions to 2050. It can be used to assess the different policy measures related to vehicle technologies, fuel quality, fiscal instruments, and traffic management considering its limitation as a non-network-based model. The open-access tool is a reliable and robust way to help assess impacts of different policy measures to be implemented in the energy and transport sectors and should facilitate long-term policy making. The tool was designed to be open access to facilitate the decision-making process in the transport sector, especially in assessing the impacts of various energy- or environmental-related policies considered to change transport activities in the long term; reach the largest user community, especially academics and policymakers; and ensure the transparency of policies and the performed impact assessment analysis in Indonesia.

As a non-network-based tool, by principally considering generalised cost development, the VEIA ID model seeks to estimate transport demand in highly disaggregated segments conserving the nature of competition amongst travel purpose, cargo type, mode, network type, and time of day. Amongst the outputs are cars and road freight vehicle stock, and newly registered and scrapped fleet, disaggregated into different vehicle technology and fuel types. By incorporating emissions and fuel consumption factors segmented into vehicle technology and vehicle age, the tool can capture the impacts of vehicle technology penetration, such as the different types of electric vehicles or standards related to engine technologies.

The tool still needs improvement. It was calibrated based on the historical data of road transport fuel consumption and vehicle statistics from 2010 to 2017, but the demand module needs to be calibrated. Data from origin–destination studies of the Ministry of Transportation need to be aggregated to produce a reference transport demand figure upon which the tool should be calibrated and validated. Further calibration also needs to occur in the fleet module (i.e., transport costs, fleet figures of non-road modes, and emissions and fuel consumption factors of non-road modes).

In addition, the current version comprises only detailed fleet submodules for car and road freight transport modes. Fleet submodules for other road transport modes, i.e., motorcycles and buses, still need to be developed to give complete calculations of energy use and emissions from all road transport activities.

It is important that policymakers start to use analytical tools, such as the VEIA-ID model, to assess the impacts of transport-related policies on energy use and climate change. A deficit in energy trade balance and energy security concerns are amongst the most urgent issues related to policies to promote the use of biofuels and to electrify mobility. Achieving the country's CO_2 emissions reduction targets is another challenge that closely relates to the two issues. Analytical tools, like the VEIA-ID model, help make decisions and set the directions of national transport policies. Lower-level strategies or policies should be assessed using more detailed tools, such as network-based models.

The inventory of emissions and fuel consumption factors in Indonesia also needs to be developed. This type of inventory, once coupled with tools such as the VEIA-ID model, should provide reliable tool suites, which can be used to measure the impacts of transport policies more accurately regarding energy use, climate change, and air pollution.

Appendix 1: Road Freight Vehicle Types

Fuel	Type	Gross vehicle weight (ton)
Diesel	Double cabin	<5 [diesel] for all CC
Gasoline	Double cabin	<5 [gasoline] for all CC
Diesel	Pick up	<5 [diesel]
Gasoline	Pick up	<5 [gasoline]
Electric	Pick up	<5 [electricity]
Diesel	Truck	5–10 [diesel]
Diesel	Truck	10–24 [diesel]
Diesel	Truck	>24 [diesel]
Gasoline	Truck	10–24 [gasoline]
CNG	Truck	>24 [CNG]
Electric	Truck	5–10 [electricity]
LNG	Truck	5–10 [LNG]
Hydrogen	Truck	5–10 [LNG]

CC engine size in cubic centimetres, *CNG* compressed natural gas, *LNG* liquified natural gas

Appendix 2: Car types

Fuel type	Vehicle type	Gross vehicle weight
Diesel	4 × 2	CC ≤ 1.500 [diesel]
Diesel	4 × 2	CC 1.501–2.500 [diesel]
Diesel	4 × 2	CC > 2.501 [diesel]
Gasoline	4 × 2	CC ≤ 1.500 [gasoline]
Gasoline	4 × 2	CC 1.501–3.000 [gasoline]
Gasoline	4 × 2	CC > 3.001 [gasoline]
Diesel	4 × 4	CC ≤ 1.500 [diesel]
Diesel	4 × 4	CC 1.501–2.500 [diesel]
Diesel	4 × 4	CC > 2.501 [diesel]
Gasoline	4 × 4	CC ≤ 1.500 [gasoline]
Gasoline	4 × 4	CC 1.501–3.000 [gasoline]
Gasoline	4 × 4	CC > 3.001 [gasoline]
Diesel	Sedan	CC ≤ 1.500 [diesel]
Diesel	Sedan	CC 1.501–2.500 [diesel]

(continued)

(continued)

Fuel type	Vehicle type	Gross vehicle weight
Diesel	Sedan	CC > 2.501 [diesel]
Gasoline	Sedan	CC ≤ 1.500 [gasoline]
Gasoline	Sedan	CC 1.501–3.000 [gasoline]
Gasoline	Sedan	CC > 3.001 [gasoline]
Gasoline	Affordable, energy-saving	CC ≤ 1.200 [gasoline]
Electric	BEV	CC ≤ 1.500 [electricity]
Electric	PHEV	CC ≤ 1.500 [electricity]
Electric	HEV	CC ≤ 1.500 [electricity]
Hydrogen	FCV	CC ≤ 1.500 [electricity]
Diesel	Flexy	CC 1.501–2.500 [diesel]
Gasoline	Flexy	CC 1.501–3.000 [gasoline]
CNG	Flexy	CC 1.501–3.000 [CNG]

CC engine size in cubic centimetres, *CNG* compressed natural gas

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Chapter 4
Assessment of the Forest Carbon Balance Due to Deforestation and Plantation Forestry in Southeast Asia

Nophea Sasaki, Yadanar Yè Myint, and Manjunatha Venkatappa

Abstract Assessment of the carbon balance due to changes in forest land uses could serve as an important benchmark for the Reducing Emissions from Deforestation and Forest Degradation (REDD+) scheme of the United Nations Framework Convention on Climate Change. Here, we assessed the carbon gains and loss due to deforestation and plantation forestry in Southeast Asia during the implementation period of the Paris Climate Agreement between 2020 and 2030. Data on forest cover and carbon stocks were obtained from the most recent forest resources assessment report by the Food and Agriculture Organization. We performed a regression analysis to obtain parameters and initial values for predicting the forest cover change, where logging was assumed to take place in both natural and plantation forests. Between 2000 and 2020, Southeast Asia lost about 0.5%, or 1.1 million hectares, every year, whilst plantation forests gained 1.8%. Carbon stocks in natural forests declined to 15.7 petagrams of carbon (PgC) in 2030 from 19.7 PgC in 2000. On average, Southeast Asia emits about 468.6 teragrams of carbon dioxide per year ($TgCO_2$ $year^{-1}$) due to the loss of natural forests and logging, or about 23% of emissions, from tropical forests. Plantation forests gain about 25.9 $TgCO_2$ $year^{-1}$ between 2000 and 2030. Between 2020 and 2030, Southeast Asia is likely to emit about 442.7 $TgCO_2$ $year^{-1}$. If a retrospective approach is used, the forest reference emission level for this region is 424.2 $TgCO_2$ $year^{-1}$ during the implementation period of the Paris Agreement. Carbon revenues under the REDD+ scheme were estimated at US$2.4 billion annually under the Paris Agreement. Our study suggests that plantation forests could play a role in increasing role wood supply to the region, but caution is needed because large-scale plantations can cause environmental destruction.

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H. Phoumin et al. (eds.), *Energy Sustainability and Climate Change in ASEAN*, Economics, Law, and Institutions in Asia Pacific,
https://doi.org/10.1007/978-981-16-2000-3_4

Keywords REDD+ scheme · Fast-growing plantation · Slow-growing plantation · Carbon removals · FREL

4.1 Introduction

Global climate change and the loss of tropical forests have been of great concern to the world for the last 20 years (Smith et al. 2020) and have driven international climate change strategies to mitigate climate change (e.g. the adoption of the Paris Climate Agreement). The Reducing Emissions from Deforestation and Forest Degradation, Conservation of Forests, Sustainable Management of Forests, and Enhancement of Forest Carbon Stocks (REDD+) scheme of the United Nations Framework Convention on Climate Change is one of the many measures that was introduced to reduce carbon emissions from the forestry sector. In fact, emissions from deforestation and forest degradation have been recognised as the second key contributing factor to greenhouse gas (GHG) emissions after the burning of fossil fuels (Sharma et al. 2020). Specifically, carbon emissions from land use change, particularly deforestation, contribute to 12–20% of global anthropogenic GHG emissions (Gorte and Sheikh 2010). As tropical deforestation is likely to continue at a high rate with serious impacts on climate change (Seymour and Harris 2019). Further loss of tropical forests can accelerate climate change because the carbon balance in tropical forests accounts for nearly half of the world's terrestrial carbon that can be sequestered by intact tropical forests (Maxwell et al. 2019).

Between 1990 and 2015, the global forest area declined from 4.5 billion hectares (ha) to 4.0 billion ha, whilst at the same time, the area of forest plantation expanded from 167.5 million ha to 277.9 million ha due to increasing demand for timber and other forest products to meet the needs of growing populations (Cuong et al. 2020). Such demand is expected to increase more than threefold in 2050 as the world's population is estimated to more than triple over the same period. From 1990 to 2016, the world lost approximately 130 million ha of its tropical forests (Nunes et al. 2020). Global timber consumption is expected to increase in the coming years (Brack 2018). According to FAO-Forestry (Adams and Castano 2001), the world's timber supply from tropical natural forests is projected to decline. However, trade in secondary processed wood products is estimated to significantly increase due to increases in forest plantation resources. In 2000, tropical plantations accounted for 45% of global forest plantations and provided 22% of the industrial roundwood supply. Sasaki et al. (2016a, b) suggested that the REDD+ scheme of the Paris Agreement provides an opportunity to manage tropical forests for timber production and carbon emission reductions. A REDD+ derivative for the conservation and sustainable management of forests and the enhancement of forest carbon stocks creates an opportunity for carbon-rich developing countries by providing payments based on forest-based emission reductions credits, against their emission baselines (Paoli et al. 2010). Obtaining such results-based payments requires assessment of the carbon balance due to changes in forest land uses over time and needs a clear understanding of carbon gain through forest management and forest plantations, or the loss of carbon stocks due to land use changes and deforestation. As part of the Paris Climate Agreement, such gains or losses need to be accounted for as they are crucial for establishing the emission baselines or the forest reference emission level (FREL) against which results-based payments could be made possible during the implementation period of the Paris Agreement between 2020 and 2030.

Although many studies have assessed the forest carbon balance in the tropics (Venkatappa et al. 2020; Asner et al. 2010; Phillips et al. 2017), these studies used intensive data and technologies that are not easy for policymakers or the general public to adapt or use. Also, these studies have been mainly about tropical forests in South America, and few studies have been done on tropical areas in Asia (Sasaki et al. 2009; Estoque et al. 2019) except with the use of relatively old data or with discussions on outdated policies. To provide a relevant study that reflects international and national trends, examination using recently available data and recent policy development is needed. This study attempts to assess the carbon balance in forests due to deforestation and plantation forestry in Southeast Asia between 2000 and 2030 to coincide with the ending period of the Paris Climate Agreement in 2030. It could provide a basis for understanding the loss of forest cover, carbon stock changes, and baseline emissions and removals, which can be used as a benchmark for measuring the performance of the emission reductions as well as the enhancement of forest carbon stocks under the REDD+ scheme. The chapter is structured as follow: analysis of the trends of forest cover changes and carbon stock changes, projection of forest cover and carbon changes in both natural and plantation forests, timber production, carbon emissions and sequestration, and policy recommendations.

Forests can also act as major carbon sinks as they can exchange huge amounts of carbon with the atmosphere (Sasaki et al. 2009). Sound forest management is a practice designed in accordance with regulations or to balance the production of desired goods, such as timber and other forest products, and other ecosystem services, such as carbon sequestration (Noraida et al. 2017). Depending on the management objectives and cutting cycles, forests are considered to be either carbon sources or sinks, and forest management is of great importance in the future global carbon cycle (Piponiot et al. 2016). The additional expansion of forest areas through tree planting could increase the terrestrial carbon sink that can contribute to removing carbon dioxide from the atmosphere (Chauhan et al. 2016), especially in tropical areas. Plantation forests would be an effective measure for atmospheric carbon because of high potential productivity. One study estimates that the rate of carbon sequestration by forest plantations is 20.3% higher than that of natural forests (Aye et al. 2011). Therefore, there is a need to assess the trend of forest management for achieving sustainable timber production and carbon sequestration in natural forests and plantation forests since these are the two types of forest category under the Food and Agriculture Organization of the United Nations (FAO) (FAO 2020). The objective of this study is to assess the carbon gains and losses due to deforestation in natural forests and plantation forestry in Southeast Asia between 2000 and 2030 with particular emphasis on the carbon balance during the implementation period of the Paris Climate Agreement.

4.2 Southeast Asia's Forests

Southeast Asia is a dynamic region comprising highly productive tropical forests in terms of valuable timber products and high biodiversity, particularly in Brunei Darussalam, Cambodia, Indonesia, the Lao PDR, Malaysia, Myanmar, Philippines, Singapore, Timor-Leste, Thailand, and Viet Nam. Indonesia has the third-largest reserves of tropical forests in the world after the Amazon and Congo, however it has been designated as the world's third-largest GHG emitter due to rapid deforestation and forest degradation, mainly from land clearing and illegal logging (Edwards et al. 2011). Teak (*Tectona grandis*) is another important timber species for commercial timber production, and Southeast Asia produces the world's most precious teak and other valuable species with high biodiversity (Estoque et al. 2019). Approximately 29 million ha of natural teak forests are found in India, Myanmar, the Lao PDR, and Thailand, of which almost half of the total area is found in Myanmar (Kollert and Cherubini 2012). In fact, Myanmar is the largest producer of teak amongst Southeast Asian countries (Roshetko et al. 2013), whilst Indonesia is the second-largest teak producer.

Mainland or continental Southeast Asia mainly comprises mixed deciduous or monsoon forests distributed in India, Myanmar, Thailand, the Lao PDR, Cambodia, and Viet Nam (Stolle and Dennis 2007; Stibig et al. 2014; Enters 2000), whereas insular or island Southeast Asia consists of moist evergreen tropical rainforests or is equatorial (Stolle and Dennis 2007), comprising a large extent of productive evergreen *Dipterocarpus* forests (Stibig et al. 2014). Whilst continental Southeast Asia comprises a small extent of moist tropical evergreen rainforests in southern parts of Myanmar, Thailand, and Cambodia, dry evergreen and semi-evergreen forests are mostly found near the Irrawaddy Delta and Mekong River (Stolle and Dennis 2007; Stibig et al. 2014). Despite being home to 15% of the world's tropical forests (Stibig et al. 2014) and being rich in a high number of endemic species (Estoque et al. 2019), Southeast Asia is one of the most deforested regions amongst the tropics (Stibig et al. 2014). Southeast Asia is considered as a major deforestation hotspot for agriculture (Zeng et al. 2018). Besides, the region is also highlighted as a biodiversity hotspot since it has the highest rate in terms of habitat loss (Sodhi et al. 2010).

Between 2000 and 2005, the rate of forest loss in Southeast Asia represented an annual loss of 2.76 million ha per year (yr^{-1}), equivalent to 1.3% of the area of forests in the region (Stolle and Dennis 2007). Indonesia alone lost nearly 1.9 million ha yr^{-1}, with an annual deforestation rate of 2.0%, whilst Myanmar and Cambodia experienced high losses of their forests of 466,000 ha and 219,000 ha, equivalent to 1.5% and 2.0% of the countries' forest areas, respectively (Stolle and Dennis 2007). Southeast Asia lost forest cover of about 268 million–236 million ha between 1990 and 2010 (Stibig et al. 2014), dropping to approximately 206.5 million ha by 2015 (Estoque et al. 2019).

Numerous studies indicated that the clearing of forest for large-scale agriculture, canopy loss due to logging and clear-cutting, the conversion of forest land into palm oil plantations, and cropland expansion are the major reasons for degrading tropical forests and aboveground carbon stocks in this region (Estoque et al. 2019; Stibig et al. 2014; Zeng et al. 2018; Imai et al. 2018). Shifting cultivation, road construction, hydropower projects, and illegal logging are the main drivers leading to deforestation and forest degradation in Southeast Asia, whilst the conversion of natural forests to forest plantations with oil palm (*Eucalyptus* spp., *Acacia* spp., and, *Pinus* spp.) are the leading drivers of natural forest loss in this region (Stolle and Dennis 2007). Although the area of natural forests has decreased in Southeast Asia, plantation forests are on an increasing trend as the region needs to produce the materials to meet the growing demand for timber and other forest products (Roshetko et al. 2013). Plantation forests are important in Southeast Asia as demand for wood materials continues to rise, but the area of natural forests is decreasing. Rubber is also another important planted species in this region in addition to teak plantations. Rubber plantations are mainly in the Lao PDR, Cambodia, Indonesia, Malaysia, and Thailand (Mather 2003).

4.3 Study Methods and Materials

4.3.1 Forest Types and Land Use Categories in Southeast Asia

Generally, there two types of forests are classified under the FAO's forest resources assessment: natural forests (NF), where trees are naturally regenerated, and plantation forests (PF), where trees are planted and managed through the planting or seeding of fast-growing and slow-growing tree species with various degrees of planting intensity (FAO 2018). According to the FAO (2020), there are three categories of forest land use in the NF of Southeast Asia. They include production forests, where commercial logging and land development are allowed, protection forests, where forests are managed primarily for biodiversity conservation purposes, and multipurpose forests, which are managed for only fuelwood collection, watershed protection, and other protection purposes (Sasaki et al. 2009). Under the PF, there are two types of forest plantations in Association of Southeast Asian Nations (ASEAN) countries: fast-growing plantations (plantations with fast-growing or exotic species) and slow-growing plantations (plantations with native or indigenous species) (Sasaki et al. 2009). Table 4.1 shows the total area of NF and PF in Southeast Asia.

Between 2000 and 2020, Cambodia experienced the highest loss of NF, declining by about 1.5% annually, followed by Myanmar (1.0%), and Indonesia (0.5%). A rapid loss in NF was seen between 2010 and 2020, during which Cambodia lost about 2.8% annually, followed by Singapore (1.2%), Myanmar (1.0%), and Indonesia (0.8%). For the whole of Southeast Asia, about 1.5 million ha, or 0.7%, were lost during 2010–2020. This 10-year trend in forest cover change could be useful for establishing the baseline emissions or even the forest reference emission level (Sasaki et al. 2016a, b) for this region. In general, the area of plantation forest increased in percentage terms,

Table 4.1 Forest area by forest type in Southeast Asia, 2000–2020

Country	Natural forest (‘000 ha)				Forest plantation (‘000 ha)			
	2000	2010	2015	2020	2000	2010	2015	2020
Brunei Darussalam	396.0	376.3	374.9	374.7	1.3	3.7	5.1	5.3
Cambodia	10,681.1	10,434.7	8302.6	7464.4	99.1	154.5	544.3	604.0
Indonesia	97,432.0	95,472.7	90,359.5	87,607.5	3848.0	4186.5	4668.4	4525.7
Lao PDR	15,845.0	15,344.8	15,084.5	14,824.3	1580.0	1595.8	1683.5	1771.3
Malaysia	18,063.8	17,638.7	17,756.2	17,416.9	1627.5	1308.9	1708.0	1697.1
Myanmar	34,837.3	31,134.9	29,586.4	28,117.6	30.7	305.2	406.0	427.1
Philippines	6,988.7	6,489.2	6,648.6	6,808.1	320.6	350.6	365.5	380.5
Singapore	17.0	17.7	16.5	15.6	0.0	0.0	0.0	0.0
Thailand	17,011.0	16,831.0	16,359.0	16,336.0	1987.0	3242.0	3702.0	3537.0
Timor-Leste	949.1	935.1	928.1	921.1	0.0	0.0	0.0	0.0
Viet Nam	9,864.5	10,304.8	10,175.5	10,293.7	0.0	0.0	0.0	0.0
Total	212,085.5	204,979.9	195,591.8	190,179.9	9494.3	11,147.2	13,082.8	12,947.9

Ha = hectare
Source Authors’ own calculations based on data published in FAO (2020)

Table 4.2 Annual changes in forest area (thousand hectares per year)

Country	Natural forest				Plantation forest		
		2000–2020	2010–2020	2015–2020	2000–2020	2010–2020	2015–2020
Cambodia	Area	−160.8	−297.0	−167.6	25.2	44.9	11.9
	(%)	−1.5	−2.8	−2.0	25.5	29.1	2.2
Myanmar	Area	−336.0	−301.7	−293.8	19.8	12.2	4.2
	(%)	−1.0	−1.0	−1.0	64.5	4.0	1.0
Indonesia	Area	−491.2	−786.5	−550.4	33.9	33.9	−28.5
	(%)	−0.5	−0.8	−0.6	0.9	0.8	−0.6
Singapore	Area	−0.1	−0.2	−0.2	0.0	0.0	0.0
	(%)	−0.4	−1.2	−1.1	0.0	0.0	0.0
Lao PDR	Area	−51.0	−52.1	−52.1	9.6	17.6	17.6
	(%)	−0.3	−0.3	−0.3	0.6	1.1	1.0
Brunei Darussalam	Area	−1.1	−0.2	0.0	0.2	0.2	0.0
	(%)	−0.3	0.0	0.0	15.1	4.2	0.7
Malaysia	Area	−32.3	−22.2	−67.9	3.5	38.8	−2.2
	(%)	−0.2	−0.1	−0.4	0.2	3.0	−0.1
Timor-Leste	Area	−1.4	−1.4	−1.4	0.0	0.0	0.0
	(%)	−0.1	−0.1	−0.2	0.0	0.0	0.0
Thailand	Area	−33.8	−49.5	−4.6	77.5	29.5	−33.0
	(%)	−0.2	−0.3	0.0	3.9	0.9	−0.9
Philippines	Area	−9.0	31.9	31.9	3.0	3.0	3.0
	(%)	−0.1	0.5	0.5	0.9	0.9	0.8
Viet Nam	Area	21.5	−1.1	23.6	0.0	0.0	0.0
	(%)	0.2	0.0	0.2	0.0	0.0	0.0
Southeast Asia (all)	Area	−1095.3	−1480.0	−1082.4	172.7	180.1	−27.0
	(%)	−0.5	−0.7	−0.6	1.8	1.6	−0.2

Source Authors' own calculations

but the increasing trend was slowing over the last five years (Table 4.2), indicating that land clearing spread to the plantation areas outside the natural forest boundary.

4.3.2 Carbon Stocks in Southeast Asian Forests

Forests are important carbon reservoirs if well protected. However, the continuous loss of tropical forests makes these reservoirs smaller year by year. In fact, carbon emissions from deforestation account for about 10%–25% of global carbon emissions (Stolle and Dennis 2007; Stibig et al. 2014). Based on forest resource assessment, aboveground and belowground carbon stocks were reported at 144.0 megagrams of carbon per hectare (MgC ha^{-1}) in Brunei Darussalam, 130.6 MgC ha^{-1} in the

Table 4.3 Aboveground and belowground carbon in Southeast Asia's natural forests

Country	Natural forests			Plantation forest carbon stock (MgC ha^{-1})
	Aboveground	Belowground	Carbon stock (MgC ha^{-1})	
Brunei Darussalam	116.1	27.9	144.0	110.7
Cambodia	32.6	18.2	50.8	61.2
Indonesia	84.0	20.2	104.2	80.4
Lao PDR	57.1	11.4	68.5	34.5
Malaysia	96.5	23.2	119.6	123.4
Myanmar	59.3	16.6	75.9	18.4
Philippines	105.5	25.2	130.6	102.0
Singapore	57.8	11.6	69.4	0.0
Thailand	66.9	16.1	83.0	55.4
Timor-Leste	70.5	19.7	90.2	58.3
Viet Nam	30.5	8.2	38.7	50.2
Weighted Average (used for this study)			92.2	55.6

MgC ha^{-1} = megagrams of carbon per hectare
Note Carbon stocks in plantation forests include aboveground and belowground carbon
Source FAO (2020)

Philippines, and as low as 38.7 MgC ha^{-1} in Viet Nam (Table 4.3). By comparing these carbon stocks with the forest area by country, the weighted average carbon stock is 92.2 MgC ha^{-1}. This number will be used in this study for estimating the carbon stocks in Southeast Asia. Other carbon pools, such as litter, deadwood, and soil organic carbon are ignored in this study because the carbon in these pools varies greatly from one forest type to another (Dar and Sundarapandian 2015).

Using the carbon stock data in Table 4.3, the total carbon stock in Southeast Asia was estimated and presented in Table 4.4. The total carbon stock in NF was 19,439.2 million metric tons of carbon (teragrams of carbon; TgC) in 2000, 18,789.0 TgC in 2010, 18,002.1 TgC in 2015, and 17,525.6 TgC in 2020. The annual carbon loss in NF was estimated at 95.7 TgC or 350.8 teragrams of carbon dioxide ($TgCO_2$) of emissions between 2000 and 2020. These emissions were equivalent to 17% of the emissions from tropical deforestation and forest degradation (Pearson et al. 2017). An increase in plantation forests resulted in carbon removals of 95.5 $TgCO_2$ from the atmosphere. By subtracting the carbon loss due to deforestation and the carbon gains due to the increase in plantation forests, the total carbon balance in Southeast East Asia was 19,057.5 TgC, declining by about 0.34% over the same period.

Table 4.4 Carbon changes, emissions, and removals in forests in Southeast Asia

Country	Carbon stock (TgC)				Annual change (2000–2020)		
	2000	2010	2015	2020	TgC	$TgCO_2$	% per year
Natural forests							
Brunei Darussalam	57.0	54.2	54.0	53.9	−0.2	0.6	−0.27
Cambodia	542.7	530.2	421.9	379.3	−8.2	30.0	−1.51
Indonesia	10,154.1	9949.9	9417.0	9130.2	−51.2	187.7	−0.50
Lao PDR	1085.9	1051.6	1033.7	1015.9	−3.5	12.8	−0.32
Malaysia	2161.3	2110.4	2124.5	2083.9	−3.9	14.2	−0.18
Myanmar	2645.7	2364.5	2246.9	2135.4	−25.5	93.6	−0.96
Philippines	912.9	847.7	868.5	889.4	−1.2	4.3	−0.13
Singapore	1.2	1.2	1.1	1.1	0.0	0.0	−0.42
Thailand	1411.1	1396.1	1357.0	1355.1	−2.8	10.3	−0.20
Timor−Leste	85.6	84.4	83.8	83.1	−0.1	0.5	−0.15
Viet Nam	381.7	398.7	393.7	398.3	0.8	−3.0	0.22
Total	19,439.2	18,789.0	18,002.1	17,525.6	-95.7	350.8	−0.49
Plantation forests							
Brunei Darussalam	0.1	0.3	0.5	0.5	0.0	−0.1	15.08
Cambodia	8.8	13.7	48.2	53.5	2.2	−8.2	25.47
Indonesia	340.8	370.8	413.5	400.8	3.0	−11.0	0.88
Lao PDR	139.9	141.3	149.1	156.9	0.8	−3.1	0.61
Malaysia	144.1	115.9	151.3	150.3	0.3	−1.1	0.21
Myanmar	2.7	27.0	36.0	37.8	1.8	−6.4	64.51
Philippines	28.4	31.0	32.4	33.7	0.3	−1.0	0.93
Singapore	0.0	0.0	0.0	0.0	0.0	0.0	0.00
Thailand	176.0	287.1	327.9	313.3	6.9	−25.2	3.90
Timor-Leste	0.0	0.0	0.0	0.0	0.0	0.0	0.00
Viet Nam	170.0	273.1	344.2	385.2	10.8	−39.5	6.33
Total	1010.9	1260.4	1502.9	1532.0	26.0	−95.5	2.58
Total forests	20,450.1	20,049.3	19,505.1	19,057.5	−69.6	255.3	−0.34

TgC= teragrams of carbon, $TgCO_2$ = teragrams of carbon dioxide
Source Authors' own calculations

4.3.3 Forest Management and Plantation Forestry

In this study, forest management focuses on the use of selective logging for commercial timber production in PF, whilst plantation forestry focuses on the use of clear-cut system timber management in plantation forests over a management cycle of

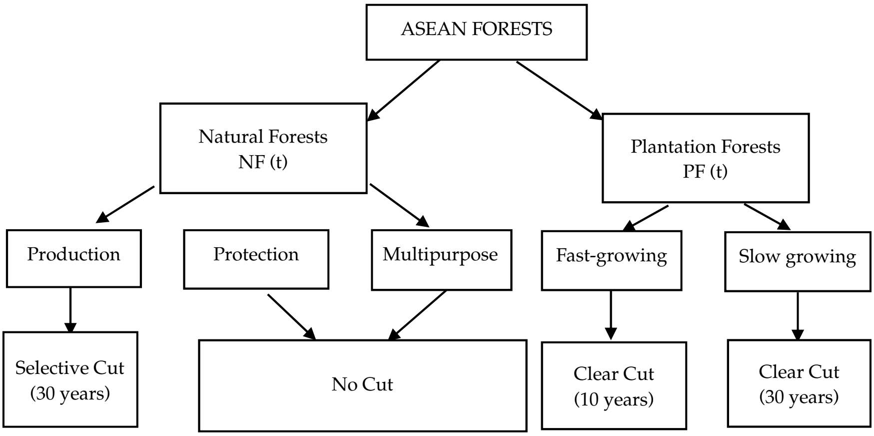

Fig. 4.1 Schematic diagram showing the forest types and management systems considered in this study. *Source* Authors' own illustration

the respective forest types. A selective logging system is applied mostly in natural forests, whilst a clear-cutting system is applied dominantly in the plantation forests in Southeast Asia (FAO 2006). In the tropics, selective logging usually has a selective cutting cycle of 30 years for natural forests (Piponiot et al. 2019a, b; Kim Phat et al. 2004), whereas productive fast-growing plantation yields export-quality timber approximately after 10 years of planting (Cossalter and Pye-Smith 2003). A previous study suggested that the cutting cycle for fast-growing *Eucalyptus* plantation should be between 10 and 15 years (Zhou et al. 2017), whilst another study found that the cutting length of fast-growing *Eucalyptus* spp. could be less than 15 years (Sands 2013) or be even 10 years (Sasaki et al. 2009). Thus, the present study assumes that the cutting cycle of fast-growing plantation is 10 years, whilst that of slow-growing plantation is 30 years. Both selective cutting and clear-cut systems are applied to production forests of the natural and plantation forests, respectively. No cutting is considered to occur in the protection and multipurpose forests (Fig. 4.1).

4.3.4 Forest Land Use Model

Although we recognised that an increase in the area of plantation forests could be due to tree planting on abundant lands (Stolle and Dennis 2007), for simplicity in this study, we assumed that the increase in PF was due to the new planting of trees on the deforested lands. With this assumption and based on the data in Table 4.4, a fraction (a) of the loss of NF is replaced by PF, whilst the remaining fraction (b) become other types of land use but not forest. Of the fraction b, 40.7% is planted with fast-growing species (*Acacia* spp. and *Eucalyptus* spp.) (Dar and Sundarapandian 2015; Pearson et al. 2017) and the remaining 59.3% goes to the slow-growing native species. The

Table 4.5 Total area of natural forests and plantation forests in Southeast Asia

Year	Natural forest (M ha)	Plantation forest (M ha)	Total (M ha)
2000	212.1	9.5	221.6
2010	205.0	11.1	216.1
2015	195.6	13.1	208.7
2020	190.2	12.9	203.1
Annual change ('000 ha)			
2000–2020	−1095.3	172.7	−922.6
2010–2020	−1480.0	180.1	−1299.9
2015–2020	−1082.4	−27.0	−1109.4
Annual change (%)			
2000–2020	−0.52%	1.82%	−0.42%
2010–2020	−0.72%	1.62%	−0.60%
2015–2020	−0.55%	−0.21%	−0.53%

M ha = Million hectares
Source Authors' own calculations
Note The rates of change in Table 4.3 were calculated from the data published in FAO (2020)

modelling timeframe for this study is between 2000 and 2030, the ending period of the Paris Agreement. Accordingly, areas of NF and PF can be predicted using the equation below, following Kim Phat et al. (2004).

$$\frac{\mathrm{dNF}(t)}{\mathrm{d}t} = (a + b) \times \mathrm{NF}(t) \tag{4.1}$$

$$\frac{\mathrm{dPF}(t)}{\mathrm{d}t} = a \times \mathrm{NF}(t) \tag{4.2}$$

where NF(t) and PF(t) are natural and plantation forests at time t (ha), $(a + b)$ is the rate of change of natural forest (%), and a is the rate of change from natural forest to plantation forest (%). Data obtained from Table 4.1 are used to calculate $a + b$ and a by performing a linear regression using data in Table 4.5. Accordingly, we obtained the parameter value for $(a + b) = -0.00556$ (0.6% decline) and the initial value of NF($t0$) = 213,463,612.5 ha ($R^2 = 0.957$). a and the initial values of PF were obtained by solving the Eqs. (4.1) and (4.2) ($a = 0.00086$, PF($t0$) = 9,494,250.0 ha).

4.3.5 Carbon Balance Model

Forest carbon stocks are affected by timber harvesting, natural regeneration, growth, and mortality (Zubizarreta-Gerendiain et al. 2016). The carbon balance in Southeast Asian forests between 2000 and 2030 can be estimated by:

$$CB(t) = TCS_{NF}(t) + TCS_{PF}(t) \tag{4.3}$$

$$\text{Carbon Loss or Gains} = CB(t_2) - CB(t_1) \tag{4.4}$$

where CB(t) is the carbon balance in Southeast Asian forests at time t, $TCS_{NF}(t)$ is the total carbon stock in natural forests at time t, and $TCS_{PF}(t)$ is the total carbon stock in plantation forests at time t.

4.3.5.1 Harvesting Approach in Natural Forests

According to the FAO (2020), production forests account for 41.5% (84.4 million ha), whilst protection and multipurpose forests make up 42.4% (93.5 million ha) and 16.1% (29.5 million ha), respectively. In natural forests, timber harvesting can only take place in production forests because cutting is not allowed in the remaining protection and multipurpose forests. Production forests are the forests where commercial logging can take place over the 30-year cutting cycle. Depending on the forest types, the exploitable diameter limit is fixed and all trees that reach this limit are selected for logging. Carbon stocks in production forests (=NF * 0.407) can be assessed through Sasaki et al. (2016a, b).

$$\frac{dCS_{NF}(t)}{dt} = MAI - LM_{NF}(t) - H_{NF}(t) \tag{4.5}$$

$$H_{NF}(t) = \frac{f_M \times f_H}{1 - i} \times \frac{CS_{NF}(t)}{T_c} \tag{4.6}$$

$$TH_{NF}(t) = H_{NF}(t) \times NF(t) \times 0.407 \tag{4.7}$$

$$TCS_{NF}(t) = \frac{CS_{NF}(t) \times NF(t)}{1{,}000{,}000} \tag{4.8}$$

where $CS_{NF}(t)$ is the carbon stock of NF at time t (MgC ha^{-1}), MAI is the mean annual increment (0.66 MgC ha^{-1} $year^{-1}$), $LM_{NF}(t)$ is the logging mortality calculated as the proportion of the $H(t)$ (MgC ha^{-1}), and $H_{NF}(t)$ is the harvested carbon at time t (MgC ha^{-1}). f_M is mature trees for harvest ($f_M = 0.43$), f_H is trees allowed to be harvested ($f_{H=}$ 0.3), i is the illegal logging rate ($i = 0.5$), and T_c is the cutting cycle (30 years); 0.407 or 40.7% is the proportion of the area of production forests in the natural forests. Initial values and parameters for Eqs. 4.5 and 4.6 were adapted from Sasaki et al. (2016a, b). The average carbon stock (aboveground and belowground) is 92.2 MgC ha^{-1}. $TH_{NF}(t)$ is the total harvested carbon (MgC), and $TCS_{NF}(t)$ is the total carbon stock remaining on the production forest at time t (TgC, or million tonnes carbon); the value 1,000,000 is the conversion factor from MgC to TgC.

4.3.5.2 Harvesting Approach in Plantation Forests

The management of PF is important to ensure that trees continue to grow with high commercial values for the final cut. Although trees grow faster in PF (Sasaki et al. 2009), the growth rate declines if management interventions are not implemented. The carbon stock in plantation forests ($CS_{PF}(t)$) is set to be equivalent to the average carbon stock in plantation forests in Southeast Asia, 44.5 MgC ha^{-1} (FAO 2020).

Accordingly, the carbon stocks in PF when a cutting cycle is applied can be calculated by (Sasaki et al. 2016a, b):

$$H_{PF}(t) = \frac{CS_{PF}(t)}{T_c} \tag{4.9}$$

$$TH_{PF}(t) = \frac{CS_{PF}(t)}{T_c} \times PF(t) \tag{4.10}$$

$$TCS_{PF}(t) = \frac{CS_{PF}(t) \times PF(t) - TH_{PF}(t)}{1{,}000{,}000} \tag{4.11}$$

where $H_{PF}(t)$ is the harvested carbon in PF at time t (MgC ha^{-1}), T_c is the cutting cycle (10 years for fast-growing plantations and 30 years for slow-growing plantations), and $TH_{PF}(t)$ is the total harvested carbon (MgC). $TCS_{PF}(t)$ is the total carbon stock remaining on the PF at time t (TgC, or million tons carbon); 1,000,000 is the conversion factor from MgC to TgC. The average carbon stock for all plantation forests in Southeast Asia was estimated at 55.6 MgC ha^{-1} (FAO 2020). This number is used in this study for both fast-growing and slow-growing plantation forests.

4.4 Results and Discussions

4.4.1 Changes in Forest Area in Southeast Asia (2000–2030)

The forest land use model indicates that the area of NF is expected to decline from 213,463,613 ha in 2000 to 180,702,267 ha in 2030, representing an annual loss of 1,092,045 ha, or 0.51%, between 2000 and 2030. Over the same period, the area of plantation forests is expected to increase to 14,568,812 ha in 2030 from 9,494,250 ha in 2000, representing an increase of 169,152 ha year^{-1} or 1.78%. Since the loss of natural forests is compensated by the increase in forest plantation, the total net loss of forests in Southeast Asia is 922,893 ha or −0.41% between 2000 and 2030. The total area of natural and plantation forests is predicted to decline to 195,271,079 ha in 2030 if the current trend of forest cover change continues (Fig. 4.2).

Between 2000 and 2020, our model predicted the loss of natural forests at 1,122,074 ha year^{-1} or −0.53% (Table 4.6). This is similar to the rate of loss reported by the FAO (2020) over the same period (1,095,281 ha or 0.52%). Using satellite

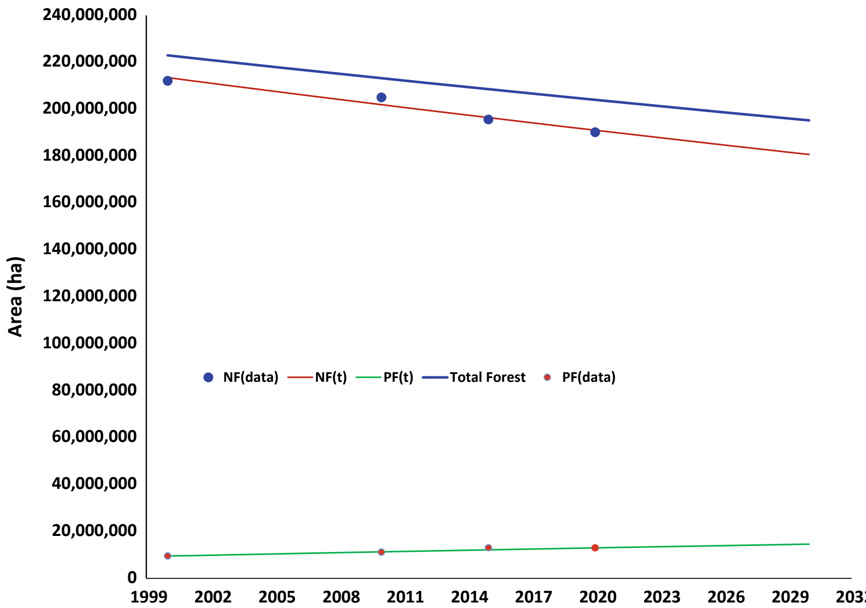

Fig. 4.2 Changes in the area of natural and plantation forests in Southeast Asia, 2000–2030. NF = natural forests, PF = plantation forests.. *Source* Authors' own calculations and graph

Table 4.6 Annual loss of forest cover in Southeast Asia

Duration	Natural forests			Plantation forests			Grand total
	PdF	PrF	Total	PF_Slow	PF_Fast	Total	
Area (ha year^{-1})							
2000–2020	−456,684.1	−665,389.9	−1,122,074.1	103,065.4	70,738	173,803.4	−948,271
2000–2030	−444,462.3	−647,582.6	−1,092,044.9	100,307.2	68,845	169,152.1	−922,893
2020–2030	−420,018.5	−611,967.9	−1,031,986.4	94,790.6	65,059	159,849.3	−872,137
Change (% year^{-1})							
2000–2020	−0.53%	−0.53%	−0.53%	1.83%	1.83%	1.83%	−0.31%
2000–2030	−0.51%	−0.51%	−0.51%	1.78%	1.78%	1.78%	−0.30%
2020–2030	−0.54%	−0.54%	−0.54%	1.23%	1.23%	1.23%	−0.31%

ha = hectare, PdF = production forests, PF_Fast = fast-growing plantation forests, PF_Slow = slow-growing plantation forests, PrF = protection forests
Source Authors' own calculations

imagery, Stibig et al. (2014) found the loss of forests in Southeast Asia to be 0.59% between 2000 and 2010, or just about 0.06% higher than our prediction over the same period.

Since the loss of natural forests is compensated by the increase in plantation forests, the net loss of forest cover in Southeast Asia is therefore 948,271 ha (2000–2020), 922,893 ha (2000–2030), or 872,137 ha (2020–2030).

4.4.2 Timber Production from Natural and Plantation Forests

Our model suggests that timber production from selective logging in the production forests was 84.9 million m^3 in 2000 but will decline to 63.0 in 2030 with a decline rate of 0.86%. Chan (2016) reported that Southeast Asia produced about 85.6 million m^3 in 2012. The decline of timber production in production forests may be due to illegal logging and logging damages under the current logging practices. On the other hands, timber production from plantation forestry continues to increase as more trees are planted. Timber production from fast- and slow-growing plantations increases to 56.6 million m^3 and 27.5 million m^3 in 2030, respectively, representing an increase of 1.8% annually between 2000 and 2030 (Fig. 4.3). Based on limited data, Thailand,

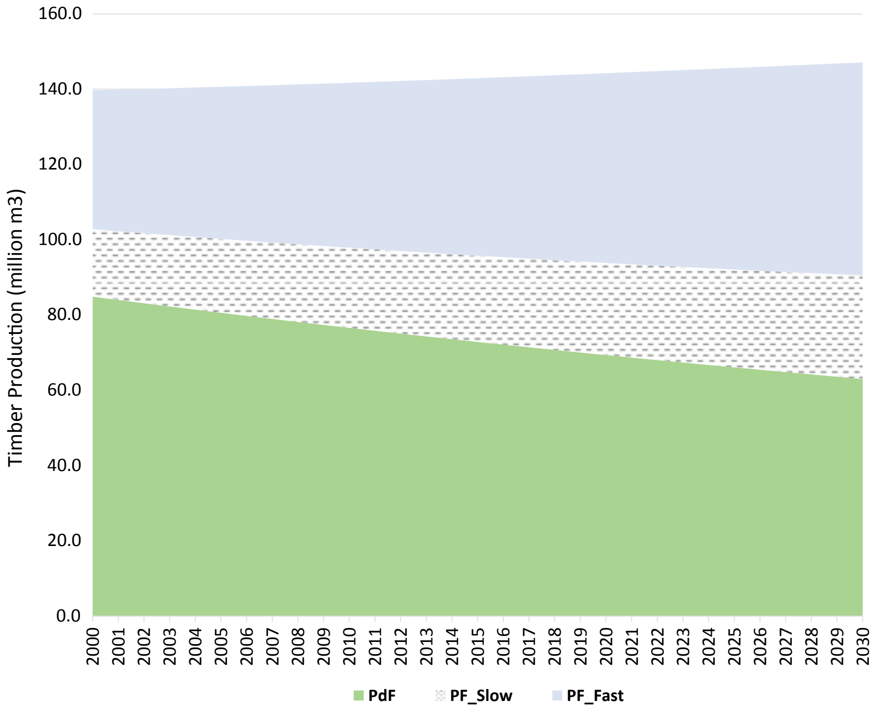

Fig. 4.3 Timber production from natural forests (production forests, PdF) and plantation forests (Slow-growing, PF_Slow; and Fast-growing, PF_Fast). *Source* Authors' own calculation and graph

Indonesia, Malaysia, the Philippines, and Viet Nam produced 34.7 million m^3 of roundwood from industrial plantations in 2012 (Jürgensen et al. 2014). Since not all data are reported, data in official documents produced by governments seem to underestimate the actual amount of timber production in the region. During the Paris Agreement period (2020–2030), the average timber production is 66.1 million m^3, 53.5 million m^3, and 26.0 million m^3 from production, fast-growing, and slow-growing plantations, respectively. Totally, about 143 million m^3 of timber can be produced from Southeast Asian forests between 2000 and 2030.

4.4.3 Carbon Loss and Gain in Southeast Asia

More specifically, carbon stocks in production and protected forests decrease from 8006.18 TgC and 11,665.02 TgC in 2000 to 5945.0 TgC and 9874.7 TgC in 2030, whereas carbon stocks in fast-growing and slow-growing forest plantations increase from 242.2 TgC and 154.7 TgC in 2000 to 371.6 TgC and 237.5 TgC in 2030, respectively. Due to deforestation, Southeast Asia's production and protected forests decline by 73.1 TgC $yr^{-1}$and 61.3 TgC yr^{-1} between 2000 and 2020, 68.7 TgC yr^{-1} and 59.7 TgC yr^{-1} between 2000 and 2030, respectively. During the Paris Agreement period, mean annual decreases in carbon stocks from production and protected forests were estimated at 59.8 TgC yr^{-1} and 56.4 TgC yr^{-1}, respectively. On the other hand, the average annual increase in the carbon stocks of fast- and slow-growing plantations was estimated at 4.1 TgC yr^{-1} and 2.6 TgC yr^{-1}, respectively, over the implementation period of the Paris Agreement (Fig. 4.4).

The total carbon stock in Southeast Asia's natural forests was 20,450.1 TgC in 2000, representing about 10% of the total carbon stock in global forests, but this declined to 17,525.6 TgC in 2020. Annually, Southeast Asia emits approximately 368 $TgCO_2$ $year^{-1}$ due to land use change and deforestation during the modelling period (2000–2030). In percentage terms, Cambodia and Indonesia have the highest loss of carbon stocks (1.51% and 1.50%, respectively), altogether emitting about 217.7 $TgCO_2$ $year^{-1}$ over the same period (Table 4.7).

4.4.4 Carbon Emissions and Removals Due to Deforestation, Logging, and Forestry Plantation

Our models suggest that logging and deforestation result in carbon emissions of 14,526.8 $TgCO_2$ over the modelling timeframe of 2000–2030, of which 65.9% are carbon emissions in production forests (PdF) and the remaining 42.1% are due to deforestation in protected and multipurpose forests (PrF) (Fig. 4.5). Average carbon emissions from logging and deforestation in natural forests are 484.2 ± 41.2 $TgCO_2$

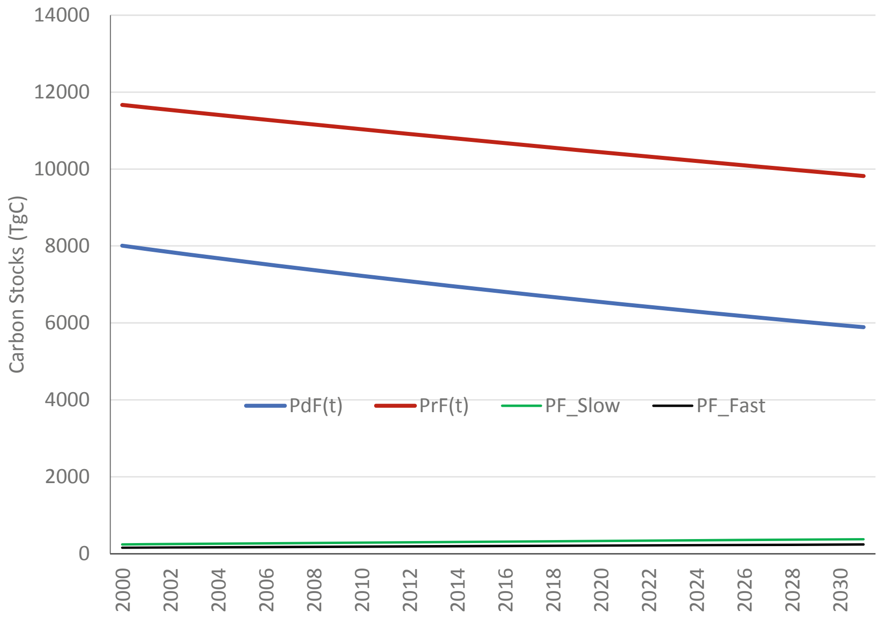

Fig. 4.4 Carbon stock changes in forests in Southeast Asia by forest type. PdF = production forests, PF_Fast = fast-growing plantation forests, PF_Slow = slow-growing plantation forests, PrF = protection forests, TgC = teragrams of carbon. *Source* Authors' own calculation and graph

Table 4.7 Carbon loss and gain in total forests in Southeast Asia, 2000–2030

Duration	Natural forests			Plantation forests			Balance
	PdF	PrF	Total	PF_Slow	PF_Fast	Total	
	Annual carbon loss (TgC)			Annual carbon gain (TgC)			
2000–2020	−73.1	−61.3	−134.5	4.4	2.8	7.3	−127.2
2000–2030	−68.7	−59.7	−128.4	4.3	2.8	7.1	−121.3
2020–2030	−59.8	−56.4	−116.2	4.1	2.6	6.7	−109.5
	Rate of loss (%)			Rate of gain (%)			
2000–2020	−0.91%	−0.53%	−1.44%	1.83%	1.83%	3.66%	−0.63%
2000–2030	−0.86%	−0.51%	−1.37%	1.78%	1.78%	3.56%	−0.60%
2020–2030	−0.91%	−0.54%	−1.45%	1.23%	1.23%	2.46%	−0.63%

PdF = production forests, PF_Fast = fast-growing plantation forests, PF_Slow = slow-growing plantation forests, PrF = protection forests, TgC = teragrams of carbon
Source Authors' own calculation

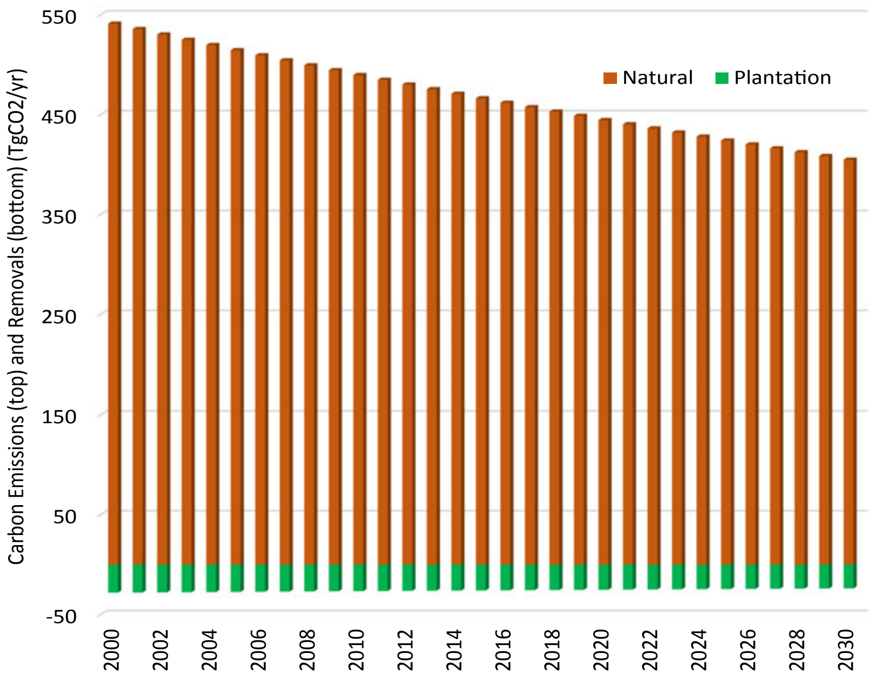

Fig. 4.5 Carbon emissions and removals in Southeast Asia, 2000–2030. $TgCO_2$ = teragrams of carbon dioxide. *Source* Authors' own calculation and graph

year^{-1} (±refers to standard deviation) or about 23.0% of emissions from tropical deforestation (Pearson et al. 2017). Total carbon emissions during the Paris Agreement period (2020–2030) are 4666.4 $TgCO_2$, or 424.2 $TgCO_2$ year^{-1}.

The 424.2 $TgCO_2$ year^{-1} emissions could be set as the FREL for Southeast Asia, against which performance under the REDD+ implementation can be compared, and the result-based payment can be claimed under the REDD+ scheme. If Southeast Asia can reduce carbon emissions by 50% of the FREL and with a carbon price of US$10 (assumed with reference to the World Bank (2020)), it could generate carbon revenues of US$2.1 billion annually during the Paris Agreement period. Since plantation forests are also sequestering carbon (801.7 $TgCO_2$ in total), resulting in carbon emissions of 24.4 $TgCO_2$ year^{-1}, Southeast Asia is eligible to claim for additional revenues of US$244.0 year^{-1} under the enhancement of carbon stocks of the REDD+ scheme during the Paris Agreement. Given that the region can also produce timber from production forest and plantation forests (Fig. 4.3), carbon revenues under the REDD+ scheme can provide good incentives for better use and management of the forest resources in Southeast Asia. As forests are also important sources of many other ecosystem services, Southeast Asia should be committed to sustainable forestry, otherwise it will face the loss of natural forests and the related consequences.

4.5 Conclusion and Policy Recommendations

Using data from the FAO's FRA 2020 along with models of land use change and forestry, this study estimated the changes in forest cover, timber production, carbon stocks, changes, carbon emissions, and removals in Southeast Asia by forest type (natural and plantation forests) and individual country between 2000 and 2030.

Our study indicates that natural forests in Southeast Asia will continue to decline over a 30-year period, losing about 1.1 million ha annually, or about 0.51%. However, part of the loss is replanted by fast-growing and slow-growing tree species, whose total area will increase by about 169,152.1 ha annually over the same period. In terms of timber production, Southeast Asia's production forests supplied 84.9 million m^3 of timber in 2000, but the timber volume will decline to 63.0 m^3 in 2030. Unlike natural forests, timber supply from fast- and slowing-growing plantations is expected to increase to 56.6 million m^3 and 27.5 million m^3, respectively, by 2030, suggesting that the future supply of timber will be from plantation forests. Loss of natural forests is responsible for 23% of the global carbon emissions from tropical deforestation. If Southeast Asia uses a retrospective approach for determining the FREL, this study estimates for the region 424.2 $TgCO_2$ $year^{-1}$ during the implementation of the Paris Agreement. On the other hand, plantation forests sequester about 25.9 $TgCO_2$ $year^{-1}$. With a carbon price of US$10 per $MgCO_2$, total revenue under the REDD+ scheme for Southeast Asia is estimated at US$2.4 billion annually.

Our study found that forest plantations play an important role in timber supply as well as carbon sequestration. Our study also found that only 8,473,200 ha of forest area gain is achieved by plantations, representing 15% of natural forest area losses. If governments slightly increase this figure to 20% or some quantity, they can achieve more timber supply and carbon sequestration in future. Our results for the FREL could be used by Southeast Asian governments as a benchmark for their emission reductions during the Paris Agreement. Nevertheless, if policies and enforcement mechanisms to control unstainable logging practices and illegal logging are not introduced, Southeast Asia's production forests will continue to be degraded until mature trees are completely harvested, resulting in a decline of timber production from the natural forests. Eventually, such deforested forests would be subject to clearing for other purposes with short-term returns. It is important that governments in Southeast Asia work together to reduce illegal logging and forest clearing whilst managing the increasing plantation forests for timber supply and emission reductions and removals whilst safeguarding the local culture and environment. Southeast Asia should ensure that the deforestation rate is reduced as much as possible, whilst the management of plantation forests should be done with the utmost care to prevent possible social and environmental destruction of the local environment and biodiversity as the inappropriate selection of tree species to be planted could make the situation better or worse.

Acknowledgements This research paper was carried out under funding from the Economic Research Institute for ASEAN and East Asia.

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Chapter 5
ASEAN Energy Landscape and Emissions: The Modelling Scenarios and Policy Implications

Han Phoumin, Fukunari Kimura, and Jun Arima

Abstract The Association of Southeast Asian Nations (ASEAN) faces tremendous challenges regarding the future energy landscape and how the energy transition will embrace a new architecture—including sound policies and technologies to ensure energy access together with affordability, energy security, and energy sustainability. Given the high share of fossil fuels in ASEAN's current energy mix (oil, coal, and natural gas comprise almost 80%), the clean use of fossil fuels through the deployment of clean technologies is indispensable for decarbonising ASEAN's emissions. The future energy landscape of ASEAN will rely on today's actions, policies, and investments to change the fossil fuel-based energy system towards a cleaner energy system, but any decisions and energy policy measures to be rolled out during the energy transition need to be weighed against potentially higher energy costs, affordability issues, and energy security risks. This paper employs energy modelling scenarios to seek plausible policy options for ASEAN to achieve more emissions reductions as well as energy savings, and to assess the extent to which the composition of the energy mix will be changed under various energy policy scenarios. The results imply policy recommendations for accelerating the share of renewables, adopting clean technologies and the clean use of fossil fuels, and investing in climate-resilient energy quality infrastructure.

Keywords Business as usual (BAU) · Alternative policy scenarios (APSs) · Energy transition · Renewables · Clean technologies · Fossil fuels · Resiliency

JEL Codes O21 · Q20 · Q30 · Q40 · Q50

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H. Phoumin et al. (eds.), *Energy Sustainability and Climate Change in ASEAN*, Economics, Law, and Institutions in Asia Pacific,
https://doi.org/10.1007/978-981-16-2000-3_5

5.1 Introduction

At the time of writing, the world has been struggling with the coronavirus disease (COVID-19) pandemic, which has damaged the world economy—including the Association of Southeast Asian Nations (ASEAN). The global economy is being pushed into a recession by the COVID-19 pandemic due to preventive and containment measures such as country lockdowns, travel restrictions, and slow or even negative growth in many sectors such as tourism, retail, and industry. The magnitude of the economic impacts is hard to predict as it depends on the success of the pandemic containment efforts around the world. The International Monetary Fund (IMF) projected the world economy and the ASEAN 5 (Indonesia, Malaysia, the Philippines, Singapore, and Thailand) to contract sharply by –4.9% and −2.5% respectively in 2020, much worse than during the 2008–2009 financial crisis (IMF 2020). Such an economic downturn is contracting energy demand and energy-related carbon dioxide (CO_2) emissions around the globe, but this crisis is seen as temporary and both energy demand and CO_2 emissions will bounce back once the economy starts to recover. Global energy demand increased 10 times from 1999 to 2019, and keeps increasing (IEA 2017. The gravity of energy demand has shifted to Asia, and emerging economies account for half of global growth in gas demand. Many of the Organisation for Economic Co-operation and Development (OECD) countries will see energy demand peak, while some countries will experience negative growth due to energy efficiency and other factors such as population growth and industrial structures. However, ASEAN will be the opposite, as it will need more energy to steer its economic growth.

ASEAN will see strong growth in fossil fuel demand to steer economic growth from 2017[1] to 2050. Fossil fuels (oil, coal, and gas) had the dominant share in the primary energy mix in 2017, at 78.0%, while their combined share is projected to increase to 81.7% in 2050 (Annex Tables 5.1, 5.2, 5.3, 5.4, 5.5, 5.6, 5.7, 5.8). Oil will be the largest energy source in the primary energy mix in 2050, at 39.6%, down from 36.9% in 2017. Coal was the second largest energy source after oil in 2017, at 21.6%, and is projected to have a 22.4% share in 2050. Natural gas is projected to have the second largest share of the primary energy mix in 2050, at 24.7%, overtaking coal.

In ASEAN, for the business-as-usual (BAU) scenario, oil was the main source of energy in the industry and transport sectors, at 30.8% and 26.8% respectively, in 2017 (Annex Tables 5.1, 5.2, 5.3, 5.4, 5.5, 5.6, 5.7 and 5.8). However, oil will have the largest share in the transport sector in 2050, at 35.6%, followed by industry, at 33.4%. Total power generation is projected to grow by 3.7% per year on average from 1041 terawatt-hours (TWh) in 2017 to 3439 TWh in 2050. Gas had the largest share of power generation in 2017, at 39.7%, and is projected to retain its spot in 2050, at 46.0%. Coal provided 36.6% of power generation in 2017, the second largest share after gas, but is projected to decrease to 35.5% in 2050. The share of hydropower was 17.6% in 2017, but is projected to drop to 10.4% in 2050 as hydropower resources

[1]The energy modelling uses 2017 for the baseline information as it is the most up-to-date baseline data in the ASEAN Member States (AMS).

are tapped to their potential. Geothermal energy had a 2.2% share in 2017 which is projected to decline to 2.1% in 2050. The remaining share (wind, solar, and biomass) was 1.4% in 2017, rising to 5.4% in 2050. However, in the alternative policy scenarios (APSs),[2] the share of solar, wind, and biomass is projected to reach 12.3%. Further, under the APS using the emission target of reducing emission by 80% in 2050, the share of solar, wind, and biomass will rise to 17.8% in 2050.

While the world, especially the OECD, moves away from fossil fuel dependence to a system based on cleaner energy through a higher share of renewables, ASEAN needs to consider how to use fossil fuels more cleanly in an energy transition. For instance, coal use has been drastically reduced in the OECD and more developed countries due to the role of gas, renewables, and advanced technologies. However, as the most abundant and reliable energy resource in ASEAN, coal use will continue to be the second largest energy source in power generation after gas in the foreseeable future, to meet fast-growing electricity demand. The increase in coal use for power generation in ASEAN countries will lead to the widespread construction of coal-fired power plants, which will result in increased greenhouse gas (GHG) and CO_2 emissions if the best available clean coal technology (CCT) is not employed (Phoumin 2015).

Meanwhile, the climate narrative which has prevailed since the Conference of the Parties (COP) 21 in 2015 and is likely to continue at the upcoming COP 26, promotes the banning of public coal financing throughout the world, through financial instruments and influence over multilateral development banks and OECD member countries. Actions taken to abate CO_2 and GHG emissions have gained momentum in the developed world, especially the OECD, but developing nations cannot afford the available technologies to reduce such emissions. Further, China is leading the financing of coal-fired power plants in the developing world as it is not bound by the OECD's rules and obligations to ban coal financing. If not paired with more sustainable energy development, it is a real concern that increasing coal use in emerging Asia will have negative effects on the region's environmental security. With the projected increase in coal-fired generation capacity, both local pollutants—CO_2 and GHG emissions—will become major issues in the future. Based on the Greenhouse Gas Emissions Data (United States Environmental Protection Agency 2020), emissions from fossil fuel combustion and industrial processes contributed about 78% of the increase in GHG emissions from 1970 to 2011. China, the United States (US), Europe, and India are the largest emitters, contributing 30%, 15%, 9%, and 6% of global GHG emissions, respectively. With substantial new generation capacity required to generate power, unabated coal-fired power generation plants are increasingly being constructed in developing Asia. These trends reflect the urgent need to address the environmental sustainability of powering emerging Asia's economic development.

Managing the energy transition in ASEAN will need to consider the presence of fossil fuels (coal, oil, and natural gas) in the short- and medium-term energy system. It will be crucial to explore ways in which to use fossil fuels in an environmentally

[2] 'APSs' refers to all scenarios [the APS and scenarios 1 to 3 (APS_RE, APS_EI, and APS_EmT)].

sustainable manner to act as a bridge to a carbon-free energy future, rather than simply ruling out them completely. For successful implementation of the energy transition and climate change policy objectives, policymakers will need to balance the other equally important policy objectives of energy security, energy access, and affordability. For instance, the policy blind of banning public financing of CCT could be counterproductive in terms of climate mitigation since the lack of finance for highly efficient but more expensive CCT would simply result in the deployment of cheaper and less efficient technologies such as critical or subcritical technology of coal-fired power plants and more CO_2 emissions.

ASEAN's shift towards a cleaner energy system will have fundamental impacts on environmental sustainability. The pace at which ASEAN Member States (AMS) have adopted national power development plans and policies has created a drastic change in the energy system, as more renewables have penetrated the electrical grid. One of the greatest challenges of increasing the share of variable renewable energy (e.g. wind and solar) in the power mix is the high cost of upgrading and integrating the systems that need more investment in grids, the internet of things, technological know-how, and quality energy infrastructure. Creating a bridge from the current energy system to a cleaner energy system will need to consider the role of cleaner use of fossil fuels and the innovative technologies that can reduce CO_2 and GHG emissions. Therefore, urgent steps need to be taken to decarbonise the energy sector through pathways to a low-carbon economy which require the rapid deployment of the clean use of fossil fuel technologies, renewable energy development, and a doubling of energy efficiency, given that the energy sector accounts for two-thirds of global GHG emissions. Thus, policy towards energy security and affordability will need to be flexible, considering the role of fossil fuels in an energy transition. To meet the growing energy demand, appropriate energy policies and cooperation are needed to facilitate energy-related infrastructure investments. These common energy challenges need to be addressed through concerted efforts—including collective measures and actions—to rapidly deploy energy efficiency and energy savings, highly efficient and low-emissions coal-fired power plant technology, and nuclear safety; and to double the share of renewable energy in the overall energy mix for inclusive and sustainable development.

The objective of this study is to explore the best energy mix under various APSs and the associated emissions. Under the APS, key considerations are realistic assumptions in terms of technologies, resource endowment, energy efficiency, and system integration challenges, when the power generation mix has a higher share of intermittent renewables such as wind and solar energy. The paper is organised as follows. Section 5.2 reviews the literature, Sect. 5.3 discusses the research methodology, Sect. 5.4 describes the results and discussion, and Sect. 5.5 concludes and presents the policy implications.

5.2 Literature Review

5.2.1 Global Commitment to Emissions Reduction (COP 21)

The Paris Agreement, negotiated at the Paris Climate Conference (COP 21), is the first universal legally binding global climate change agreement, adopted by the majority of leaders on 22 April 2016. It aims to limit the average temperature rise to well below 2 °C above pre-industrial levels (baseline: 1850–1900) and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognising that this would significantly reduce the risks and impacts of climate change (EU 2020).

Bridging the gap from current policies and actions to climate neutrality by the end of this century is very challenging. The world will need to reduce emissions by 7.6% per year from 2020 to 2030 to limit global warming to 1.5 °C. If we do nothing, temperatures are expected to rise 3.2 °C above pre-industrial levels by the end of century—posing a serious threat to our living environment (UNEP 2019). If emissions cuts are delayed, it will become very difficult to meet the limit of a global temperature rise of well below 1.5 °C by 2100. UNEP (2019) stated that delaying emissions cuts until 2025 would steepen the need to cut emissions to 15.5% per year, which would be extremely difficult to achieve, especially for the developing world. As parties to the Paris Agreement, countries have submitted comprehensive national climate action plans known as Nationally Determined Contributions (NDCs). Some countries have not yet finalised their NDCs, but have carried out preparatory work known as Intended Nationally Determined Contributions (INDCs).

About 78% of all global emissions come from G20 nations, requiring their strong commitment to long-term zero emissions targets by 2100. Amongst the G20 nations, China, the US, the European Union (EU) 28,[3] and India contributed more than 55% of the total emissions over the last decade (UNEP 2019). Thus, the speed of emissions reduction is very concerning, and full decarbonisation of the energy sector may go beyond renewables and energy efficiency. The carbon sinks will rely on the clean use of fossil fuels with carbon capture, utilisation, and storage (CCUS). Developing countries may face difficulties in achieving emissions reduction targets without international support, such as technologies for the clean use of fossil fuels and the other climate abatement initiatives. However, their emissions contribution remains small compared with that of the G20 nations. Developing nations can contribute more in terms of the conservation of natural resources such as forestry and the management of improved agricultural practices.

[3]The EU 28 refers to the 28 countries which were members of the EU until 31 January 2020 when the United Kingdom left the group (Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovenia, Slovakia, Spain, Sweden, and United Kingdom).

5.2.2 ASEAN and EU Energy Policy Directions

Phase 2 of the ASEAN Plan of Action for Energy Cooperation (APAEC), which is under preparation for endorsement by the ASEAN Ministers on Energy Meeting in 2020, will set key energy policy targets and will have energy policy implications for energy infrastructure related investment in the region (ASEAN Centre for Energy 2020). Key targets include the revision of the new energy efficiency and conservation target from a 30% reduction in energy intensity by 2025 (based on 2005 levels) to more ambitious levels—a new target of 35–40% reduction is likely—and will involve the expansion of energy efficiency and conservation measures to transport and industries. It will also establish a new sub-target for the share of renewables in installed power capacity, which will complement the existing target of a 23% share of renewables in the total primary energy supply (TPES) by 2025. APAEC Phase 2 will also include policy measures to pursue smart grids and renewable energy grid integration; and measures to address emerging and alternative technologies such as hydrogen, energy storage, bioenergy, nuclear energy, and CCUS. APAEC Phase 2 will maintain the focus on energy connectivity and market integration, but will add a sub-theme on the energy transition and energy resilience on how the region will need to have a strategy to deal with fossil fuels and new technologies.

The ASEAN region has wide economic development gaps in terms of gross domestic product (GDP), population growth, energy use, and technologies. However, each country is committed to addressing the common climate change issue. Countries share their commitments through various policies such as energy intensity targets or through targets for the share of renewables in the energy mix. Nevertheless, emerging countries face energy access and affordability issues, while promoting renewables and other clean energy technologies remains expensive. Although solar and wind module costs have dropped drastically, the system cost remains expensive when applied in developing countries. Making these clean and green technologies available to developing countries in ASEAN will require policy attention, including regulations and financing mechanisms, with support from developed countries.

The EU aims to be climate neutral by 2050 (EU 2020). Amongst other targets, the 2030 climate and energy framework includes EU-wide targets and policy objectives for 2021–2030. The key targets for 2030 include (i) at least 40.0% cuts in GHG emissions from 1990 levels, (ii) at least a 32.0% share for renewable energy, and (iii) at least a 32.5% improvement in energy efficiency. For GHG emissions, a cut of at least 40.0% below 1990 levels is targeted by 2030. This will enable the EU to move towards a climate-neutral economy and implement its commitments under the Paris Agreement. For renewables, the binding renewable energy target for the EU for 2030 is at least 32.0% of final energy consumption, including a review clause by 2023 for an upward revision of the target. For energy efficiency, a headline target of at least 32.5% is to be achieved collectively by the EU in 2030, with an upward revision clause by 2023. To help achieve these targets, a transparent and dynamic governance process will help deliver on the 2030 climate and energy targets in an efficient and coherent manner. The EU has adopted integrated monitoring and reporting rules to ensure progress towards its 2030 climate and energy targets and its international commitments under the Paris Agreement.

5.2.3 Review of INDCs' Emissions Reduction Commitments and Targets by ASEAN Member States

COP 21 was a very successful conference, at which leaders around the globe showed their solidarity in fighting global climate change. Countries laid out targets or programmes aimed at reducing CO_2 emissions. Some countries have clear policies and targets, while others have no targets—especially developing countries. In the AMS, the key commitments are varied, reflecting each country's socio-economic and environmental situation. The following paragraphs summarise the key commitments of AMS for mitigating climate change (Kimura and Phoumin 2018).

Cambodia proposes a GHG mitigation contribution for 2020–2030 (UNFCCC 2015), conditional on the availability of support from the international community. Cambodia is expected to contribute a maximum reduction of 3100 gigagrams of carbon dioxide equivalent ($GgCO_2eq$) by 2030 compared with 2010 baseline emissions of 11,600 $GgCO_2eq$. The Lao People's Democratic Republic (Lao PDR) is a highly climate-vulnerable country whose GHG emissions were only 51,000 $GgCO_2eq$ in 2000—negligible compared with total global emissions. The Lao PDR has ambitious plans to reduce its GHG emissions through increased carbon stock by expanding forest cover to 70% of the country's land area by 2020. The Lao PDR electricity grid draws on renewable resources for almost 100% of output, and the government has laid the foundations for implementing a renewable energy strategy that aims to increase the share of small-scale renewable energy to 30% of total energy consumption by 2030.

Viet Nam's intended unconditional contribution[4] to GHG emissions reduction efforts during 2021–2030 is to reduce its GHG emissions by 8% in 2030 compared with the BAU scenario, in which the emissions intensity per unit of GDP will decline by 20% from 2010 levels and forest coverage will increase by 45%. Under its conditional contribution, Viet Nam intends to cut emissions by 25% from 2010 levels if international support is received through bilateral and multilateral cooperation (UNFCCC 2015). Further, the emissions intensity target per unit of GDP will be reduced by 30% from 2010 levels. Thailand expects its GHG emissions to reach 555 million tonnes of carbon equivalent ($MtCO_2e$) by 2030 in the BAU case, with 76.8% mainly from the energy and transport sectors. According to Thailand's INDC, the country intends to reduce GHG emissions by 20% of the BAU emissions in 2030. This

[4]Developing countries announced two sets of mitigation targets to be reached under the Paris Agreement. The low target or unconditional target can be reached without outside support. However, the conditional target can be reached only with outside support.

means that Thailand's amount of GHG emissions reduction should be 111 $MtCO_2e$ in 2020.

From 2016 to 2030, Myanmar aims to increase the share of renewables in rural electrification to 30%, increase hydropower capacity to 9.4 gigawatts, and distribute about 260,000 energy-efficient cooking stoves to rural areas (UNFCCC 2015). For energy efficiency, Myanmar aims to achieve 20% electricity-saving potential of the forecast electricity consumption by 2030. Under the INDC framework, Brunei Darussalam targets reducing its energy consumption by 63% by 2035 against the BAU scenario. Furthermore, the country aims to achieve a 10% share of renewable energy in power generation by 2035. With regards to the transport sector, the target is to reduce CO_2 emissions by 40% from morning peak-hour vehicle use by 2035 compared with the BAU scenario. Another target in its INDC is to enhance the stocks of carbon sinks by increasing the current 41–55% of the country's total forest area in 2016.

Indonesia's INDC specifies conditional and unconditional mitigation targets. It intends to reduce 29% of its emissions against the BAU scenario by 2030 in the unconditional scenario. If there is additional international support, Indonesia intends to reduce an additional 12% of the emissions. The intended contributions cover five sectors: energy (including transport); industrial processes and product use; agriculture; land use, land use change, and forestry; and waste. The amount of emissions under the 29% and 41% reduction targets would be 0.848 $GtCO_2eq$ and 1.119 $GtCO_2eq$, respectively. Malaysia intends to reduce its GHG emissions intensity of GDP by 45% by 2030 relative to the emissions intensity of GDP in 2005 (UNFCCC 2015). This consists of 35% on an unconditional basis and a further 10% conditional upon receipt of climate finance, technology transfer, and capacity building from developed countries.

The Philippines targets a GHG emissions reduction of 70% by 2030 relative to its BAU scenario of 2000–2030. The mitigation contribution is conditioned on the extent of financial resources—including technology development and transfer—and capacity building that will be made available to the Philippines (Kimura and Phoumin 2018). Singapore pledged in 2009 to reduce carbon emissions unconditionally from 7 to 11% lower than its BAU level by 2020. It committed to a further 16% reduction by 2020 after the COP 21 in Paris on 12 December 2015.

5.3 Methodology and Scenario Assumptions

The energy models of ASEAN countries were developed using the Long-range Energy Alternatives Planning (LEAP) system software, an accounting system used to develop projections of energy balance tables based on final energy consumption and energy input/output in the transformation sector. Final energy consumption is forecast using energy demand equations by energy and sector and future macroeconomic assumptions. The macroeconomic module also projects prices for natural gas and coal based on exogenously specified oil price assumptions. Demand equations are econometrically calculated in another module using historical data, and future parameters are projected using the explanatory variables from the macroeconomic module. An econometric approach means that future demand and supply will be heavily influenced by historical trends. However, the supply of energy and new technologies is treated exogenously. For electricity generation, the respective ASEAN countries provided specific assumptions to determine the future electricity generation mix based on each national power development plan.

Historical data and their availability vary in the 10 AMS. It is very challenging to collect long-term historical data in countries such as Cambodia, the Lao PDR, and Myanmar. Further, there are many missing data points in the historical data that need to be estimated. The LEAP application is very useful in dealing with such minimal data, and it allows expert judgement on how the future growth of demand in each fuel should be estimated. If good historical data are available, linear forecasting is used to forecast future values based on a time series of historical data. The new values are predicted using linear regression, assuming a linear trend ($y = mx + c$) where the Y term corresponds to the variable to be forecast and the X term is years. Multiple regressions are used to predict the future growth of energy demand by sector, such as transport, industry, and the commercial and residential sectors.

In this modelling work using the LEAP application, the baseline for the 10 AMS was 2017—the latest available baseline data. For future energy demand, the projected demand growth is based on government policies, population and economic growth, and other key variable such as energy prices, using the International Energy Agency (IEA) world energy model (IEA 2019). The BAU case is future predicted energy demand based on the government's current energy policies. However, the APSs are somewhat different to the BAU case in terms of policy changes and targets, as they have a greater share of renewables, including possible nuclear uptake if the government's alternative policies include nuclear as an energy option and more efficient power generation and energy efficiency in the final energy consumption.

Key variables and assumptions used in the model include the average annual growth rate of the population and the GDP, and energy efficiency and renewable targets (Fig. 5.1).

In this study, the BAU scenario assumes that past developments, current energy demand, and technologies will affect future demand. However, the study also developed several APSs based on various assumptions—e.g. changes in policies such as a higher share of renewables in the energy mix; changes in energy intensity as a result of economic structural changes towards more efficient energy consumption per unit of GDP; technological developments in terms of thermal efficiency and final energy efficiency applications in the industrial, transport, commercial, and residential sectors; and other targets towards stronger policy in emissions reduction targets. The APSs are as follows:

- **APS**. The APS uses the assumptions of more efficient final energy consumption, more efficient power generation, a higher share of renewables, and the introduction of nuclear power plants, based on each AMS government policy. The assumptions used in the APS are described in the table below.

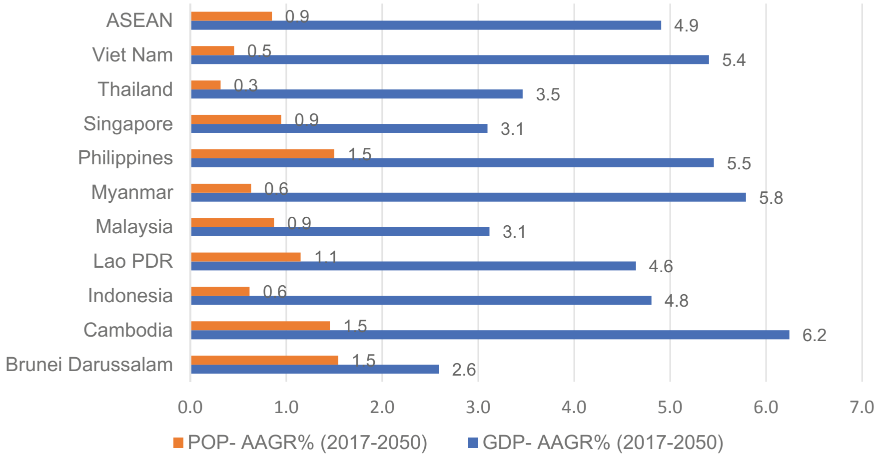

Fig. 5.1 Average annual growth rate of GDP (%) and population in AMS, 2017–2050 AMS = ASEAN Member States, ASEAN = Association of Southeast Asian Nations, GDP-AAGR = average annual growth rate of GDP, POP-AAGR = average annual growth rate of the population
Source Authors' calculations

- **APS_RE**. The APS_RE is the APS with a higher share of renewable targets at the ASEAN level. In the APS_RE, the targets are increases of 23%, 30%, and 50% in the share of renewables in the primary energy supply by 2025, 2030, and 2050, respectively, from 2005 levels. The increase in the renewable share is expected from solar, wind, geothermal, and hydro. As hydro and geothermal energy are limited by resources, the maximum share is set based on the resource endowment.
- **APS_EI**. The APS_EI is the APS using energy intensity reduction targets of 30%, 40%, and 50% from 2005 levels by 2025, 2030, and 2050, respectively. A greater reduction in energy intensity means that the energy consumption per unit of GDP becomes more efficient as a result of the application of energy efficiency, technological development, or any economic structural transformation of the economies shifting from energy-intensive sectors such as industry to less energy-intensive sectors such as services.
- **APS_EmT**. The APS_EmT is the APS using emission reduction targets of 40% and 80% from the BAU scenario by 2030 and 2050, respectively. This is the top–down policy target in which the energy mix composition needs to be changed towards cleaner energy to meet such targets. This will have many policy implications if the AMS wish to reduce emissions by as much as half from the BAU scenario by 2050.

Other Assumptions of Energy Saving Targets under the APS by AMS

Country	Assumptions
Brunei Darussalam	Electricity: 35% reduction target by 2050
Cambodia	Specific fuel efficiency target by 2050 included (coal, oil, gas, biomass industry, 10%; electricity efficiency target, 20%)
Indonesia	Sectoral target by 2050 (commercial and residential, 10%; transport, 20%; bioethanol blending increase to 15% from 3 to 7% in 2010)
Lao PDR	Biodiesel: 20% blend from 1 to 5% in 2010; utilisation of biofuels equivalent to 10% of road transport fuels
Malaysia	16% electricity saving by 2050 in industry, commercial, and residential sectors; 16% oil saving in final consumption by 2050; replacement of 5% of diesel in road transport with biodiesel
Myanmar	Target saving by 2050 included (transport and residential by 20%; industry, commercial, and others by 10%); replacement of 8% of transport diesel with biodiesel
Philippines	20% saving of oil and electricity by 2050; displacement of 20% of diesel and gasoline with biofuels by 2025
Thailand	Energy efficiency targets by 2050 included (transport, 70%; residential, 10%; commercial, 40%; and industry, 20% reduction of final energy demand); biofuels to displace 12.2% of transport energy demand
Viet Nam	20% reduction for all sectors; 10% ethanol blend in gasoline for road transport

AMS = ASEAN Member State, APS = alternative policy scenario, ASEAN = Association of Southeast Asian Nations, Lao PDR = Lao People's Democratic Republic
Source Kimura and Phoumin (2019)

5.4 Results and Analyses

The results of various energy supply and demand scenarios in ASEAN are in Annex Tables 5.1, 5.2, 5.3, 5.4, 5.5, 5.6, 5.7 and 5.8. ASEAN's energy system is predicted to be more efficient because energy intensity is expected to drop from the baseline in the future scenarios. However, the energy system will largely depend on fossil fuel consumption. The results from the energy model predicted that all ASEAN's emissions in the future scenarios will remain high because fossil fuel remains the dominant share in the future energy mix. Fossil fuel consumption—coal, oil, or natural gas—is associated with emissions, although natural gas has less emissions than coal and oil. It is also important to note that the trend of natural gas use in the energy transition is very promising, as its share has grown quickly in the primary energy mix as well as in power generation. Thus, ASEAN's energy transition will need to consider cleaner use of fossil fuels through clean technologies and a gradually increasing share of renewables and clean energy. Any policy changes to meet the emissions reduction in ASEAN need to be cautioned about high energy costs, energy access, affordability, and energy security risks. Below are the key results from the study.

More efficient use of energy. ASEAN's primary energy supply grows at an annual average rate of 3.1% from 2017 to 2050 under the BAU scenario, reaching 1823 million tonnes of oil equivalent (Mtoe) in 2050 from 639 Mtoe in 2017 (Fig. 5.3). However, under the APS of ambitious emissions reduction targets (APS_EmT), the primary energy supply is predicted to reduce by 21 and 44% from the BAU in 2030 and 2050, respectively (Annex Tables 5.1 and 5.2). ASEAN as a group achieves a significant reduction in energy intensity of 30.3% in the BAU case (a drop of energy intensity from 228 in 2017 to 154 in 2050). However, the scenario of emissions reduction targets (APS_EmT) could achieve a reduction of 60% in energy intensity in 2050 from the BAU scenario (a drop of energy intensity from 228 in 2017 to 86 in 2050) (Fig. 5.2).

Reliance on fossil fuel consumption. The results from the energy demand and supply modelling under various policy scenarios draw attention to the high reliance on fossil fuel use in ASEAN's energy system. The total combined share of fossil fuels (oil, gas, and coal) in the primary energy supply was 78% in 2017; and they are predicted to have an 87%, 82%, and 80% share in 2050 under the BAU, APS, and APS with emission reduction targets (APS_EmT) scenarios, respectively (Figs. 5.4 and 5.5).

Oil remains the dominant fuel in the primary energy supply, with a share of 37% in 2017. The share of oil is projected to be 42%, 41%, and 38% in the BAU scenario, APS, and APS_EmT in 2050, respectively (Figs. 5.6 and 5.7). Oil is mainly used in

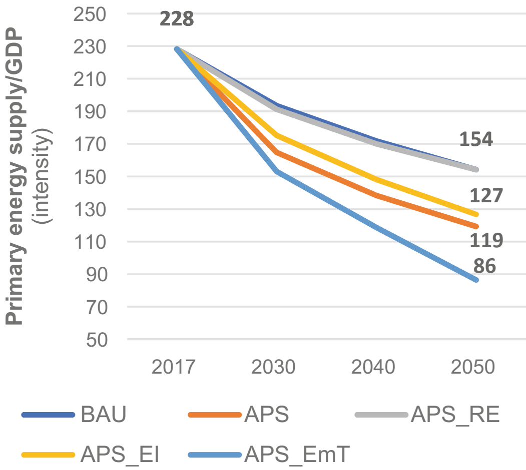

Fig. 5.2 Energy intensity in ASEAN APS = alternative policy scenario, APS_EI = alternative policy scenario with energy intensity targets, APS_EmT = alternative policy scenario with emission reduction targets, APS_RE = alternative policy scenario with renewable targets, ASEAN = Association of Southeast Asian Nations, BAU = business as usual, GDP = gross domestic product
Source Authors' calculations

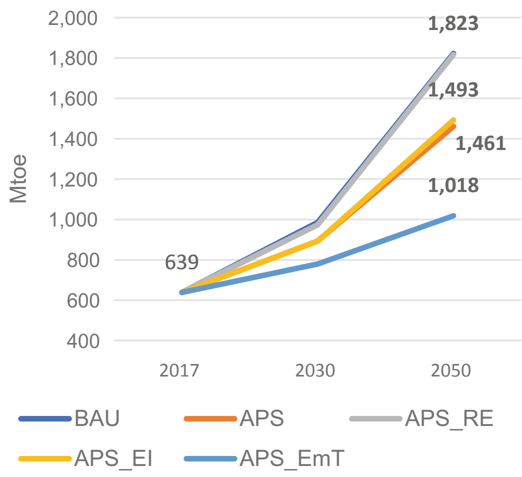

Fig. 5.3 Primary energy supply (TPES) in ASEAN APS = alternative policy scenario, APS_EI = alternative policy scenario with energy intensity targets, APS_EmT = alternative policy scenario with emission reduction targets, APS_RE = alternative policy scenario with renewable targets, ASEAN = Association of Southeast Asian Nations, BAU = business as usual, Mtoe = million tonnes of oil equivalent, TPES = total primary energy supply
Source Authors' calculations

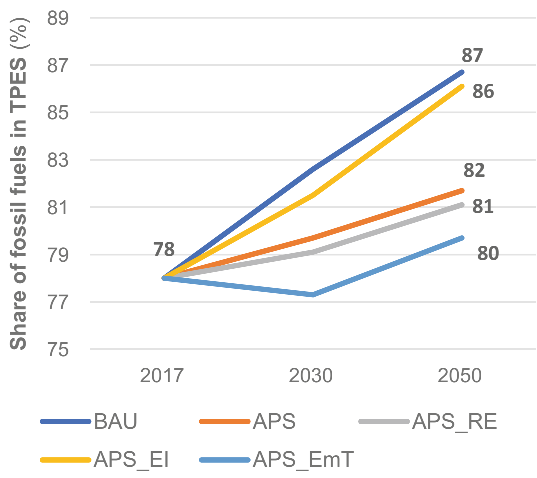

Fig. 5.4 Share of fossil fuels (coal, oil, gas) in the TPES APS = alternative policy scenario, APS_EI = alternative policy scenario with energy intensity targets, APS_EmT = alternative policy scenario with emission reduction targets, APS_RE = alternative policy scenario with renewable targets, BAU = business as usual, TPES = total primary energy supply
Source Authors' calculations

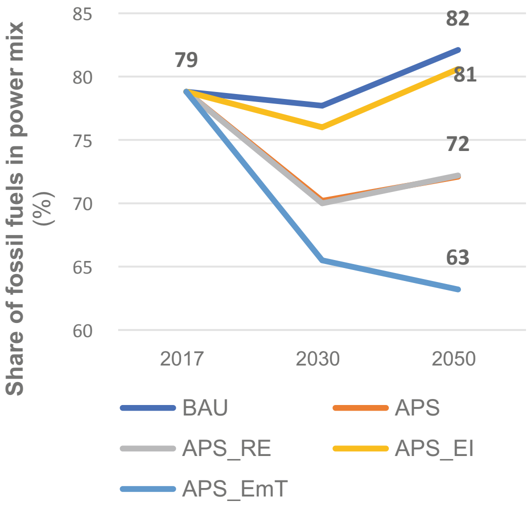

Fig. 5.5 Share of fossil fuels in the power mix APS = alternative policy scenario, APS_EI = alternative policy scenario with energy intensity targets, APS_EmT = alternative policy scenario with emission reduction targets, APS_RE = alternative policy scenario with renewable targets, BAU = business as usual
Source Authors' calculations

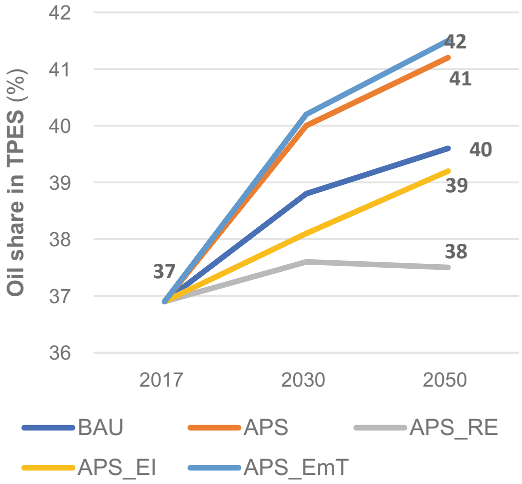

Fig. 5.6 Oil share in TPES in ASEAN APS = alternative policy scenario, APS_EI = alternative policy scenario with energy intensity targets, APS_EmT = alternative policy scenario with emission reduction targets, APS_RE = alternative policy scenario with renewable targets, ASEAN = Association of Southeast Asian Nations, BAU = business as usual, TPES = total primary energy supply
Source Authors' calculations

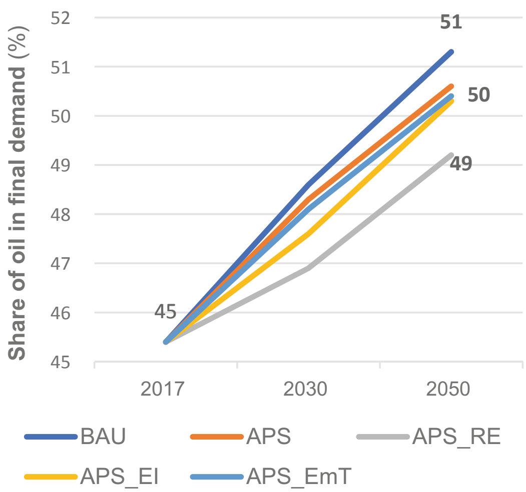

Fig. 5.7 Oil share in final demand in ASEAN APS = alternative policy scenario, APS_EI = alternative policy scenario with energy intensity targets, APS_EmT = alternative policy scenario with emission reduction targets, APS_RE = alternative policy scenario with renewable targets, ASEAN = Association of Southeast Asian Nations, BAU = business as usual
Source Authors' calculations

the transport and industrial sectors in the final energy demand. The share of oil in the final energy demand was 45% in 2017, and its share grows to 51%, 50%, and 49% in 2050 for the BAU scenario, APS, and APS_EmT, respectively. This indicates that ASEAN as a group will rely heavily on oil consumption for the foreseeable future. For most countries in ASEAN, the growing oil import dependency will need to be safeguarded by resilient infrastructure and mechanisms such as oil stockpiling (either government stock or inventory stock by the oil importing companies). Most countries in ASEAN have a stock requirement of 15–50 days, varying from country to country. However, the stock requirement for OECD members will need to be at least 90 days of net oil imports to meet the emergency oil stock holding requirement in case of supply disruption (IEA 2020).

The share of coal in the primary energy supply was 22% in 2017; and it is predicted to be 23%, 17%, and 14% in the BAU scenario, APS, and APS_EmT in 2050, respectively. Coal has the second largest share in power generation, at 37% in 2017; and it is predicted to be 36%, 27%, and 19% in the BAU scenario, APS, and APS_EmT in 2050, respectively. Under the APS of emission reduction targets (APS_EmT), the share of coal is projected to drop significantly for both the primary energy supply as well as the share in the power generation mix (Figs. 5.8 and 5.9).

Although ASEAN relies heavily on fossil fuels (oil, coal, and gas), some AMS have shifted drastically to use more gas in power generation and other final uses, such as the industrial and transportation sectors. ASEAN as a group had a 20% share of gas in the primary supply in 2017, but its share in the primary energy supply is projected to increase to 25% and 23% in 2050 for the BAU case and APS,

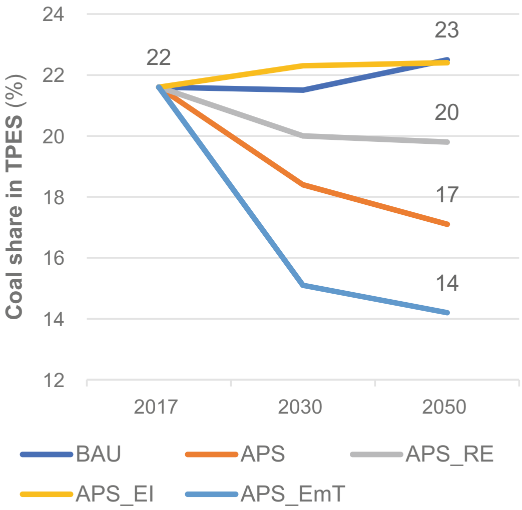

Fig. 5.8 Coal share in TPES in ASEAN APS = alternative policy scenario, APS_EI = alternative policy scenario with energy intensity targets, APS_EmT = alternative policy scenario with emission reduction targets, APS_RE = alternative policy scenario with renewable targets, ASEAN = Association of Southeast Asian Nations, BAU = business as usual, TPES = total primary energy supply
Source Authors' calculations

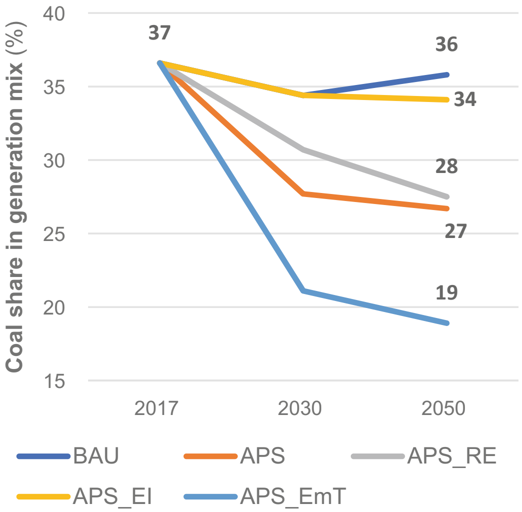

Fig. 5.9 Coal share in generation mix in ASEAN APS = alternative policy scenario, APS_EI = alternative policy scenario with energy intensity targets, APS_EmT = alternative policy scenario with emission reduction targets, APS_RE = alternative policy scenario with renewable targets, ASEAN = Association of Southeast Asian Nations, BAU = business as usual
Source Authors' calculations

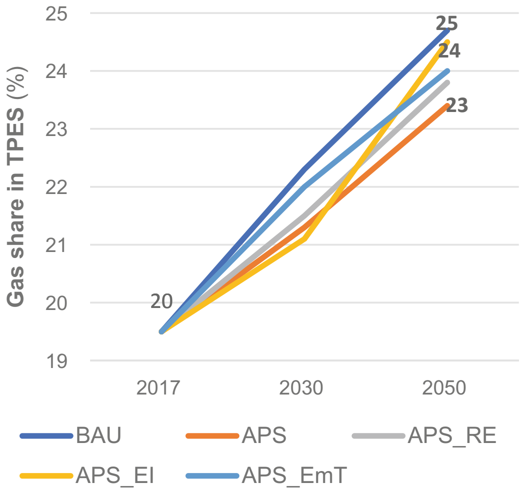

Fig. 5.10 Gas share in TPES in ASEAN APS = alternative policy scenario, APS_EI = alternative policy scenario with energy intensity targets, APS_EmT = alternative policy scenario with emission reduction targets, APS_RE = alternative policy scenario with renewable targets, ASEAN = Association of Southeast Asian Nations, BAU = business as usual, TPES = total primary energy supply
Source Authors' calculations

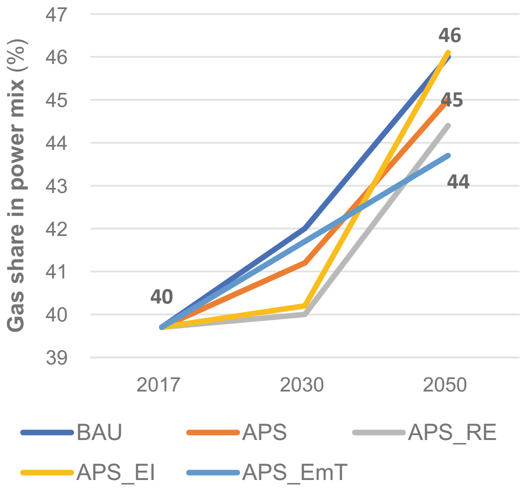

Fig. 5.11 Gas share in generation mix APS = alternative policy scenario, APS_EI = alternative policy scenario with energy intensity targets, APS_EmT = alternative policy scenario with emission reduction targets, APS_RE = alternative policy scenario with renewable targets, ASEAN = Association of Southeast Asian Nations, BAU = business as usual
Source Authors' calculations

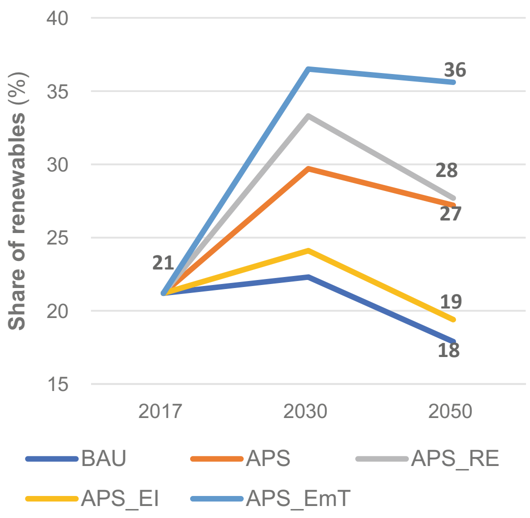

Fig. 5.12 Renewables share in power mix APS = alternative policy scenario, APS_EI = alternative policy scenario with energy intensity targets, APS_EmT = alternative policy scenario with emission reduction targets, APS_RE = alternative policy scenario with renewable targets, ASEAN = Association of Southeast Asian Nations, BAU = business as usual
Source Authors' calculations

respectively. Remarkably, the share of gas, at 40% in 2017, was a dominant fuel in the power generation mix; and it is projected to increase to 46%, 45%, and 44% in 2050 for the BAU case, APS, and APS_EmT, respectively (Figs. 5.10 and 5.11).

Increasing but not sufficient share of renewables. The share of renewables (hydropower, geothermal, biomass, wind, and solar) in the power mix was 21% in 2017. Its share is projected to increase to 36%, 28%, and 27% in the APS_EmT, APS_RE, and APS in 2050 (Fig. 5.12). The share of renewables is projected to be higher in 2030 than 2050 because hydropower and geothermal resources are limited. However, the share of wind and solar is projected to increase from 2% in 2017 to 18%, 12%, and 11% in 2050 under the APS_EmT, APS_RE, and APS, respectively (Fig. 5.13).

Although renewables are key to achieving emissions reductions, their share in the energy mix is not high enough to decarbonise emissions to meet the climate target of reducing emissions to net zero from 2050 until the turn of this century (Figs. 5.14 and 5.15).

Achieving the APS_EmT is very unlikely because this scenario assumes the most efficient technologies and the highest share of renewables to achieve emissions reduction targets. Although the emissions reduction target was set at 80% from the BAU scenario to the APS_EmT, given the plausible challenges of integrating wind and solar in ASEAN's system, only 55% could be achieved for all combined types of renewables. Thus, the remaining emissions coming from fossil fuels will need to be decarbonised through CCUS technologies or the growth of natural carbon stock.

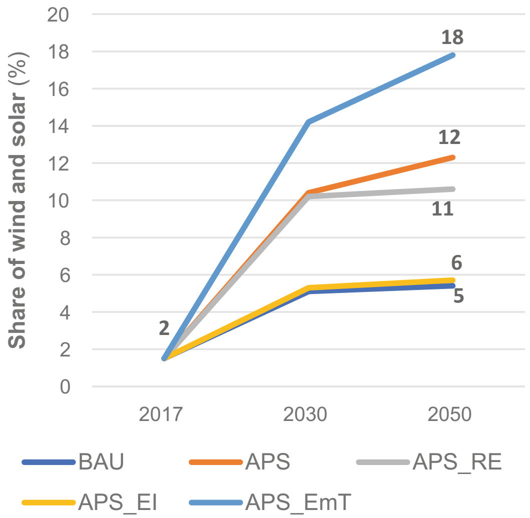

Fig. 5.13 Share of wind and solar in power mix APS = alternative policy scenario, APS_EI = alternative policy scenario with energy intensity targets, APS_EmT = alternative policy scenario with emission reduction targets, APS_RE = alternative policy scenario with renewable targets, ASEAN = Association of Southeast Asian Nations, BAU = business as usual
Source Authors' calculations

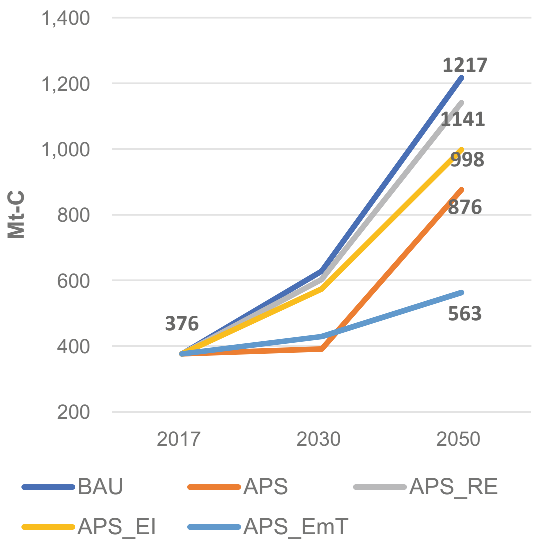

Fig. 5.14 Emission reduction in various scenarios APS = alternative policy scenario, APS_EI = alternative policy scenario with energy intensity targets, APS_EmT = alternative policy scenario with emission reduction targets, APS_RE = alternative policy scenario with renewable targets, ASEAN = Association of Southeast Asian Nations, BAU = business as usual
Source Authors' calculations

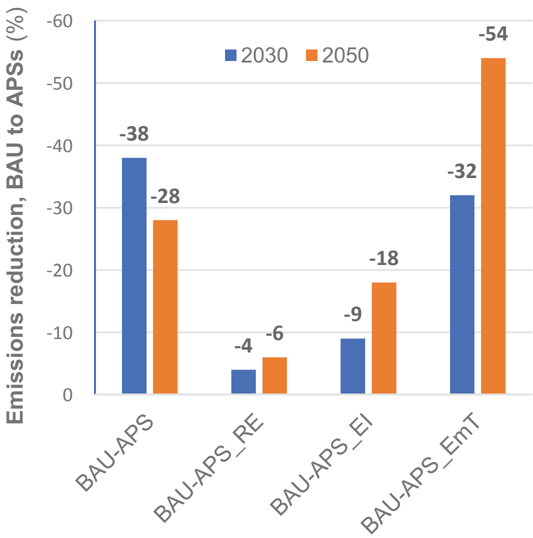

Fig. 5.15 Emission reduction in the power mix APS = alternative policy scenario, APS_EI = alternative policy scenario with energy intensity targets, APS_EmT = alternative policy scenario with emission reduction targets, APS_RE = alternative policy scenario with renewable targets, ASEAN = Association of Southeast Asian Nations, BAU = business as usual
Source Authors' calculations

ASEAN's emissions keep increasing in the foreseeable scenarios. ASEAN as a group will see emissions doubling or tripling from 2017 to 2050, varying from the BAU case to the APSs. In the BAU scenario, emissions could reach 1217 million tonnes of carbon (Mt-C), almost triple the baseline level of 376 Mt-C in 2017. However, emissions could also be lower, at 876 Mt-C for the APS and 563 Mt-C for the APS_EmT (Fig. 5.14). To limit the global temperature rise to 1.5 °C by 2100, emissions will need to be slashed by 45% from 2010 levels by 2030, then reach net zero emissions by 2050 (The Climate Reality Project 2018). Thus, ASEAN as a group will miss this target and it will make it more difficult to cut emissions by 2050.

Required investment in power generation. Figure 5.16 is the estimated required investment for solar and wind energy. Accelerating the share of variable renewables, such as solar and wind, in ASEAN's power mix will require \$56 billion–\$118 billion from the BAU scenario to the APSs in the case of solar photovoltaic and \$12 billion–\$50 billion in the case of wind, in 2050 (Fig. 5.16). The total investment in the power generation of additional capacity will be \$540 billion in the BAU scenario and \$511 billion in the APSs—reflecting the reduced investment in fossil fuels and the increase in renewables, which will have less capital costs, driven by technological development, expected in 2050.

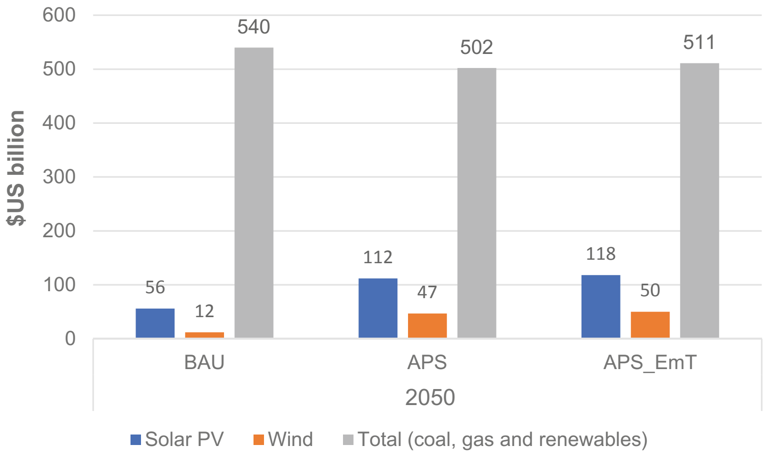

Fig. 5.16 Required investment for variable renewable energy (solar and wind) by 2050 APS = alternative policy scenario, APS_EI = alternative policy scenario with energy intensity targets, APS_EmT = alternative policy scenario with emission reduction targets, APS_RE = alternative policy scenario with renewable targets, ASEAN = Association of Southeast Asian Nations, BAU = business as usual
Source Authors' calculations

5.5 Implications of the Scenario Results

In 2020, fossil fuels (oil, coal, and natural gas) have the largest share of ASEAN's primary energy mix, at 78%. They are expected to continue to have a dominant share in the BAU scenario in 2050, at 86%, but could drop slightly to an 82% and 80% share under the APS and APS emission reduction target (APS_EmT) respectively in 2050, when considering more efficient power generation, an increasing share of renewables, and energy efficiency measures (Annex Tables 5.1, 5.2, 5.3, 5.4, 5.5, 5.6, 5.7, 5.8 and 5.9). Although oil has the largest share in the primary energy mix, natural gas and coal are the dominant energy sources in the power generation mix, at 37% and 44% respectively in 2017; and their share is projected to be 46% and 36% respectively in 2050.

Need for cleaner use of fossil fuels and clean technologies. The composition of the future energy system depends on the current actions, policies, and future policy changes. However, all decisions need to be weighed against potentially higher energy costs, affordability, and energy security risks. Coal consumption has dropped globally in recent years, but Southeast Asia has seen the opposite trend—coal consumption has been concentrated in power generation although its share of the primary energy supply remains the same from the BAU scenario to the APS, while the actual quantity of coal consumption is predicted to increase significantly from 143 Mtoe in 2017 to 251 Mtoe in 2050. The relatively high level of coal consumption in ASEAN could be attributable to affordability and energy security issues. As coal will be the second most dominant source of energy for power generation, there is a real concern that many

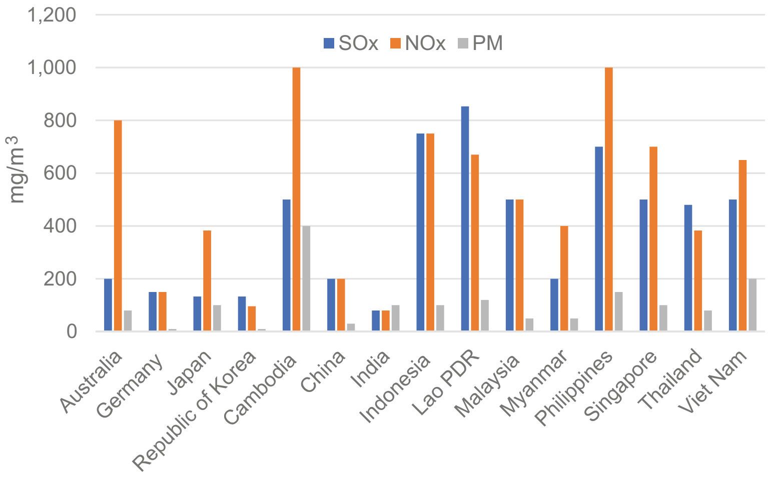

Fig. 5.17 Emissions standards for newly constructed coal-fired power plants in selected countries Lao PDR = Lao People Democratic Republic, mg/m3 = milligram per cubic metre, NOx – nitrogen oxides, PM = particulate matter, SOx – sulphur oxides.
Source Motokura et al. (2017)

ASEAN countries cannot afford clean technologies such as CCT (advanced ultra-supercritical (A-USC) or ultra-supercritical (USC) technology) due to the higher up-front cost of these technologies compared with conventional high-emissions coal power plants (subcritical technology). At the same time, ASEAN as a bloc has lower emissions standards for coal-fired power plants than advanced countries such as Germany, Japan, and the Republic of Korea, where CCT is mandatory (Fig. 5.17). This means that ASEAN countries have relatively high allowable emissions in terms of sulphur oxides (SOx), nitrogen oxides (NOx), and particulate matter (PM).

Promoting natural gas uses in ASEAN's energy transition. Natural gas has a significant role to play in ASEAN's transition to a cleaner energy system. ASEAN as a group is forecast to continue to be a net natural gas exporter until 2030, but the situation will change due to declining domestic natural gas production and increasing domestic energy demand in ASEAN (Kobayashi and Phoumin 2018). Demand for liquefied natural gas (LNG) in ASEAN is driven by increasing demand from the power generation and industrial sectors. Most AMS will see rising LNG imports in the foreseeable future because of sustained growth in electricity demand, the public preference for a cleaner fuel, and depleting domestic production. Prospects for the use of natural gas in ASEAN are optimistic, and demand is likely to increase 3.5 times in the BAU case (from 129 Mtoe in 2027 to 450 Mtoe in 2050)—depending on the future stability of gas and LNG market prices, and whether ASEAN and East Asia can create a competitive gas/LNG market in the future, with potential supply of gas/LNG from Australia, US, and other sources. Thus, ASEAN is expected to be a key market for future gas demand, so investment in gas infrastructure (such as gas pipelines and LNG receiving terminals) is crucial to support the increasing demand for gas in ASEAN.

ASEAN's scaling up renewable share and adoption of smart grid. Energy sustainability in ASEAN and around the globe requires an increased share of renewables in the energy mix to decarbonise emissions. Currently, ASEAN's power generation mix is dominated by coal, gas, and hydropower (Annex Tables 5.1, 5.2, 5.3, 5.4, 5.5, 5.6, 5.7 and 5.8). Intermittent renewables (solar and wind) comprise the most abundant energy resources in ASEAN, but have contributed negligible amounts (1.4% in 2017, 2.4% in 2020, and 10% and 12% in 2050 for the APS) to the power mix. Many ASEAN grid operators hold misperceptions about intermittent renewable energy. Although the production cost of renewable energy has dropped dramatically in recent years, its share in the power generation mix remains small. The misperceptions about renewable energy stem from its variable and intermittent nature, which adds costs to grid systems as it requires back-up capacity from conventional gas power plants. Technically, wind and solar power output varies depending on the strength of the wind or the amount of sunshine. However, this risk of variable energy output can be minimised if power systems are integrated within countries and within the ASEAN region. The aggregation of output from solar and wind from different geographical locations has a balancing effect on the variability (NREL 2020). However, the ASEAN Power Grid is making slow progress and the integrated ASEAN power market may remain unrealised due to several reasons, such as regulatory and technical harmonisation issues between the ASEAN Power Grid and utilities.

Challenges of power system integration in ASEAN. In the recent development of the power mix in ASEAN, some countries have accelerated the increase in the share of solar in the power mix without properly considering the poor gird infrastructure and power system integration challenges. As a result, electricity from solar has been curtailed. It is important to note that the shift from fossil fuels towards renewables in the energy transition will involve costs and investments for all energy-related infrastructure, which will hugely affect energy affordability. For AMS that can afford significant investments in renewable energies, an important concern is the need for electricity storage and smart grids to support higher renewable energy penetration levels in the electricity sector. Smart grid technologies are already making significant contributions to electricity grids in some developed countries of the OECD. However, these technologies are undergoing continual refinement and hence are vulnerable to potential technical and non-technical risks. Renewable energy growth will thus be constrained by infrastructure development as well as by the evolution of technology, including the capacity to assess and predict the availability of renewable energy sources (Kimura et al. 2017). These capacities of smart grids offer additional benefits, notably the promise of higher reliability and overall electricity system efficiency.

Long-term emissions reduction and COVID-19. Due to the drastic decline in energy consumption, daily global emissions dropped by 17% in the first quarter of 2020 compared with 2019 levels (Le Quéré et al. 2020). However, an economic recovery could see the levels of CO_2 emissions bouncing back very quickly. Indeed, global data from late May 2020 show an all-time high for CO_2 levels, as countries started to reopen their economies. The sudden drop in current emissions has nothing to do with low-carbon energy policy measures—it is just the impact of the pandemic slowing down all economic activities. It is also understandable that the energy structure cannot be changed overnight, given its large dependence on fossil fuels. The results have shown that ASEAN emissions will be 1217 Mt-C in the BAU and 565 Mt-C to 876 Mt-C in the APSs, in which they are supposed to fall to zero emissions if the rise in temperature is to keep within 1.5 °C by the end of this century. This means that ASEAN will not be able to achieve the emissions reduction targets. This necessitates a serious review of the commitment in the NDCs or INDCs to limit the emissions to half by 2030 and reach net zero emissions by 2050. It also points to the urgent need for carbon sink technologies such as CCUS.

ASEAN's energy transition from a system based on fossil fuels to a system based on cleaner energy use will rely on investment in quality infrastructure—including renewable and cleaner use of fossil fuels, and CCUS—to reduce global GHG emissions and avoid the most serious impacts of climate change. Clean technologies and CCUS are the obvious choice to reduce fossil fuel emissions in ASEAN, while accelerating the use of renewables and the application of energy efficiency in all sectors.

Need for quality energy infrastructure and investment. To satisfy the growing energy demand in ASEAN, huge energy-related infrastructure investment is necessary between now and 2050. This study estimates that about \$500 billion–\$550 billion will be necessary in the power generation sector, of which combined variable renewables (wind and solar) will require \$68 billion–\$168 billion from the BAU scenario to the APSs, respectively. More broadly, the IEA (2017) projected that \$2.1 trillion will be required for oil, gas, coal, and power supply infrastructure in ASEAN. More than 60% of investment goes to the power sector, with transmission and distribution accounting for more than half of the total necessary investment. Globally, the Ministry of Finance of Japan (2019) estimated that the infrastructure investment gap is estimated to be \$15 trillion from now until 2040. Asia alone will have a \$4.6 trillion investment gap from now until 2040 (Ministry of Finance, Japan 2019). The huge potential for energy infrastructure related investment will need to be guided by appropriate policies to promote quality infrastructure and resilience in ASEAN for growth and sustainability. Thus, ASEAN will need to prepare an array of policies suited to specific conditions to facilitate investment opportunities.

5.6 Conclusions and Policy Implications

The results of various scenarios have shown that ASEAN's current and future energy mix relies greatly on fossil fuels. The current share of fossil fuels is almost 80% in the primary energy supply and its future share is projected to be 87% under the BAU scenario and 78% under the APS. ASEAN's emissions will remain very high in all APS scenarios. To limit the temperature rise to 2 °C, emissions will need to fall to half by 2030 and reach net zero emissions by 2050 from 2010 levels. Thus, the clean use of fossil fuels through clean technologies and CCUS will be the only technological options to decarbonise emissions from fossil fuel use. In the energy transition, natural gas should be promoted as a transitional fuel in ASEAN, given the abundant supply from Australia. Renewables, energy efficiency, and green hydrogen[5] should be accelerated—along with the adoption of clean ecotechnologies—in the medium to long term in ASEAN's future energy system. Policies to manage ASEAN's energy transition need to be weighed against potentially higher energy costs, affordability, and energy security risks. Oil is the dominant energy source in the transport sector, while natural gas and coal are the dominant energy sources for power generation in ASEAN. The higher share of natural gas in ASEAN's power mix is a step in the right direction in promoting natural gas use in the energy transition towards a cleaner energy system.

In many ASEAN countries, coal use in power generation has been locked into the foreseeable future energy mix, as current and future coal-fired power generation generally involves 20- to 35-year power purchasing agreements with state-owned utilities to provide electricity. Thus, ignoring coal use in ASEAN means ignoring the reality and emissions of coal use. Considering the clean use of coal as part of ASEAN's energy transition is crucial to address the priorities of energy affordability and climate change. The deployment of CCT is urgent in the ASEAN region. Although ASEAN's energy targets have been set to include more renewables, ASEAN faces challenges in implementing such targets because renewables remain expensive in terms of the system integration cost to achieve high penetration in the grid system. Smart grids using the internet of things will provide a new green investment infrastructure which allows more penetration of renewables, but significant investment is required such as hard grids, internet of things technologies and applications, data management, and human resources.

A cleaner energy system in ASEAN relies on today's actions, policies, and investments to accelerate a higher share of renewables, the adoption of clean technologies and clean use of fossil fuels, and investment in climate-resilient energy quality infrastructure. The need for variable renewable investment in the power mix is estimated to be $118 billion in the APSs. Finally, willingness to pay is crucial if ASEAN is to leapfrog from its current energy system towards more efficient and clean technologies and a higher share of renewables in the energy mix.

Below are the key policy implications from the study:

- AMS will require assistance from developed countries to support the deployment of clean coal technologies, so that some developing countries in ASEAN will be able to afford clean coal technologies (e.g. USC or A-USC) to remove pollutants and increase the efficiency of power plants.
- The current climate narrative and policy approach of banning coal use should be reviewed to assist emerging Asia to afford CCTs, if alternative energy options are not available or feasible for emerging Asia in the medium term to meet energy demand. Treating CCTs as technology solutions in the energy transition will be a

[5]Green hydrogen refers to the hydrogen production from renewable electricity.

win–win solution for the world in terms of mitigating emissions and for Asia in sustaining energy accessibility and affordability.

- Emerging Asia will rely on whatever CCTs are available in the market at an affordable price. The up-front cost of such USC or A-USC technology is higher than that of supercritical (SC) and sub-critical (C) technology. Thus, it is necessary to lower such costs through policies such as attractive financing loan schemes for USC technologies, or a strong political institution to deliver public financing for CCTs to emerging Asia.
- A policy framework should clearly state the corporate social responsibilities of developed and developing nations, respectively, by highlighting the near- and long-term policy measures towards the coal industry and coal-fired power generation. As emissions in ASEAN are expected to rise until 2050, carbon recycling technologies will be necessary. In this regard, the world needs to accelerate the research, development, and deployment of CCUS for commercialisation in the near future.
- There is a need to accelerate smart grid infrastructure development and investment, and energy cooperation from developed countries to share the experience of energy system integration, to achieve a higher share of renewables in the power system.
- ASEAN should promote natural gas use in the energy transition, as it creates only half the emissions that coal produces. Thus, investment in natural gas infrastructure will be crucial to increase natural gas use in ASEAN.
- ASEAN should accelerate the penetration of renewables, while increasing the adoption of clean technologies and the deployment of CCUS in the foreseeable future.
- ASEAN's leaders should consider the gradual removal of blanket fossil fuel subsidies, but should replace them with subsidies targeted at vulnerable groups to help meet their basic energy needs and support their well-being.
- Other energy policy measures should consider the potential higher energy costs, energy affordability and accessibility, and energy security risks. Regular surveys to assess people's willingness to pay for energy costs will be key in planning policy measures/reforms.

Annex

See Tables 5.1, 5.2, 5.3, 5.4, 5.5, 5.6, 5.7 and 5.8.

Table 5.1 Estimates of primary energy supply and percentage changes from BAU to APSs, 2030 (Mtoe)

Item	2017	2030								
	Baseline	BAU	APS	% change (BAU vs APS)	APS_RE	% change (BAU vs APS_RE)	APS_EI	% change (BAU vs APS_EI)	APS_EmT	% change (BAU vs APS_EmT)
Coal	143	220	164	– 25	195	– 12	199	– 10	118	– 46
Oil	228	374	357	– 5	366	– 2	340	– 9	314	– 16
Natural gas	119	214	190	– 11	209	– 2	188	– 12	172	– 20
Nuclear	0	0	0	0	0	0	0	0	0	0
Hydro	16	24	24	0	25	7	23	– 4	24	0
Geothermal	20	32	32	1	34	6	30	– 5	32	2
Biomass	105	102	102	1	113	11	97	– 5	97	– 5
Solar, wind, ocean	1	6	12	90	12	81	6	– 7	10	62
Biofuels	7	12	11	– 7	18	48	10	– 17	13	5
Electricity	– 1	2	0	– 108	2	19	0	– 104	0	– 106
Total	639	986	893	– 9	974	– 1	893	– 9	780	– 21

APS = alternative policy scenario, APS_EI = alternative policy scenario with energy intensity targets, APS_EmT = alternative policy scenario with emission reduction targets, APS_RE = alternative policy scenario with renewable targets, BAU = business as usual, Mtoe = million tonnes of oil equivalent.
Source Authors' calculations

Table 5.2 Estimates of primary energy supply and percentage changes from BAU to APSs, 2050 (Mtoe)

	2017					2050				
Item	Baseline	BAU	APS	% change (BAU vs APS)	APS_RE	% change (BAU vs APS_RE)	APS_EI	% change (BAU vs APS_EI)	APS_EmT	% change (BAU vs APS_EmT)
Coal	143	409	251	– 39	360	– 12	335	– 18	145	– 65
Oil	228	721	602	– 17	681	– 6	586	– 19	423	– 41
Natural gas	119	450	342	– 24	432	– 4	366	– 19	245	– 46
Nuclear	0	0	6	557	0	0	0	0	7	718
Hydro	16	31	30	– 3	35	16	30	– 3	28	– 8
Geothermal	20	63	74	17	101	61	51	– 19	41	– 35
Biomass	105	99	104	4	127	28	87	– 13	91	– 8
Solar, wind, ocean	1	14	25	80	24	71	12	– 16	24	72
Biofuels	7	28	23	– 20	50	76	21	– 26	13	– 56
Electricity	– 1	7	6	– 12	6	– 10	6	– 7	3	– 59
Total	639	1823	1461	– 20	1817	0	1493	– 18	1018	– 44

APS = alternative policy scenario, APS_EI = alternative policy scenario with energy intensity targets, APS_EmT = alternative policy scenario with emission reduction targets, APS_RE = alternative policy scenario with renewable targets, BAU = business as usual, Mtoe = million tonnes of oil equivalent

Source Author's calculations

Table 5.3 Estimates of final energy consumption and percentage changes from BAU to APSs, 2030 (Mtoe)

Item	2017	2030								
	Baseline	BAU	APS	% change (BAU vs APS)	APS_RE	% change (BAU vs APS_RE)	APS_EI	% change (BAU vs APS_EI)	APS_EmT	% change (BAU vs APS_EmT)
Industry	148	248	227	−8	241	−3	220	−11	199	−20
Transportation	129	231	201	−13	231	0	201	−13	184	−20
Others	141	190	177	−7	189	−1	176	−8	158	−17
Non-energy	62	80	80	0	66	−18	66	−18	66	−18
Total	480	750	686	−9	727	−3	663	−12	607	−19

APS = alternative policy scenario, APS_EI = alternative policy scenario with energy intensity targets, APS_EmT = alternative policy scenario with emission reduction targets, APS_RE = alternative policy scenario with renewable targets, BAU = business as usual, Mtoe = million tonnes of oil equivalent

Source Authors' calculations

Table 5.4 Estimates of Final Energy Consumption and Percentage Changes from BAU to APSs, 2050 (Mtoe)

Item	2017	2050								
	Baseline	BAU	APS	% change (BAU vs APS)	APS_RE	% Change (BAU vs APS_RE)	APS_EI	% Change (BAU vs APS_EI)	APS_EmT	% Change (BAU vs APS_EmT)
Industry	148	453	386	– 15	448	– 1	381	– 16	250	– 45
Transportation	129	483	374	– 23	486	1	376	– 22	246	– 49
Others	141	294	253	– 14	294	0	253	– 14	190	– 36
Non-energy	62	126	126	0	109	– 13	109	– 13	109	– 13
Total	480	1356	1139	– 16	1337	– 1	1119	– 17	794	– 41

APS = alternative policy scenario, APS_EI = alternative policy scenario with energy intensity targets, APS_EmT = alternative policy scenario with emission reduction targets, APS_RE = alternative policy scenario with renewable targets, BAU = business as usual, Mtoe = million tonnes of oil equivalent

Source Authors' calculations

Table 5.5 Estimates of power generation mix and percentage changes from BAU to APSs, 2030 (TWh)

Item	2017	2030								
	Baseline	BAU	APS	% change (BAU vs APS)	APS_RE	% change (BAU vs APS_RE)	APS_EI	% change (BAU vs APS_EI)	APS_EmT	% change (BAU vs APS_EmT)
Coal	381	608	449	−26	582	−4	552	−9	298	−51
Oil	26	23	21	−9	21	−8	22	−5	10	−57
Natural gas	414	743	669	−10	660	−11	645	−13	591	−20
Nuclear	0	0	0	0	0	0	0	0	0	0
Hydro	183	267	276	4	397	49	267	0	278	4
Geothermal	23	37	37	1	39	7	35	−5	38	2
Others	14	91	169	86	193	113	86	−5	201	122
Total	1041	1768	1622	−8	1892	7	1607	−9	1416	−20

APS = alternative policy scenario, APS_EI = alternative policy scenario with energy intensity targets, APS_EmT = alternative policy scenario with emission reduction targets, APS_RE = alternative policy scenario with renewable targets, BAU = business as usual, TWh = terawatt-hour

Source Authors' calculations

Table 5.6 Estimates of power generation mix and percentage changes from BAU to APSs, 2050 (TWh)

Item	2017	2050								
	Baseline	BAU	APS	% change (BAU vs APS)	APS_RE	% change (BAU vs APS_RE)	APS_EI	% change (BAU vs APS_EI)	APS_EmT	% change (BAU vs APS_EmT)
Coal	381	1232	772	−37	1054	−14	1005	−18	398	−68
Oil	26	12	12	1	12	0	11	−3	12	0
Natural gas	414	1582	1303	−18	1700	7	1359	−14	919	−42
Nuclear	0	0	21	2137	0	0	0	0	28	2757
Hydro	183	356	344	−3	537	51	346	−3	326	−8
Geothermal	23	73	86	17	118	61	59	−19	47	−35
Others	14	185	356	93	406	120	167	−10	376	104
Total	1041	3439	2895	−16	3827	11	2948	−14	2105	−39

APS = alternative policy scenario, APS_EI = alternative policy scenario with energy intensity targets, APS_EmT = alternative policy scenario with emission reduction targets, APS_RE = alternative policy scenario with renewable targets, BAU = business as usual, TWh = terawatt-hour
Source Authors' calculations

Table 5.7 Estimates of CO_2 emissions and percentage changes from BAU to APSs, 2030 (Mt-C)

	2017	2030								
Item	Baseline	BAU	APS	% change (BAU vs APS)	APS_RE	% change (BAU vs APS_RE)	APS_EI	% change (BAU vs APS_EI)	APS_EmT	% change (BAU vs APS_EmT
Coal	147	227	144	−37	197	−13	197	−13	122	−46
Oil	138	249	147	−41	258	3	238	−5	202	−19
Natural gas	91	152	100	−34	148	−3	139	−9	105	−31
Total	376	628	391	−38	603	−4	574	−9	429	−32

APS = alternative policy scenario, APS_EI = alternative policy scenario with energy intensity targets, APS_EmT = alternative policy scenario with emission reduction targets, APS_RE = alternative policy scenario with renewable targets, BAU = business as usual, Mt-C = million tonnes of carbon equivalent
Source Authors' calculations

Table 5.8 Estimates of CO_2 emissions and percentage changes from BAU to APSs, 2050 (Mt-C)

Item	2017	2050								
	Baseline	BAU	APS	% change (BAU vs APS)	APS_RE	% change (BAU vs APS_RE)	APS_EI	% change (BAU vs APS_EI)	APS_EmT	% change (BAU vs APS_EmT
Coal	147	432	264	−39	360	−17	317	−27	151	−65
Oil	138	503	395	−21	507	1	437	−13	280	−44
Natural gas	91	281	216	−23	275	−2	244	−13	132	−53
Total	376	1217	876	−28	1141	−6	998	−18	563	−54

APS = alternative policy scenario, APS_EI = alternative policy scenario with energy intensity targets, APS_EmT = alternative policy scenario with emission reduction targets, APS_RE = alternative policy scenario with renewable targets, BAU = business as usual, Mt-C = million tonnes of carbon equivalent

Source Authors' calculations

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Chapter 6
Expediting Transition Towards HELE Coal-Fired Electricity Generation Technologies in Southeast Asia: A Comparative Economic Analysis of HELE and Subcritical Coal-Fired Technologies

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Abstract To decarbonise the electricity generation sector under the International Energy Agency's 2 °C scenario, electricity generation from less efficient subcritical coal plants needs to be completely phased out by 2050. In addition, large potential exists in the Southeast Asia region for the deployment of high-efficiency, low-emission (HELE) electricity generation technologies. A cost–benefit analysis of HELE technologies against the less efficient subcritical electricity generation plants is thus carried out to find a persuasive scenario supporting a quicker transition from subcritical stations towards HELE technologies in the region. A levelised cost of electricity (LCOE) analysis is carried out for both the coal-fired technologies under four potential policy scenarios. To evaluate the LCOEs, scenario 1 does not take into consideration any carbon pricing or costs associated with the desulphurisation (deSO$_x$) and denitrification (deNO$_x$) facilities. Scenario 2 (scenario 3) incorporates carbon pricing (costs associated with the deSO$_x$ and deNO$_x$ facilities), while scenario 4 includes both carbon pricing and costs associated with the deSO$_x$ and deNO$_x$ facilities. A novelty of this study is that it includes advanced ultra-supercritical (A-USC)

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H. Phoumin et al. (eds.), *Energy Sustainability and Climate Change in ASEAN*, Economics, Law, and Institutions in Asia Pacific,
https://doi.org/10.1007/978-981-16-2000-3_6

plants, and a sensitivity analysis is performed under each scenario to evaluate the uncertainty affecting the future coal prices on coal plants with 20- and 25-year lifespans. This study demonstrates that HELE technologies are competitive against the subcritical plants under all four scenarios, and both the technologies derive benefit from lifetime extensions and low coal prices. It is revealed that future deployments of HELE technologies can be expedited by factoring in carbon pricing in the LCOE costs of coal-fired power plants under scenario 2. It thus necessitates strengthening the carbon pricing policy for coal-fired power plants in Southeast Asia to support a quicker transition from less efficient subcritical stations towards HELE coal-fired technologies.

Keywords High-efficiency, low-emission · Carbon dioxide emissions · Carbon pricing · Subcritical · Desulphurisation · Denitrification · Cost–benefit analysis · levelised cost of electricity

6.1 Introduction

Coal-fired electricity generation plants with a total capacity of about 1700 gigawatts (GW) account for over 41% of the electricity generation worldwide (IEA 2014). Coal-fired electricity generation is responsible for over 28% of global carbon dioxide (CO_2) emissions (Agami Reddy et al. 2017), and scientific studies suggest that CO_2 emissions are responsible for global warming and the associated devastating public health and environmental impacts.

As the pressure to act against global warming is increasing, several coal user countries have been working on their national plans to kick-start global efforts to reduce CO_2 emissions from their electricity generation sectors through the development and deployment of high-efficiency, low-emission (HELE) coal-fired power generation technologies. HELE technologies utilise higher temperatures and pressures than less efficient subcritical technologies (IEA 2012a; WCA and ACE 2017). HELE electricity generating plants include supercritical (SC), ultra-supercritical (USC), advanced ultra-supercritical (A-USC), integrated gasification combined cycle (IGCC), and integrated gasification fuel cell (IGFC) technologies which have been developed to increase the efficiency of coal-fired electricity generation plants—thus reducing CO_2 and other greenhouse gas (GHG) and non-GHG emissions. HELE units emit 25–33% less CO_2 than the global average CO_2 emissions from the existing electricity generation fleet, and up to 40% less than the oldest technologies (WCA and ACE 2017). Table 6.1 shows the efficiency ratings, CO_2 intensity factors, and fuel consumption values for subcritical, SC, USC, and A-USC power plants.

Every 1% improvement in the efficiency of coal-fired electricity generation plants results in a 2–3% reduction in CO_2 emissions (WCA 2014). Since 2000, HELE power plants have reduced global CO_2 emissions by over 1 billion tons (IEA 2010). HELE technology is a vital first step to carbon capture and storage (CCS). The International Energy Agency (IEA) *Energy Technology Perspectives 2012* 2 °C scenario (2DS)

Table 6.1 HELE Technologies—LHV-based efficiency improvements, intensity factors, and fuel consumption

Item	Efficiency rate (% net LHV basis)	CO_2 intensity	Coal consumption	Steam temperature
A-USC	45%–50%	670–740 g CO_2/kWh	290–320 g/kWh	700 °C
USC	Up to 45%	740–800 g CO_2/kWh	320–340 g/kWh	600 °C
SC	Up to 42%	800–880 g CO_2/kWh	340–380 g/kWh	Approx. 550 °C–600 °C
Subcritical	Up to 38%	≥880 g CO_2/kWh	≥380 g/kWh	<550 °C

A-USC = advanced ultra-supercritical; CO_2 = carbon dioxide; g = gram; HELE = high-efficiency, low-emission; kWh = kilowatt-hour; LHV = low heating value; SC = supercritical; USC = ultra-supercritical
Source IEA (2012b)

indicates that to limit the average rise in global temperature to 2 °C, it is necessary to cut more than half of the energy sector related CO_2 emissions by 2050 (compared with 2009) (IEA 2012a). Combined with CCS, HELE technologies are expected to cut global average CO_2 emissions from coal-fired plants by as much as 90% to attain the 2DS by 2050 (IEA 2012b).

Southeast Asia consists of 10 countries in the Association of Southeast Asian Nations (ASEAN): Brunei Darussalam, Cambodia, Indonesia, the Lao People's Democratic Republic (Lao PDR), Malaysia, Myanmar, the Philippines, Singapore, Thailand, and Viet Nam. The vast availability of coal reserves in the region and its lower cost has made coal the largest and preferred source for electricity generation. The IEA forecasts that installed coal-fired electricity generation capacity will increase to around 160 GW by 2040, making a large contribution to growth in the generation capacity of the region (IEA 2017a). In addition, coal-fired generation will overtake natural gas by 2040 to become the largest source of power capacity. Furthermore, the IEA confirms that low emission coal will be the generation of choice in the region and will provide 40% of electricity generation by 2040. There is a regional understanding among ASEAN Member States (AMS) that the growing use of coal will necessitate a HELE technology energy pathway supported by renewables.

The levelised cost of electricity (LCOE) is often cited as a convenient summary measure of the overall competitiveness of different electricity generating technologies (US Energy Information Administration 2018). To influence the type of technology that project developers select in ASEAN countries, several LCOE studies focusing on renewable energy technologies have been conducted (Veldhuis and Reinders 2015; Talavera et al. 2016; Blum et al. 2013; Holland and Derbyshire 2009; Abraham et al. 2012; Januar 2017; Lau et al. 2014; ADB 2015; Huber et al. 2015; ACE 2016). Lau et al. (2014) presented a detailed analysis of photovoltaic (PV) grid parity based on the calculation of the PV LCOE for the residential sector in Malaysia. The Asian Development Bank (ADB 2015) conducted LCOE analysis for renewable energies in the Greater Mekong Subregion countries—Cambodia, the Lao PDR, Myanmar, Thailand, and Viet Nam. Huber, Roger, and Hamacher (2015) concluded that the most economical options for electricity generation in the ASEAN region are hydro, biomass, and geothermal. ACE (2016) analysed the LCOE of selected renewable energy technologies in several ASEAN countries, and advised on the necessary policies to reach a significant competitive edge for those selected renewable energy technologies.

Phuangpornpitak and Kumar (2007) provided in-depth analysis of the renewable hybrid mini-grid systems with solar PV, wind, battery, and diesel that have been installed in the national parks of Thailand. Keeley and Managi (2019) assessed the economic viability of renewable hybrid mini-grid systems in Indonesia. Further, Blum, Wakeling, and Schmidt (2013) investigated the LCOE of isolated renewable hybrid mini-grid systems in Indonesia.

There is also some limited work on LCOE, focused on coal technologies and a comparison of coal technologies with other electricity generation technologies for the Southeast Asian region. A cost–benefit analysis of USC, SC, and subcritical plants was carried out by the Economic Research Institute for ASEAN and East Asia (ERIA) in Otaka and Han (2015). The ERIA study confirmed that USC is generally competitive against SC and subcritical plants. Further, a World Coal Association (WCA) and ASEAN Centre for Energy (ACE) report suggested that various coal-fuelled electricity generation technologies are the lowest LCOE option available for mass deployment in Southeast Asia (WCA and ACE 2017).

The ASEAN governments are promoting HELE technologies as a key step towards CO_2 mitigation. The AMS are thus making a transition from less efficient subcritical stations towards HELE coal-fuelled facilities. Current research suggests that almost half the coal stations under construction or in development are expected to make use of advanced HELE coal-fired technology. The analysis also indicates that 23% of coal capacity under construction or in development is SC, while a further 29% of proposed projects have not finalised the technology choice (WCA and ACE 2017). HELE coal-fired technologies are more expensive to build than subcritical technologies due to more expensive materials, complex boilers, and precise control systems. The high cost is a main restriction element for the large-scale deployment of HELE technologies. Subcritical electricity generating plants have been traditionally preferred due to their lower up-front costs and shorter lead times. It is therefore highly likely that project developers will end up accepting the lower efficiency and poorer emission rates from subcritical coal-fired technology. However, to decarbonise the electricity sector by 2050 under 2DS, electricity generation from subcritical coal plants needs to be completely phased out by 2050; and following 2020, more efficient CCS-fitted HELE coal-fired plants are to be employed. IEA thus recommends the implementation of national energy plans and policies to rapidly phase out the construction and deployment of subcritical coal-fired plants (IEA 2017b). Although ASEAN is transitioning from less efficient subcritical stations towards HELE coal-fuelled facilities, the current deployment progress is slow and subcritical units are still being deployed. Scope thus exists for policy support to expedite the transition from less efficient subcritical units to HELE units. This study aims to demonstrate the economic feasibility of HELE against subcritical coal-fired power plants to find a policy scenario that will result in a more rapid decline of subcritical coal-fired electricity generation and shift new project investments to HELE technologies. It is novel because it includes A-USC and performs a sensitivity analysis under each scenario to evaluate the effects of the uncertainty regarding future coal prices on coal plants with 20- and 25-year lifespans.

The research study leads us to two novel results:

1. Future deployments of HELE technologies can be expedited if a carbon pricing policy is implemented for coal-fired electricity generating plants; and
2. A-USC coal-fired power plants are the most economically attractive choice for deployment in Southeast Asia, followed by USC and SC plants.

It is thus concluded that HELE technologies are more economically attractive than subcritical technologies, and Southeast Asian governments should focus on devising and implementing carbon pricing policies to phase out subcritical plants and support faster deployment of HELE technologies.

6.2 Methodology

6.2.1 LCOE

There are a number of approaches to calculating the cost of electricity assessed over a lifetime, e.g. levelised cost, marginal cost, and avoided cost. The LCOE represents the lifetime average cost of electricity as a constant unit price ($ per megawatt-hour ($/MWh)) for a specific electricity generation project, and is a commonly used metric to assess the overall competitiveness of different electricity generation projects. It has been used by the public and private sectors as well as international bodies such as the IEA, the Intergovernmental Panel on Climate Change (IPCC), the International Renewable Energy Agency (IRENA), and investment banks. We thus chose to base our study on this measure.

The LCOE metric is generally calculated as follows (WCA and ACE 2017; Holmes 2017; Tran and Smith 2018; Rhodes et al. 2017):

$$LCOE = \frac{\text{Life cycle cost}(\$)}{\text{Lifetime energy production (MWh)}}. \tag{6.1}$$

The LCOE in (6.1) considers the project's overall expected lifetime costs (including construction, fuel, financing, maintenance, insurance, taxes, and incentives), which are then divided by the project's lifetime expected power output (MWh).

As the value of the United States (US) dollar ($) today does not have the same economic value as in the future, it is converted to present value terms through the use of discounting to account for costs that occur at different points in time. The present value of all expenses is then divided by the present value of electricity generation. The LCOE can thus be calculated as follows:

$$LCOE_{NPV} = \frac{\sum_{t=0}^{N} \frac{[I_t + M_t + F_t]}{(1+r)^t}}{\sum_{t=0}^{N} \frac{[E_t]}{(1+r)^t}}, \tag{6.2}$$

where:

I_t = capital expenditure in year t associated with the construction of the plant;
M_t = non-fuel operation and maintenance (O&M) costs in year t;
F_t = fuel price expenditures in year t;
E_t = net electricity production in MWh in year t;
N = economic lifetime in years,
t = year of lifetime (1, 2, …, N), and.
r = discount rate or interest rate.

If the net output of the plant is constant over the life of the plant, and if the operating, maintenance, and fuel costs are also constant, Eq. (6.2) can be reduced to:

$$LCOE = \frac{CAPEX \times FCF + O\&M_{fixed}}{CF \times 8,760} + O\&M_{\mathrm{var}iable} + \Pi_{fuel} \times HR, \tag{6.3}$$

where:

- FCF is the fixed charge factor. The factor turns capital costs into a uniform annual amount and is given by:

$$FCF = \frac{r(1+r)^N}{(1+r)^N - 1}.$$

- $CAPEX$ is the capital expenditure. There are no publicly available CAPEX data sets for ASEAN countries. For our analysis, these figures are replaced with engineering, procurement, and construction (EPC) costs, in which other costs may also incur (e.g. land cost, the cost of any additional emission controls, and other financing costs);
- $O\&M_{fixed}$ is the fixed O&M cost ($ per megawatt ($/MW));
- CF is the capacity factor. It is a fraction between 0 and 1 representing the total generation of a plant as proportion of its nameplate capacity;
- 8760 is the number of hours in a year;
- $O\&M_{\mathrm{var}iable}$ is the variable O&M cost ($/MW);
- Π_{fuel} is the fuel price [$ per million British thermal units ($/MMBtu)]; and

- *HR* is the heat rate (MMBtu/MWh).

In addition to emissions (contributing to climate change), coal-fired power plants are a major source of CO_2 air pollution tied to heart and lung diseases. The toxic pollutants arising from coal power plants include sulphur oxides (SO_x) and nitrogen oxides (NO_x), as well as mercury (Hg) and particulate matter (PM). Studies have confirmed that these emissions severely impact human health (Shahzad Baig and Yousaf 2017). Our analysis suggests that the correct interpretation of the LCOE results of coal-fired plants are blurred by the fact that cost–benefit analysis does not reflect costs to society such as CO_2, SO_x, and NO_x. Since HELE power plants emit less SO_x, NO_x, and CO_2 into the atmosphere than subcritical designs, their emission abatement denitrification (deNO_x) and desulphurisation (deSO_x) facilities and climate costs are expected to be less than those of subcritical plants of the same capacity. LCOEs for HELE and subcritical coal technologies are therefore evaluated and analysed through four potential policy scenarios, based on possible combinations of carbon pricing, no carbon pricing, controls over SO_x and NO_x emissions, and no controls over SO_x and NO_x emissions in Southeast Asia.

The cost of coal-fired electricity generation is heavily contingent on coal prices. Since the Asian benchmark thermal coal prices have been growing, based on (6.3), the sensitivity of LCOE generation values is thus analysed to evaluate the impact of rising coal prices in Southeast Asia on subcritical, SC, USC, and A-USC coal-fired units with lifespans of 20 and 25 years, under each scenario.

6.2.2 Scenario Descriptions

6.2.2.1 Scenario 1 (Base Scenario)

This scenario assumes no future for carbon pricing and no controls over NO_x and SO_x emissions in Southeast Asia. The associated carbon costs and NO_x and SO_x emission reduction costs are thus not accounted, and LCOE analysis is simply based on the base plant EPC, O&M, fuel costs, and financing costs.

6.2.2.2 Scenario 2 (Climate Change Mitigation Scenario)

Carbon pricing is a cost-effective way of reducing risks, costs, and GHG emissions. It provides a mechanism to account for the environmental, social, and economic costs of climate change. National power development plans across Southeast Asian countries have started to include analyses of the impact of pricing on the electricity mix. Carbon pricing mechanisms are at different levels of development stages in ASEAN countries and ASEAN governments are expected to consider providing incentives for the decarbonisation of the electricity generation sector via technology-neutral mechanisms such as carbon pricing (IEA 2016). Several countries, cities, states, and provinces across the globe—and a growing number of commercial entities—are putting a shadow price on carbon to reduce their carbon footprint in a cost-effective manner (CPLC 2017). Shadow pricing is thus a tangible way to demonstrate a serious commitment to climate change mitigation. In the absence of a uniform carbon price in Southeast Asia, we assume a small price of $10/ton as a shadow price on carbon for the achievement of low emissions to help limit global mean temperatures under 2DS. It is expected that the adoption of carbon pricing in Southeast Asia, under this scenario, will accelerate the deployment of HELE coal-fired power plants.

6.2.2.3 Scenario 3 (Pollution Control Scenario)

This scenario assumes legislation that could take the form of ASEAN agreements to limit SO_x and NO_x emissions, linked through a uniform emission standard mechanism in the ASEAN region. This scenario thus adds the cost of deSO_x and deNO_x facilities to the respective coal-fired plants in our analysis. It is expected that strict pollution control technology requirements/adoption could add heavy financial costs to subcritical plants and thus help phase out generation from subcritical coal-fired electricity generation plants. The approach is expected to accelerate the deployment of HELE plants (all of which reduce NO_x and SO_x emissions in the ASEAN region).

6.2.2.4 Scenario 4 (Climate Change Mitigation and Pollution Control Scenario)

This scenario encourages both climate change mitigation and air pollution emission reduction efforts. Under this scenario, the costs of deSO_x and NO_x facilities and carbon pricing are thus integrated into the overall costs of coal-fired plants.

6.2.3 General Assumptions

Collectively, large-scale operational coal-fired electricity generation units around the world are major contributors to total emissions. The cost–benefit analysis was thus targeted at 1000 MW capacity coal-fired plants. All coal plants were modelled with an assumed capacity factor (CF) of 80%. Based on the plant capacity and utilisation rate, the total annual generation was thus 7008 gigawatt-hours (GWh).

Within a project capital structure, a project may receive equity investment from a private equity firm or group of investors, with an insurance wrap from a development finance institution. In this framework, investors are likely looking for faster returns based on 20- to 25-year cash flow projections (Financial Innovations Lab 2015). Although the coal-fired plant life cycle is about 25–30 years, for practical reasons this study analyses the return cash flow for 20- and 25-year expected lifetimes for each coal technology.

Table 6.2 HHV based coal-fired power plant efficiencies and heat rates

Item	Efficiency rate (% net HHV basis)	Heat rate of fuel (Btu/kWh, HHV basis)
A-USC	47	7259.57
USC	42	8123.81
SC	39	8748.72
Subcritical	35	9748.57

A-USC = advanced ultra-supercritical, Btu = British thermal unit, HHV = high heating value, kWh = kilowatt-hour, SC = supercritical, USC = ultra-supercritical
Source Authors (2015)

The efficiency figures in Table 6.1 are based on the low heating value (LHV) of the fuel and net output (LHV, net). Coal-fired station efficiencies based on high heating value (HHV) are generally 2–3% lower than those based on LHV efficiencies. We thus added three percentage points to the higher-end LHV-based efficiencies in Table 6.1 to obtain HHV-based efficiencies for different coal-fired plants and associated heat rates (Table 6.2).

Coal has a calorific value of 4000 kilocalories per kilogram (kcal/kg) and emissions (adjusted from the IPCC default emission factors) of 1.43 kg/kg-coal. The kilowatt-hours (kWh) generated CO_2 per kg of coal were computed by dividing the coal heat content (in Btu per kg) by the HR (in Btu per kWh). Coal requirements to generate 1 kWh of electricity (in kg-coal/kWh) were multiplied by the emission factor to obtain the levelised kg-CO_2 emissions per kWh.

The general assumptions for electricity generation plant specifications and coal composition are summarised in Table 6.3.

6.2.4 *Cost Assumptions and Methodologies*

For the analysis in this paper, the LCOE consists of base plant costs, deSO_x and deNO_x costs, financing costs, and emission costs. Base plant costs are divided into EPC, O&M, and fuel costs. Similarly, deSO_x and deNO_x costs consist of EPC, O&M, and additional fuel costs (Table 6.4).

The cost assumption of EPC is adopted from Otaka and Han (2015). The EPC cost consists of generator, turbine, boiler, and auxiliary machine costs; construction costs; and other management costs. The standard assumption is that all coal technologies pay equivalent connection costs and land costs. These costs are thus not taken into consideration.

For the 25-year life cycle of the plant, the SC and subcritical capital costs are discounted from the USC capital costs ($1931 million per 1000 MW), based on a cost index from JICA (2012). Subcritical plant capital costs are indexed at 100, while SC and USC are indexed at 106.5 and 108.5, respectively. Based on these

Table 6.3 General Assumptions for Cost–Benefit Analysis

		Values	Remarks
Plant	Capacity	1000 MW	For cash flow purposes
	Operation	20, 25 years	
	Operation rate	80%	
	Thermal efficiencies	47% (A-USC), 42% (USC), 39% (SC), 35% (subcritical)	HHV based values. A 3% decrease in thermal efficiency is assumed
	Annual generation	7008 GWh	
Coal specifications	Heating value	4000 kcal/kg or 1008.656 Btu/kg	
	CO_2 emissions	1.43 kg-CO_2/kg coal	Based on the IPCC (2006) default emissions for stationary combustion in the energy sector

A-USC = advanced ultra-supercritical, Btu = British thermal unit, CO_2 = carbon dioxide, GWh = gigawatt-hour, HHV = high heating value, kcal = kilocalorie, kg = kilogram, kWh = kilowatt-hour, MW = megawatt, SC = supercritical, USC = ultra-supercritical
Source Authors (2015)

Table 6.4 LCOE breakdown costs

		Factors
LCOE	Base plant	EPC
		O&M
		Fuel cost
	$deSO_x$ $deNO_x$	EPC
		O&M
		Additional fuel cost
	Financing	IRR
	CO_2	Carbon

CO_2 = carbon dioxide; $deNO_x$ = denitrification; $deSO_x$ = desulphurisation; EPC = engineering, procurement, and construction; IRR = internal rate of return; LCOE = levelised cost of electricity; O&M = operation and maintenance
Source Authors (2015)

indexes, capital costs for SC are estimated at $1897 million, and capital costs for subcritical are estimated at $1786 million. Likewise, the A-USC capital cost is an escalating cost index factor of 107.5. Therefore, the EPC cost of different types of coal combustion technologies are: A-USC at $2100 million, USC at $1931 million, SC at $1897 million, and subcritical at $1786 million. For the cost assumption of the 20-year life cycle of the plant, the cost estimates for different types of coal-fired power generation technologies are: A-USC at $2625 million, USC at $2413.75 million, SC at $2371.25 million, and subcritical at $2232.5 million.

Base plant O&M costs are calculated by dividing non-fuel O&M costs by annual generation (7008 GWh). The annual costs for this analysis are calculated by applying O&M cost differences from Sargent and Lundy (2009) to the annual O&M costs for USC from JICA (2012). Annual O&M costs are thus estimated at $0.60/kWh for A-USC, $0.70/kWh for USC, $0.72/kWh for SC, and $0.75/kWh for subcritical power plants.

Thermal coal prices grew since the second half of 2016 due to robust Chinese demand and supply tightness at several production sites (S&P Global Platts 2018). For example, the free on board Kalimantan 4200 kcal/kg gross caloric value as the received coal price rose 34% from the start of 2017 to $49.60/metric ton in January 2018. Coal prices in April 2020 dipped to their lowest level since 2010 due to the coronavirus disease (COVID-19) pandemic. Import prices of the majority of ASEAN coal reserves have seen strong momentum since mid-November 2020 and have been trending upward due to steady economic recovery. To assess the impact of high coal prices on LCOE values, the annual average fuel price assumptions used in this study were $50/ton, $80/ton, and $100/ton. For the breakdown of these costs and calculation methodologies, the interested reader is advised to refer to Otaka and Han (2015).

6.3 Results

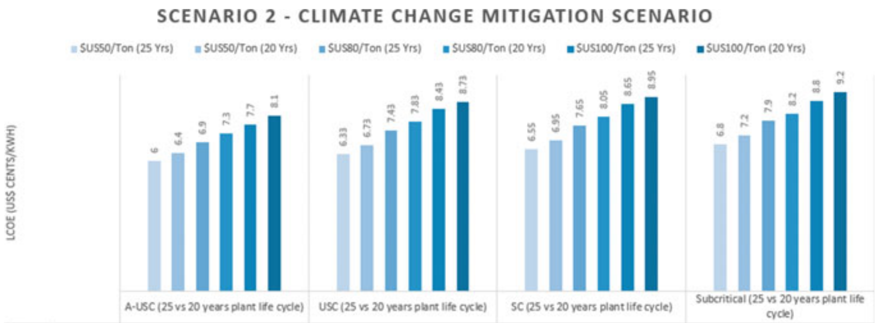
Figures 6.1, 6.2, 6.3 and 6.4 show the LCOE sensitivity analysis results in US cents/kWh for scenarios 1–4, respectively. The scenario 1 results in Fig. 6.1 suggest that HELE plants are competitive against subcritical plants without coal pricing and deSO_x and deNO_x costs. A comparison of the scenario 1–4 results in Figs. 6.1, 6.2, 6.3 and 6.4, respectively, reveal that LCOEs increase as the carbon price and deSO_x and deNO_x costs are included. However, HELE plants retain their competitive edge over the subcritical plants. The study suggests that scenario 1 offers the best economic case for HELE plants due to the lowest LCOE values for HELE plants, followed by scenarios 3, 2, and 4.

In all scenarios, for different coal prices and operating lifespans of 20 and 25 years, both coal technologies derive benefit from lifetime extensions and low coal prices. However, HELE coal technologies derive more benefit due to lower LCOE values than the subcritical technology. It is immediately apparent that, in all scenarios, A-USC offers the best economic value, followed by USC and SC. This competitiveness of HELE technologies is associated with levelised avoided costs related to high efficiency (and thus fuel savings) and low emissions.

The lower LCOEs of HELE against the subcritical technology are necessary to shift investment decisions in favour of HELE and expedite the deployment of HELE plants in the region. We thus evaluated the difference in LCOE values between

	A-USC (25 vs 20 years plant life cycle)	USC (25 vs 20 years plant life cycle)	SC (25 vs 20 years plant life cycle)	Subcritical (25 vs 20 years plant life cycle)
$US50/Ton (25 Yrs)	4.7	4.8	5	5.2
$US50/Ton (20 Yrs)	5.1	5.2	5.4	5.5
$US80/Ton (25 Yrs)	5.7	6.1	6.3	6.5
$US80/Ton (20 Yrs)	6.1	6.5	6.7	6.8
$US100/Ton (25 Yrs)	6.5	7	7.2	7.4
$US100/Ton (20 Yrs)	6.9	7.4	7.5	7.7

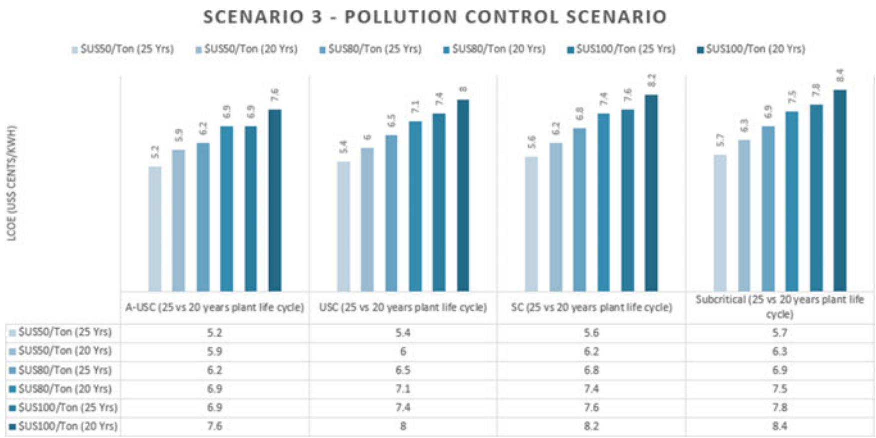
Fig. 6.1 Scenario 1—sensitivity analysis of LCOE for different coal prices and economic lifespan of the subcritical and HELE plants A-USC = advanced ultra-supercritical; CO_2 = carbon dioxide; HELE = high-efficiency, low-emission; kWh = kilowatt-hour; LCOE = levelised cost of electricity; SC = supercritical; USC = ultra-supercritical
Source Authors



	A-USC (25 vs 20 years plant life cycle)	USC (25 vs 20 years plant life cycle)	SC (25 vs 20 years plant life cycle)	Subcritical (25 vs 20 years plant life cycle)
$US50/Ton (25 Yrs)	6	6.33	6.55	6.8
$US50/Ton (20 Yrs)	6.4	6.73	6.95	7.2
$US80/Ton (25 Yrs)	6.9	7.43	7.65	7.9
$US80/Ton (20 Yrs)	7.3	7.83	8.05	8.2
$US100/Ton (25 Yrs)	7.7	8.43	8.65	8.8
$US100/Ton (20 Yrs)	8.1	8.73	8.95	9.2

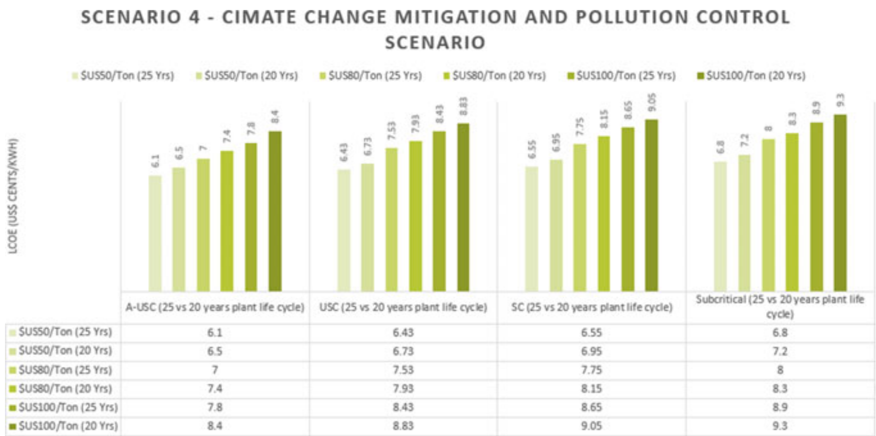
Fig. 6.2 Scenario 2—sensitivity analysis of LCOE for different coal prices and economic lifespan of the subcritical and HELE plants A-USC = advanced ultra-supercritical; CO_2 = carbon dioxide; HELE = high-efficiency, low-emission; kWh = kilowatt-hour; LCOE = levelised cost of electricity; SC = supercritical; USC = ultra-supercritical
Source Authors

HELE and subcritical technologies for each scenario using the LCOE difference metric $\Delta LCOE = |LCOE_{HELE} - LCOE_{Subcritical}|$. These differences are displayed in Figs. 6.5, 6.6, 6.7 and 6.8, for scenarios 1–4, respectively. A close analysis of these results suggests that the addition of carbon pricing in scenario 2 causes an improved gap between the LCOE values of subcritical and HELE plants compared



	A-USC (25 vs 20 years plant life cycle)	USC (25 vs 20 years plant life cycle)	SC (25 vs 20 years plant life cycle)	Subcritical (25 vs 20 years plant life cycle)
$US50/Ton (25 Yrs)	5.2	5.4	5.6	5.7
$US50/Ton (20 Yrs)	5.9	6	6.2	6.3
$US80/Ton (25 Yrs)	6.2	6.5	6.8	6.9
$US80/Ton (20 Yrs)	6.9	7.1	7.4	7.5
$US100/Ton (25 Yrs)	6.9	7.4	7.6	7.8
$US100/Ton (20 Yrs)	7.6	8	8.2	8.4

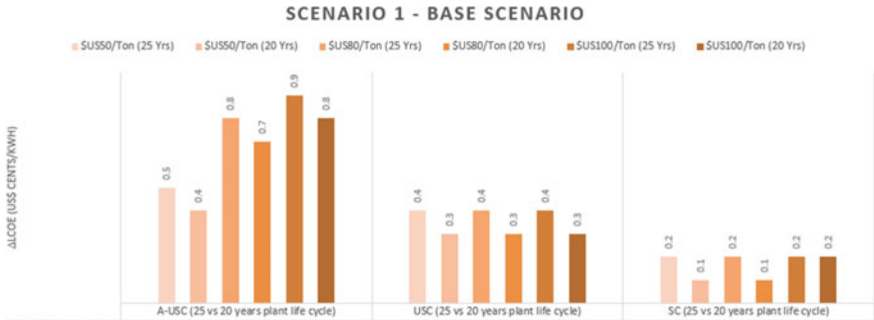
Fig. 6.3 Scenario 3—sensitivity analysis of LCOE for different coal prices and economic lifespan of the subcritical and HELE plants A-USC = advanced ultra-supercritical; CO_2 = carbon dioxide; HELE = high-efficiency, low-emission; kWh = kilowatt-hour; LCOE = levelised cost of electricity, SC = supercritical, USC = ultra-supercritical
Source Authors



	A-USC (25 vs 20 years plant life cycle)	USC (25 vs 20 years plant life cycle)	SC (25 vs 20 years plant life cycle)	Subcritical (25 vs 20 years plant life cycle)
$US50/Ton (25 Yrs)	6.1	6.43	6.55	6.8
$US50/Ton (20 Yrs)	6.5	6.73	6.95	7.2
$US80/Ton (25 Yrs)	7	7.53	7.75	8
$US80/Ton (20 Yrs)	7.4	7.93	8.15	8.3
$US100/Ton (25 Yrs)	7.8	8.43	8.65	8.9
$US100/Ton (20 Yrs)	8.4	8.83	9.05	9.3

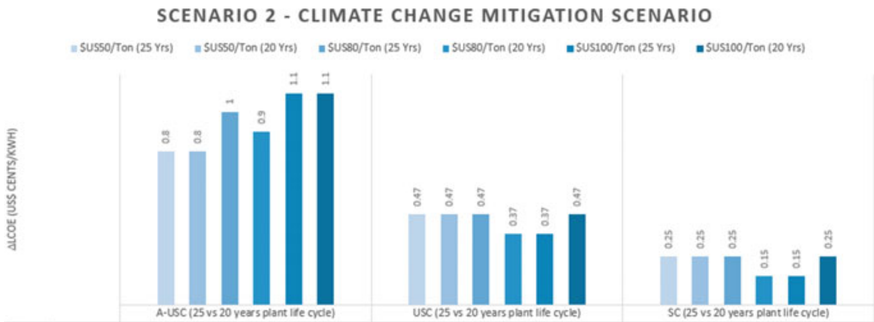
Fig. 6.4 Scenario 4—sensitivity analysis of LCOE for different coal prices and economic lifespan of the subcritical and HELE plants A-USC = advanced ultra-supercritical; CO_2 = carbon dioxide; HELE = high-efficiency, low-emission; kWh = kilowatt-hour; LCOE = levelised cost of electricity; SC = supercritical; USC = ultra-supercritical
Source Authors

with scenarios 1, 3, and 4. It is important to mention that this gap can be further improved by increasing the carbon price. Although scenario 2 yields higher LCOE prices compared with scenarios 1 and 3 (Figs. 6.1, 6.2 and 6.3), the low difference in LCOE values of HELE and subcritical technologies in scenarios 1 and 3 (Figs. 6.5 and 6.7) and scenario 2 lower LCOE values compared with scenario 4 (Figs. 6.2 and



	A-USC (25 vs 20 years plant life cycle)	USC (25 vs 20 years plant life cycle)	SC (25 vs 20 years plant life cycle)
$US50/Ton (25 Yrs)	0.5	0.4	0.2
$US50/Ton (20 Yrs)	0.4	0.3	0.1
$US80/Ton (25 Yrs)	0.8	0.4	0.2
$US80/Ton (20 Yrs)	0.7	0.3	0.1
$US100/Ton (25 Yrs)	0.9	0.4	0.2
$US100/Ton (20 Yrs)	0.8	0.3	0.2

Fig. 6.5 Scenario 1—LCOE differences between HELE and subcritical technologies for different coal prices and economic lifespan of the plant A-USC = advanced ultra-supercritical; CO_2 = carbon dioxide; HELE = high-efficiency, low-emissions; kWh = kilowatt-hour; LCOE = levelised cost of electricity; SC = supercritical; USC = ultra-supercritical
Source Authors



	A-USC (25 vs 20 years plant life cycle)	USC (25 vs 20 years plant life cycle)	SC (25 vs 20 years plant life cycle)
$US50/Ton (25 Yrs)	0.8	0.47	0.25
$US50/Ton (20 Yrs)	0.8	0.47	0.25
$US80/Ton (25 Yrs)	1	0.47	0.25
$US80/Ton (20 Yrs)	0.9	0.37	0.15
$US100/Ton (25 Yrs)	1.1	0.37	0.15
$US100/Ton (20 Yrs)	1.1	0.47	0.25

Fig. 6.6 Scenario 2—LCOE differences between HELE and Subcritical Technologies For Different Coal Prices And Economic Life Span Of The Plant A-USC = advanced ultra-supercritical; CO_2 = carbon dioxide; HELE = high-efficiency, low-emission; kWh = kilowatt-hour; LCOE = levelised cost of electricity; SC = supercritical; USC = ultra-supercritical
Source Authors

6.4) are good enough to shift economics strongly in favour of HELE plants. A similar observation reveals that scenario 4 is the second-best option, followed by scenarios 3 and 1.

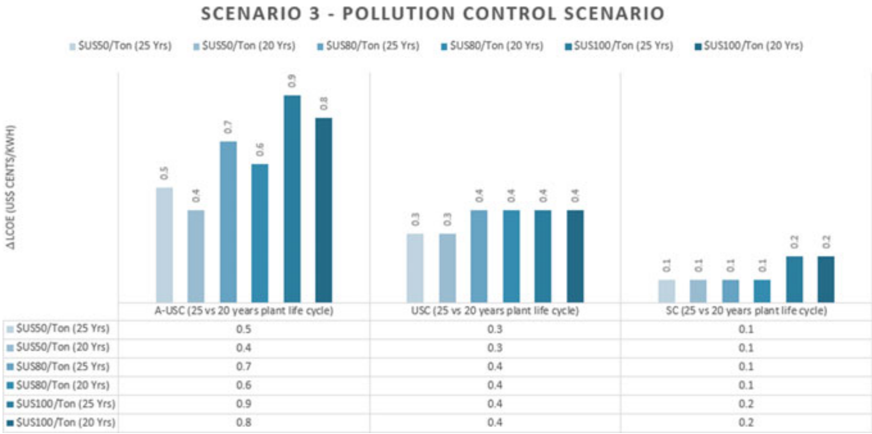


Fig. 6.7 Scenario 3—LCOE differences between HELE and subcritical technologies for different coal prices and economic lifespan of the plant A-USC = advanced ultra-supercritical; CO_2 = carbon dioxide; HELE = high-efficiency, low-emission; kWh = kilowatt-hour; LCOE = levelised cost of electricity; SC = supercritical; USC = ultra-supercritical
Source Authors

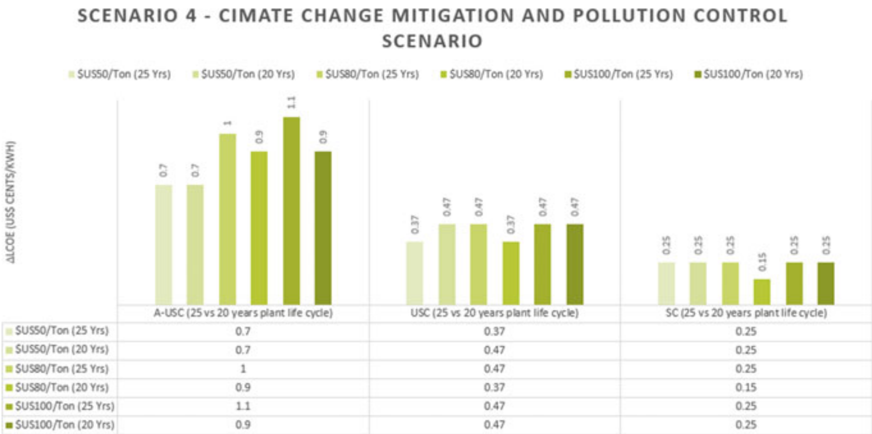


Fig. 6.8 Scenario 4—LCOE differences between HELE and subcritical technologies for different coal prices and economic lifespan of the plant A-USC = advanced ultra-supercritical; CO_2 = carbon dioxide; HELE = high-efficiency, low-emission; kWh = kilowatt-hour; LCOE = levelised cost of electricity; SC = supercritical; USC = ultra-supercritical
Source Authors

6.4 Discussion

WCA and ACE (2017) confirmed that advanced coal technologies have a slightly higher LCOE than subcritical coal due to the initial higher capital costs. In contrast, results obtained in our work suggest that HELE technologies are economically competitive against subcritical plants. Since the WCA study does not cover details of the LCOE calculations, methodology, data, and assumptions, the LCOE results for coal technologies in our work are not directly comparable with the WCA's LCOE results for coal technologies. In our work, sensitivity analysis is carried out to evaluate the impact of different coal prices for 1000 MW capacity coal-fired plants with lifespans of 20 and 25 years, and relies on IEA listed thermal efficiencies for both technologies under different scenarios from the ERIA study (Otaka and Han 2015). Therefore, our work in this paper is not comparable with the ERIA study (Otaka and Han 2015). Neither the WCA nor the ERIA study includes an economic feasibility study of A-USC for the Southeast Asia region. In our work, A-USC emerges as the most economically attractive choice for the region, followed by USC and SC.

To meet the 2DS targets, policies and associated measures are needed to address both the long- and short-term challenges linked to electricity generation from coal-fired plants. In the short term, the implementation of an efficient and impactful harmonised carbon pricing policy for coal-fired plants in all AMS is necessary to displace the subcritical plants and shift investments to emerging HELE opportunities in the ASEAN market. This would yield clean coal technology for Southeast Asia and bring many benefits to the environment and people of the region.

A recent study by the ERIA (Han 2017) indicated that AMS have lower emission standards of SO_x, NO_x, and particulates than advanced countries of the Organisation for Economic Co-Operation and Development (OECD) such as Japan, the Republic of Korea, and Germany, where clean coal technology is compulsory. In view of our analysis results, it is therefore important that tighter emissions levels for the design and operation of coal-fired plants be established through national legislation. ASEAN emission standards must match the current emission standards of air pollutants from coal-fired plants in OECD countries. Minimising the emission of air pollutants in ASEAN countries should be a precondition for the future use of coal-fired electricity generation plants to pave the way for HELE coal technologies.

Eventually, a long-term carbon policy—coupled with emissions standards and effective enforcement—will be needed under the second-best driver scenario 4 to shift the balance in favour of HELE plants. However, since the inclusion of these steps causes a further rise in the scenario 2 LCOE values, AMS need to better understand how this move will affect regional economic development before they become an effective policy tool.

The cost of solar and wind technologies is also expected to drop in the future. In countries with strict emission controls for coal-fired electricity generating plants (with carbon pricing and strict emission standards in place), switching from coal to these renewables would thus be expected. Nevertheless, the intermittent nature and low load factors associated with solar and PV technologies will likely limit their effectiveness in the region. In our future work, we aim to extend our cost–benefit analysis study by including solar and wind sources of energy generation in the ASEAN region. Financing costs also account for a considerable share of the LCOE and competitiveness of technology (IRENA 2018). In recent years, multilateral development banks have adopted more restrictive finance policies for coal electricity generating plants to reduce emissions (WCA and ACE 2017). Exploring the impact of variations in financing costs on the feasibility of HELE plants in the Southeast Asia region would be another interesting research direction.

6.5 Conclusions

Across Southeast Asia, there is a vital need to deploy HELE technologies rather than employing less efficient subcritical technology. The deployment of HELE technologies is progressing in the region, but the overall rate of deployment falls short of achieving the 2DS. ASEAN should therefore increase efforts to eliminate generation from subcritical plants and increase generation from HELE plants to meet the 2DS targets. This study reveals that the pollution control scenario (i.e., the implementation of a carbon pricing policy) surpasses the other scenarios in displacing subcritical plants sooner to pave the way for HELE technologies.

The study also confirms that:

- reduced coal prices and increased lifespans benefit both HELE and subcritical coal-fired power plants;
- HELE coal-fired power plants are economically competitive against subcritical plants; and
- A-USC coal-fired power plants are the most economically attractive choice for deployment in Southeast Asia, followed by USC and SC plants.

The conclusion is that HELE plants are economically competitive against subcritical plants, and in the short run, Southeast Asian economies should focus on devising and implementing carbon pricing to support quicker deployment of HELE and displacement of subcritical technologies. Ultimately, in the long run, a strong carbon price signal will be needed with strict emission standards to enable the transition to HELE technologies.

While this study focuses specifically on ASEAN countries, its broader lessons are applicable for the global deployment of HELE coal plants.

Conflicts of Interest The authors declare no conflicts of interest.

Funding Financial support from ERIA, and UON Singapore (UONS) under Grant number UONS_SRG_1602 is gratefully acknowledged.

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Part II
Policy Measures for Promoting Renewable Energy Projects

Chapter 7
Utilising Green Finance for Sustainability: Empirical Analysis of the Characteristics of Green Bond Markets

Farhad Taghizadeh-Hesary, Aline Mortha, Naoyuki Yoshino, and Han Phoumin

Abstract With increasing concern over climate change, many see green finance as a solution to fund sustainable projects. In particular, green bonds—a type of debt instrument which aims to finance sustainable infrastructure projects—are growing in popularity. While the literature does not contest their effectiveness in fighting climate change, research highlights the high level of risks and low returns associated with this instrument. This research investigates green bonds' characteristics, depending on the issuing region, with a special focus on Asia and the Pacific. Our findings prove that green bonds in Asia tend to show higher returns but higher risks and higher heterogeneity. Generally, the Asian green bonds market is dominated by the banking sector, representing 60% of all issuance. Given that bonds issued by this sector tend to show lower returns than average, we recommend policies that could increase the rate of return of bonds issued by the banking sector through the use of tax spillover. Diversification of issuers, with higher participation from the public sector or de-risking policies, could also be considered.

Keywords Green bonds · Asia and the Pacific · Green finance

JEL Classification Codes G12 · Q56 · O53

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H. Phoumin et al. (eds.), *Energy Sustainability and Climate Change in ASEAN*, Economics, Law, and Institutions in Asia Pacific,
https://doi.org/10.1007/978-981-16-2000-3_7

7.1 Introduction

Since the beginning of the century, the world has been consistently growing at around 3%, without following a sustainable path. The past decade (2010–2020) has been marked by rising environmental awareness and demand for the promotion of renewable energy sources. Alarming reports from the Intergovernmental Panel on Climate Change have shown that climate change is a pressing matter that needs to be addressed, and in 2015, United Nations members agreed on keeping global warming below 2 °C through Nationally Determined Contributions. The United Nations also acknowledged the matter by including 'Climate Action' in the Sustainable Development Goals. Yet, the Intergovernmental Panel on Climate Change and the United Nations Environment Programme reports highlight that further actions need to be taken to reach this goal and fulfil the Sustainable Development Goals. One of the biggest barriers in the development of renewable energy is the low level of investment (Sachs et al. 2019). As of 2018, the majority of the world's investment in energy still went to carbon-emitting sources—fossil fuels. For instance, while 39% of investments in power supply generation went to renewable energy, they only represented 19% of total investments in the energy sector (IEA 2019). In comparison, fossil fuels received about 60% of total investments in the same year (IEA 2019), with the remainder going to nuclear, biofuels, or battery storage, which are still, to a lesser extent, sources of greenhouse gas (GHG) emissions.

Funding green infrastructure projects remains an issue. In general, these projects require large borrowings, as they are capital-intensive (Peimani 2019). In addition, green projects are usually associated with 'high risk and low returns at the initial research and development stage' (Noh 2019: 40). Difficulties in accessing finance for green projects is especially the case in Asia, whose financial sector is dominated by banks; hence, banks are the main source of funding (Sachs et al. 2019). Venture capitalists are scarce in Asia, including East and Southeast Asia (Peimani 2019), although they are more likely to provide funds for green projects, while banks generally deem green projects risky (Noh 2019). In addition to risk overvaluation, Yoshino et al. (2019) highlighted the existence of a maturity mismatch between bank loans, which are generally short-term, and green projects, which are thought to be medium- to long-term projects. Thus, banks are not usually well suited to providing loans for green projects. Second-level financial institutions (e.g. insurance or pension funds) may provide funds for longer-term projects as they hold long-term money, but are reluctant to invest in electricity projects whose tariffs are generally regulated by the public sector (Yoshino et al. 2019). Overall, traditional finance is failing to provide enough funding for green projects, so there is a need for innovative finance to fill this gap. This research aims at analysing green bonds—a special type of green finance instrument.

Green bonds are fixed-income securities whose popularity has increased significantly in the past few years. While their definition varies, they are usually understood as a form of debt instrument used to finance green projects, such as renewable energy infrastructure or projects that comprise an energy efficiency dimension. The Asia and the Pacific region has been increasing its use of this instrument to bridge the gap between infrastructure projects and access to financing. In 2018, Asia and the Pacific achieved the highest regional growth of green bond issuance, with an annual rate of 35% (CBI 2019). The region has consistently been the second largest issuer of green bonds by volume since 2016, and accounts for the most diverse pool of issuers in the world, with 345 different institutions (CBI 2020a). While this new instrument may be favoured in Asia, one cannot help but wonder how the peculiar nature of the Asian financial sector, which is dominated by traditional forms of banking, may affect the characteristics of green bonds issued in the region, in terms of associated returns and risks. The recent literature on the topic has shown that green bonds tend to show lower returns than their conventional counterparts (Agliardi and Agliardi 2019; Baker et al. 2018; Gianfrate and Peri 2019; Zerbib 2020). Pham (2020) also showed that the green bond market was more volatile, and hence riskier, than the conventional bond market. However, the studies mentioned above conducted global analyses of green bonds, even though issuers' regional characteristics may play a crucial role in determining the risks and returns of these instruments.

There are several reasons behind the hypothesis that the characteristics of green bonds may depend on the region of issuance. First, economic theory and empirical research confirm that the performance of fixed-income instruments is highly dependent on macroeconomic variables such as changes in financial markets, economic uncertainty, or daily economic activity (Broadstock and Cheng 2019). Therefore, it is likely that the performance and associated risks of green bonds vary depending on the region's economic activity or the investors' uncertainty evaluation and risk aversion. A second rationale for this hypothesis comes from the difference in the inherent characteristics of financial markets, based on the region, as previously explained. This research aims to fill the gap in the literature by conducting a comparative study of the characteristics of green bonds, based on the region. In particular, we seek to determine whether the domination of traditional banking has an impact on the return of green bonds issued in Asia and the Pacific.

The study is organized as follows: Sect. 7.2 presents a literature review, which discusses green finance and recent academic debates related to green bonds. Section 7.3 introduces the data set used in this study and discusses our methodology. Section 7.4 shows the empirical results of this research, and Sect. 7.5 concludes this chapter and provides policy recommendations.

7.2 Literature Review

7.2.1 An Introduction to Green Finance and Green Bonds

The concept of green finance emerged in the 2010s and can be defined as 'a type of future-oriented finance that simultaneously pursues the development of financial industry, improvement of the environment, and economic growth' (Noh 2019:

40). Green finance is a broad concept that includes sustainable finance, for socially inclusive green projects; environmental finance, to promote environmental protection; carbon finance, targeting a reduction in GHG emissions; and climate finance, focusing on climate change adaptation and mitigation (Noh 2019). The term 'green finance' also covers a wide range of instruments, from private loans to insurance, and includes equity, derivatives, and fiscal or investment funds (Noh 2019).

In this research, we focus on green bonds. Since their creation in 2007, $754 billion worth of green bonds have been issued—primarily in the United States, China, and France—in compliance with the Green Bond Principles (CBI 2020a). Green bonds can be issued by central and local governments, banks, or corporations; and include any debt format (CBI 2019). Since 2014, Asia–Pacific's bond issuance has been growing at 35%, placing the region second in terms of green bond volume (CBI 2019). Figure 7.1 shows the evolution of the amount issued for green bonds, per region of issuance. The graph clearly shows that green bonds are a relatively new form of financial instrument, as their issuance started timidly in the early 2010s and skyrocketed after 2015. Europe is the leading issuer of green bonds, although Asia–Pacific has witnessed steady growth in recent years.

Increasing awareness of climate change could be the reason behind the surge in popularity of this instrument. Typically, green bonds are a form of fixed-income finance which can be applied to many debt formats such as private placements, securitisations, and covered bonds, as well as green loans (CBI 2020a). The particularity of this form of finance is their target, as the term only encompasses finance for climate change solutions whose proceeds go to green assets (CBI 2020a). To clarify which bonds could be qualified as such, a consortium of investment banks established the

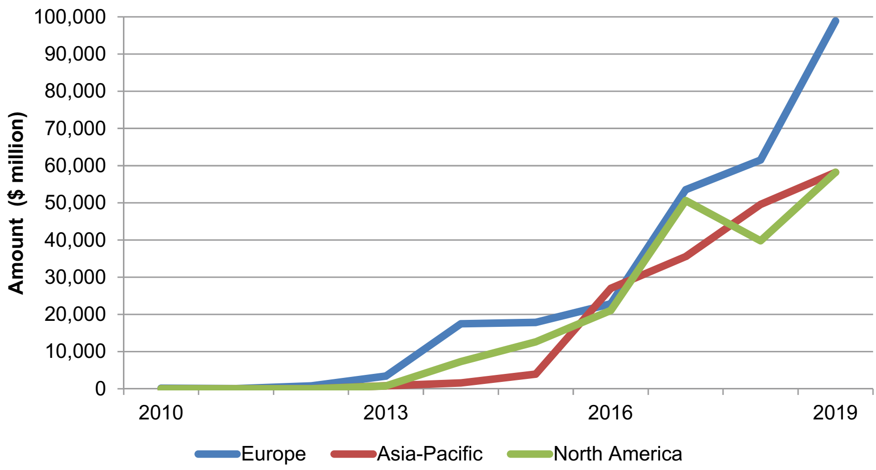

Fig. 7.1 Evolution of the amount issued for green bonds per region. *Note* 'North America' includes issuers from other regions of the world, apart from Europe and Asia-Pacific. However, the majority of the issuance in this category is from the United States and Canada. Source Authors' compilation, using data from CBI (2020b)

Green Bonds Principles in 2014, based on four main components: (i) the use of the proceeds, (ii) the process for project evaluation and selection, (iii) the management of the proceeds, and (iv) reporting (CBI 2020b). The principles do not define what is 'green' about the bonds, but merely list target sectors in which green bonds are considered valid.[1] However, these principles simply have an indicative value, and were only agreed on by the investment banks that created them. To date, there is no general taxonomy for green bonds, although the European Union has proposed including one in the upcoming European Green Deal (CBI 2020a).

7.2.2 Characteristics and Challenges of Green Bonds

The increasing popularity of this instrument has attracted the attention of academic researchers. Studies have provided some empirical proof that green bonds can be useful in fighting climate change (Flaherty et al. 2017). The main academic debate regarding green bonds is the existence of the 'green premium', also called 'greenium', defined as 'a discount that makes green bonds funded cheaper than other bonds from the same issuer' (Agliardi and Agliardi 2019: 610). Many recent studies have attempted to compare the yields of green bonds with those of conventional bonds, and the results vary depending on the methodology used. Zerbib (2020) conducted a global study, matching green bonds with similar conventional bonds and applying a two-step regression method; and concluded that green bonds had lower yields, on average. This effect was especially pronounced for bonds issued by the financial sector and low-rated bonds (Zerbib 2020). This conclusion is shared by recent studies such as Agliardi and Agliardi (2019), Baker et al. (2018), and Gianfrate and Peri (2019).

Other studies, however, tend to have mixed results. For instance, Bachelet et al. (2019) showed that the green premium was actually positive, meaning that matched green bonds had higher yields than their closest brown counterparts. Authors explain their results by arguing that the sign of the green premium depends on the issuer, and that privately issued bonds generally have a positive premium (Bachelet et al. 2019). Similarly, Hachenberg and Schriereck (2018) found that the sign of the green premium was not obvious, and depended on the rating achieved by the bond. In particular, highly rated green bonds consistently showed higher returns, which, authors argued, could make up for the external costs of issuance (Hachenberg and Schriereck 2018). Finally, Tang and Zhang (2020) could not find statistically significant evidence of the existence of the green premium, even though they used several methodologies such as matching with difference-in-differences and traditional panel techniques (fixed effect). Because of the lack of consensus regarding the green premium, MacAskill et al. (2021) provided a comprehensive literature review on

[1] The sectors are listed as follows: energy, buildings, transport, water management, waste management and pollution control, nature-based assets, industry and energy-intensive business, information technology, and communications.

the topic, detailing the methodology of each paper. The authors concluded that the majority of the studies on the topic prove the existence of a green premium in secondary markets.

Interestingly, there does not appear to be a consensus on the riskiness of green bonds either. While Bachelet et al. (2019) found that green bonds had lower variance than conventional bonds, the results of Pham (2020), who studied the volatility of the green bond market using a multivariate GARCH approach, contradict this theory. Pham (2020) proved that the market of labelled green bonds was highly volatile—far more so than the unlabelled market of conventional bonds. Generally, green bonds are strongly affected by changes in stock, changes in energy, and high-yield corporate bond markets (Reboredo and Ugolini 2020), as well as the liquidity risk of the bond market (Febi et al. 2018). There also appears to be a close link between green bonds and fixed-income and currency markets, with the green bonds receiving price spillover from the latter (Reboredo and Ugolini 2020).

Apart from their generally low returns and high risks, green bonds also represent a challenge for their issuers. Both Hachenberg and Schiereck (2018) and Sartzetakis (2020) highlighted that issuing green bonds tends to be more expensive than issuing a conventional bond, due to additional costs arising from the certification, reporting, and administrative burden of the proceeds. Sartzetakis (2020) also pointed out the need to bridge the informational gap between issuers and investors, as well as offering clear and unified green criteria to provide assurance of the green nature of the investment (Sartzetakis 2020). The major issue faced by green bonds is generally the lack of uniform definition and labelling. While the Green Bonds Principles are a major step towards this direction, they remain an informal form of labelling that was only generated by a handful of private actors, and hence, does not have global legitimacy.

A review of the literature has revealed the evolution and contribution of green bonds. As fixed-income instruments, green bonds can be useful in fighting climate change and bridging the investment gap for green projects. At the same time, these bonds are characterised by lower returns and higher risks than their conventional counterparts. Administrative costs arising from certification and lack of uniform taxonomy have added to their relative lack of attractiveness. Nevertheless, there is ongoing debate regarding the characteristics of green bonds, particularly the existence of a green premium. While results tend to vary depending on the bond rating and issuer (Bachelet et al. 2019; Hachenberg and Schriereck 2018), our research aims at proposing a regional study of the returns and risks of green bonds, with a focus on Asia and the Pacific due to the unique nature of its financial sector.

7.3 Methodology and Data Description

In this section, we detail the approach taken in this study to determine the regional characteristics of green bonds, with a specific focus on those issued in Asia and the Pacific.

7.3.1 Data and Description of Variables

The study combined two data sets from Bloomberg New Energy Finance (BNEF) and the Climate Bonds Initiative (CBI). The BNEF database only provides bonds with an issued amount of at least \$100. Both sources are considered authorities on data related to green finance, and have been employed in many recent studies (e.g. Bachelet et al. 2019; Baker et al. 2018; Chiesa and Barua 2019; Hachenberg and Schriereck 2018; Zerbib 2020). In this research, we only focus on green bonds with a minimum of \$100 in size, issued from 2014 to 2020. Hence, this study presents an analysis of unbalanced panel data of 1014 bonds, from 2017 to 2020, for a total of 1174 observations. To be precise, since we are missing many observations of the rate of return of bonds in 2017 and 2018, the length of the panel is about two time periods. A description of the variables used in the study is in Table 7.1.

In this research, we also used data on issue size and maturity provided by CBI for bonds issued from 2010 to 2020, for a total of 5358 observations. While this database contains a greater amount of green bonds, financial information such as returns and coupon rate were not provided. Therefore, we only used this data set in part of our analysis.

7.3.2 Methodology

To determine the characteristics of green bonds, we propose several methods, each assessing different dimension of bonds. First, an analysis of the distribution of issuers, maturity, and issued size is proposed, to determine whether green bonds issued in Asia present an inherent difference in their nature. We then move on to a mean–variance analysis, distinguishing between regions and sectors of issuance, to discuss how Asian green bonds compare with their counterparts in terms of risks and returns. Finally, the latter part of the empirical analysis is devoted to investigating the impact of the sector of issuance on the performance of green bonds, as measured by the rate of return, depending on the region.

To this end, we develop an econometric model, which is given by the following equation:

$$Return_{i,t} = \alpha + \sum_{i=1}^{4} \beta_i Sector_i + \sum_{t=2018}^{2020} \gamma_t Year_t + \chi_1 Coupon_i + \chi_2 Maturity_{i,t} + \epsilon_{i,t} + u_{i,t}, \tag{7.1}$$

where $Return_{i,t}$ denotes the rate of return of bond i at year t; $Sector_i$ is a set of dummy variables denoting the bond i's issuing sector; $Year_t$ is a set of dummy variables for time fixed effects; $Coupon_i$ is the bond i's coupon rate; $Maturity_{i,t}$

Table 7.1 Description of variables

Name of variable	Observations	Unit	Description	Source
Rate of return	1174	%	Rate of return on investment, as measured on 10 January each year	Bloomberg NEF
Days to maturity	2332	Days	Remaining days before the principal of a security is due and payable	Bloomberg NEF
Amount issued	2,332	$	Cumulative amount issued from the original security pricing date through to the current date for debt securities. The amount will include taps/increases or reopenings	Bloomberg NEF
Coupon rate	2332	%	Current interest rate of the security	Bloomberg NEF
Issuer name	2332	/	Name of the issuing entity	Bloomberg NEF
Region of issuance	2332	/	Set of dummy variables, with possible values being Asia and the Pacific, Europe, and North America/Others	Bloomberg NEF
Sector of issuance	2332	/	Set of dummy variables, with possible values being banking and finance, public, manufacturing, power and utilities, construction, and others	Authors' compilation, based on issuer name provided by Bloomberg NEF

Source Authors' compilation

denotes the number of days until the bond i reaches maturity at year t; and $\epsilon_{i,t}$ and $u_{i,t}$ are idiosyncratic and time-varying error terms, respectively.

While many studies use yield as a dependent variable (Bachelet et al. 2019; Hachenberg and Schriereck 2018; Zerbib 2020), we decided to use the rate of return of the bonds as our dependent variable, as an approximation of the bond's performance, due to limitations on data availability. Since this study aims to determine the impact of the type of issuer on the bond's performance, we also include a set of four dummy variables, representing the issuer's sector, constructed based on the issuer name provided by BNEF. Sectors analysed in the study are grouped into five categories: public, banking and finance, manufacturing, power and utilities, and other issuers. Public issuers are generally state and regional development banks and international organisations, but we do not include state-owned enterprises in this category. Banking and finance are essentially composed of national and local banking institutions, but investment banks and insurance are also considered. Finally, manufacturing in our sample is mostly composed of information technology and paper companies, while other issuers are dominated by companies belonging to real estate and construction.

The choice of remaining control variables is based on existing literature on the topic. The coupon rate, issued size, and maturity are often used in studies tackling the existence of the green premium, as they are essential components for matching green and brown bonds (Bachelet et al. 2019; Zerbib 2020) or as control variables in regression (Agliardi and Agliardi 2019; Chiesa and Barua 2019; Hachenberg and Schriereck 2018). Furthermore, we decided to include year fixed effects to control for variation over time, since our other control variables describe fixed characteristics of bonds.[2] Through these dummy variables, we aim to capture the effects of changes in financial market and economic policy uncertainty, as these macroeconomic variables were shown to have a significant impact on green bonds' returns (Broadstock and Cheng 2019). Tang and Zhang (2020) took a similar approach, by including year fixed effects as a control variable in their regression.

7.4 Empirical Analysis

This section presents the results of the empirical analysis and is divided into three parts. The study will first discuss the characteristics of green bonds, based on summary statistics and a general description of the data set, and will move on to mean–variance and regression analysis.

7.4.1 Summary Statistics

Since this study aims at identifying the regional characteristics of green bonds, we first delve into the description of our data set. To this end, we present summary statistics in Table 7.2, while Fig. 7.2 presents the distribution of issuers per sector and per region. Note that the summary statistics of Table 7.2 are constructed using data from CBI (2020b) due to the larger amount of bonds in their database. Summary statistics of the data set from BNEF are presented in Appendix 1, for reference.

There are already several takeaways regarding the regional characteristics of green bonds, based on Table 7.2. The number of green bonds issued in North America is a little less than three times the amount of bonds issued in the Asia–Pacific and Europe combined. However, North American bonds are characterised by their small issued

[2]The variable *Maturity* is time dependent, but its variation is fixed over time so it cannot fully capture changes in time periods.

Table 7.2 Summary statistics

Item	Amount issued ($ million)			Time to maturity		
	Asia–Pacific	Europe	North America	Asia–Pacific	Europe	North America
Observations	624	835	3899	608	823	3886
Mean	288.28	349.73	49.71	8505.14	4624.98	4502.73
Standard deviation	443.31	628.25	129.91	46,149.90	25,339.42	2067.03
Minimum	0.99	0.38	0.02	161	19	24
Maximum	4355.1	7558.6	2250.0	364,635.0	364,877.0	36,594.0

Source Authors' compilation

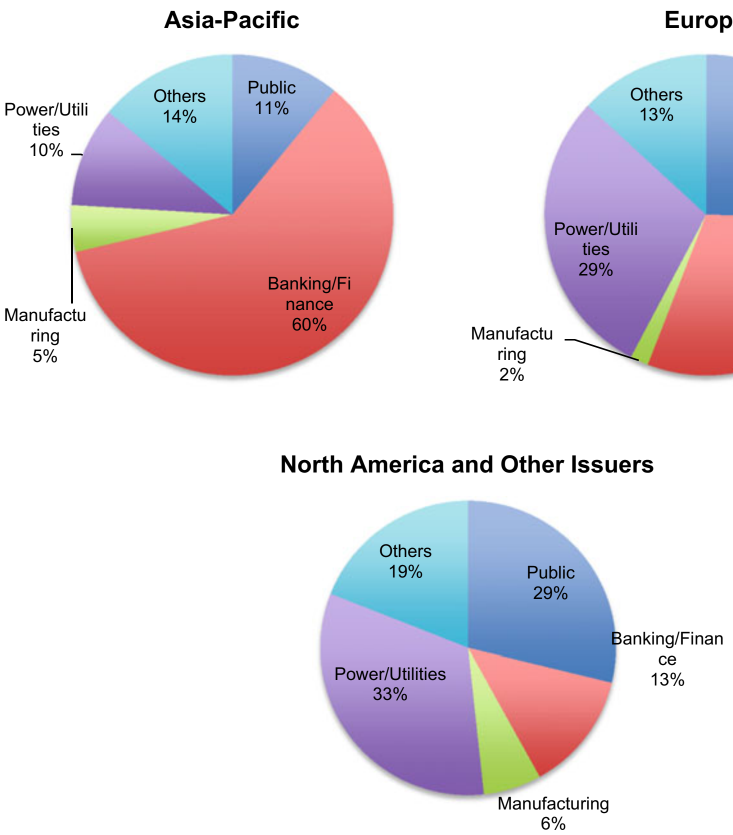

Fig. 7.2 Distribution of green bonds Issuers by sector and by region. *Source* Authors' compilation

amount, which explains why the region is lagging the Asia–Pacific and Europe in the overall green bonds market, as shown in Fig. 7.1. The dominance of small green bonds also explains the small share of North American bonds in the BNEF sample size. While bonds issued in the Asia–Pacific are comparable in size to their European counterparts, they are characterised by long-term orientation, as the number of days before reaching maturity is almost twice that of European and North American bonds. Nonetheless, it is important to note that Asian bonds are far more diverse in terms of maturity, and to a lesser extent size, than bonds issued in other regions of the world. Therefore, it might be difficult to reach an overall conclusion on the characteristics of Asian bonds, solely based on an analysis of summary statistics.

The sectoral distribution of green bond issuers provides another insight into the particular nature of Asian green bonds. While the share of issuers in Europe, North America, and the rest of the world is quite balanced between the public, utilities, and banking categories, the banking and finance sector share in the Asia–Pacific represents almost two-thirds of the total issuance. Regardless of the region, however, issuance from manufacturers, real estate, construction, and other types of firms is relatively uniform. The imbalance observed in the Asia–Pacific comes from the low shares of the public and utilities sectors, with the amount of bonds issued even lower than that of real estate, construction, and other sectors. This observation confirms our initial hypothesis of the dominance of traditional forms of banking in Asia. As the literature review showed, the Asian financial sector is mostly composed of traditional banking institutions (Peimani 2019), but this result confirms that this trend is also passed onto green finance instruments such as green bonds. Because of the risk overvaluation and maturity mismatch in traditional forms of banking (Yoshino et al. 2019), it is likely that the banking dominance has a significant impact on the performance of green bonds.

7.4.2 Mean–Variance Analysis

Since the dominance of banking and finance—as the issuers of green bonds in Asia—may affect the bonds' performance, we present a mean–variance analysis of the rate of return of bonds, based on the region of issuance and the type of issuer. The results of this analysis on the overall sample are presented in Fig. 7.3, and numerical values for mean and variance are provided in Appendix 1.

The overall analysis of the mean and variance of the returns of bonds shows high variation between regions of issuance. The relatively high variance of Asian bonds reflects the diversity of these bonds (confirmed in Sect. 4.1). In Europe, the bonds issued appear to have higher risks, with relatively low returns, and, in comparison with Asian and North American bonds, do not seem to be appealing to investors.

Figure 7.4 represents the main focus of our mean–variance analysis, as it provides a sectoral analysis of the risks and returns of green bonds, based on the region of issuance. As in Fig. 7.3, specific numerical values for the mean and variance are reported in Appendix 2. First, the mean and variance values for the manufacturing

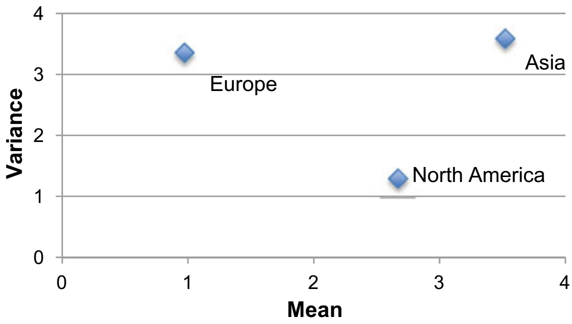

Fig. 7.3 Mean-variance analysis of the rate of return of green bonds. *Source*Authors' compilation

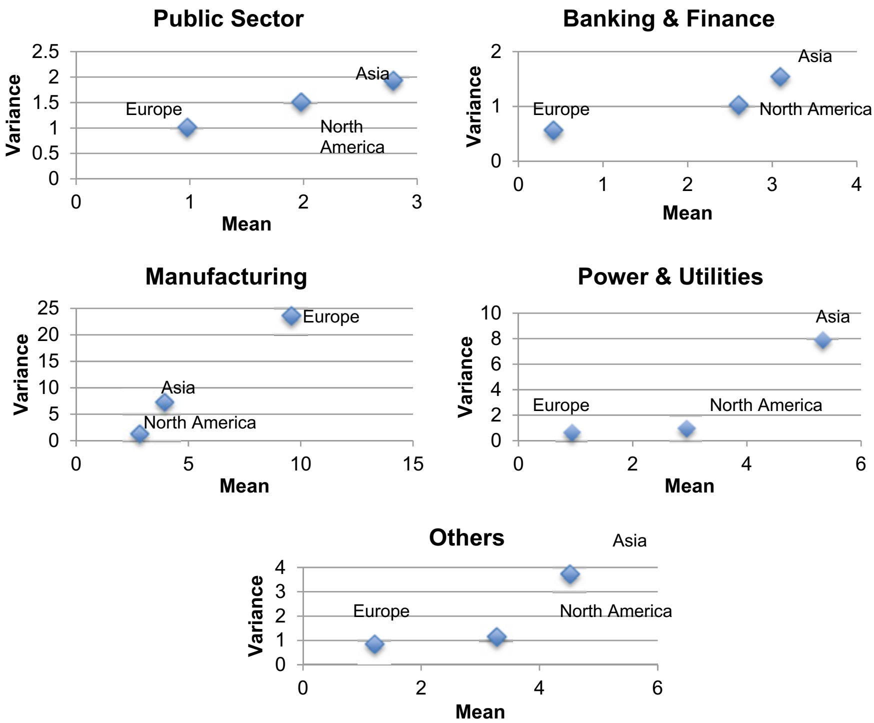

Fig. 7.4 Mean-variance analysis of rate of return of green bonds, by sector of issuance. *Source*Authors' compilation

sector stand out, as they are twice as large as those of other sectors, especially in the case of European bonds. These extreme values could be explained by the size of this particular subsample, as manufacturers represent around 5% of all issuance on average. With the notable exception of the manufacturing sector, Asian bonds tend to offer higher returns than those issued in Europe and North America, but also come with higher risks. It is interesting to note that bonds issued by companies in banking and finance in Asia do not present a striking difference with those issued by other sectors, contrary to what our hypothesis would suggest. On the other hand, bonds issued by power and utilities stand out due to their high variance, compared with other sectors. This feature could explain the small share of issuance of power and utilities in the Asia–Pacific, especially as their low risk characterises bonds issued by power and utilities companies in Europe and North America. Indeed, if bonds issued by power and utilities are deemed risky, then it is not surprising that they attract few investors, hence their relatively low share. Generally, European bonds are characterised by low returns but have low associated risks, with both the mean and variance around 1. This could explain the dominance of Europe in the green bond markets, as they could be considered more reliable assets by investors.

7.4.3 Regression Analysis

The core of our empirical findings lies in the regression analysis. While summary statistics and mean–variance analysis can highlight the characteristics and features of data on sectoral issuers and the difference in performance depending on the region and type of issuer, it cannot provide a conclusion on the relationship between the issuer and performance, nor can it help elucidate the significance of the difference in performance, depending on the region and issuer.

To answer these questions, the study introduces a regression analysis, estimated based on the equation provided in 3.2, whose results are presented in Table 7.3. Equations are estimated on each of the three regional subsamples, using White robust standard errors to control for model misspecifications, such as heteroskedasticity. The relatively short length of the panel ($t = 2$ for most observations) exempts us from additional time series testing on the data. Therefore, we use traditional panel data analysis estimation methods: pooled ordinary least squares (OLS) and generalised least squares (GLS) random effects (RE) estimator. The lack of time-varying independent variables precludes the use of a fixed effect (FE) estimator. Indeed, the inclusion of a cross-sectional FE dummy variable (for each bond) does not allow us to determine the impact of the bonds' characteristics, such as the sector of issuance. Instead, adding both FE and sectorial dummy variables provokes issues of multicollinearity, as individual characteristics are both captured by FE dummy and sectorial dummy variables. Therefore, the study prefers the RE estimator, in line with Hachenberg and Schriereck (2018).

The regression analysis provides further information on the characteristics of green bonds, as the level of significance of the variables tends to vary depending on the region of issuance. While the size and level of significance of the control variables (such as maturity and coupon rate) is rather uniform regardless of the region, the same cannot be said for variables of interest—sectoral dummy variables. The majority of sectoral dummy variables shows a lack of significance, with the notable exception

Table 7.3 Regression results

Item	Asia–Pacific		Europe		North America	
	Pooled OLS	GLS regression (random effect)	Pooled OLS	GLS regression (random effect)	Pooled OLS	GLS regression (random effect)
Days to maturity	8.80e−06 (7.28e−05)	4.97e−06 (8.85e−05)	−1.15e−06 (1.74e−06)	−1.15e−06 (1.51e−06)	3.87e−05*** (1.08e−05)	4.85e−05*** (1.28e−05)
Coupon rate	1.14*** (0.13)	1.14*** (0.16)	1.57** (0.69)	1.57 *** (0.56)	0.78*** (0.04)	0.76*** (0.04)
Banking	−0.62*** (0.19)	−0.57** (0.24)	0.33 (0.38)	0.33 (0.31)	−0.07 (0.14)	−0.04 (0.18)
Manufacturing	1.84 (1.20)	1.79 (1.50)	5.30 (4.87)	5.30 (4.70)	−0.06 (0.11)	0.05 (0.13)
Power/Utilities	1.04 (1.00)	0.97 (1.05)	−0.30* (0.15)	−0.30 (0.20)	−0.07 (0.11)	0.03 (0.15)
Others	−0.52 (0.34)	−0.42 (0.45)	−0.35 (0.33)	−0.35 (0.33)	−0.04 (0.12)	0.05 (0.16)
2018	0.06 (0.23)	0.25* (0.13)	0.07 (0.22)	0.07 (0.15)	0.10 (0.13)	−4.96e-03 (0.06)
2019	−0.05 (0.25)	−0.01 (0.19)	0.33* (0.18)	0.33*** (0.11)	0.27** (0.12)	0.36 *** (0.07)
2020	−0.63** (0.24)	−0.60*** (0.17)	0.08 (0.30)	0.08 (0.29)	−0.66*** (0.10)	−0.69*** (0.05)
Constant	0.06 (0.33)	5.83e−03 (0.40)	−1.11 (0.96)	−1.11 (0.77)	0.51*** (0.13)	0.50 *** (0.13)
Observations	366	366	603	603	205	205
R-squared	0.47	0.56	0.26	0.49	0.86	0.87

GLS = generalised least squares, *OLS* = ordinary least squares
Notes Standard errors, presented in parentheses, are obtained using the White method, robust with heteroskedasticity and serial correlation. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively
Source Authors' compilation

of banking and finance in the Asia–Pacific. In fact, our results prove that bonds issued by companies in the banking and financial sector consistently display lower rates of return. Not only does this sector issue low-performing bonds, but the size of the associated coefficient (0.62 or 0.57, depending on the method of estimation) is relatively large, as the average return of Asian bonds is 3.52. This is all the more striking as it appears that no other sectoral dummy variable shows such high levels of significance in other regions. This result confirms that the dominance of traditional forms of banking in the Asian financial sector has an impact on the characteristics of green bonds, specifically on the performance of bonds.

The significance of year dummy variables also provides a few other takeaways from this study. As the rate of return is measured on 10 January each year, each dummy captures the state of the market at the beginning of the year. Keeping this in mind, it comes as no surprise that bonds performed relatively poorly at the beginning of 2020 in the Asia–Pacific. As the majority of Asian bonds were issued in China, their performance took a severe hit from the outbreak of the coronavirus disease (COVID-19) at the end of 2019, as shown by the negative and large coefficient linked with the 2020 dummy variable. The negative sign of the same variable in the North American sample could reflect the level of dependence of the United States economy on China: the negative expected performance of Asian bonds could therefore bring down American bonds as well. Finally, the level of significance of the control variables is in line with the literature on the topic. For instance, the coupon rate was also found to be a significant variable in Chiesa and Barua (2019) and Bachelet et al. (2019). Similarly, maturity is often used as a control variable in studies assessing bonds' performance, but is generally not found to be significant (Chiesa and Barua 2019; Hachenberg and Schriereck 2018).

7.4.4 Test and Diagnostics

This section provides a discussion of the results of the tests and diagnostics to assess the quality of the results presented in the previous section. The results of the poolability test are shown in Table 7.4, while Table 7.5 displays the diagnostics, and more specifically, the distribution of standard errors between idiosyncratic and time-invariant terms. A first form of diagnostic consists of assessing the model's goodness of fit, based on the reported R-squared coefficients. Regardless of the region of issuance, half of the coefficients reflect a relatively high goodness of fit, around 0.5. The variation in the remaining values could be related to the varying sample size, but we can safely conclude that, overall, our model is acceptable, based on goodness of fit.

Table 7.4 Misspecification tests

Item	Regional sample	Test statistic	Probability
Poolability test	Asia and the Pacific	5.00	0.00***
	Europe	1.08	0.24
	North America and other issuers	31.13	0.00***

Source Authors' compilation

Table 7.5 Diagnostics

Item	Asia–Pacific	Europe	North America
Idiosyncratic error term $\epsilon_{i,t}$	2.03	3.31	0.28
Time-invariant error $u_{i,t}$	1.52	<0.00	0.33
Fraction of variance due to individual heterogeneity	0.36	<0.00	0.59

Source Authors' compilation

Table 7.4 presents the results of the poolability test, related to model misspecification, and allows us to decide between the pooled OLS estimates and the FE/RE estimates. The test results suggest that results from RE are more reliable in the case of Asia and the Pacific and North America. In the case of Europe, however, the test seems to favour pooled OLS, even though the model showed a lower R-squared overall. Overall, the results of the misspecification tests confirm the validity of our results.

Finally, we introduce empirical estimates of $\epsilon_{i,t}$ and $u_{i,t}$, time-varying and idiosyncratic error terms, in Table 7.5. As one would expect, the size of the idiosyncratic error term is rather large in all models. It is worth noting that, for European bonds, the majority of the unobserved terms are captured by time-varying factors, meaning that European bonds are quite homogenous in terms of risks. This was already observed by the mean–variance analysis of European bonds. As for the region of interest in this study, it appears that variance due to heterogeneity across bonds accounts for 36% of unobserved factors determining performance, thereby confirming the high risks associated with Asian green bonds. Indeed, if the performance of Asian bonds has such high variation, they are naturally considered less reliable by investors in general.

7.5 Conclusion and Policy Implications

7.5.1 Conclusion and Further Steps

The increasing prominence of green bonds as a financial tool to fight climate change has sparked the interest of many researchers in recent years. While it has been recognised that green bonds can be useful for climate policy, the existence of a green bond premium—meaning that green bonds show a lower rate of return than their brown or conventional counterparts—remains open to academic debate. Furthermore, researchers seem to have reached a consensus that green bonds tend to be riskier assets. However, research on green bonds provides general conclusions on the global green bonds market. No study so far has looked at the regional characteristics of green bonds, based on the place of issuance.

There are several reasons behind the hypothesis that the characteristics of green bonds may depend on the region of issuance. As economic theory and empirical research confirm that the performance of fixed-income instruments is highly dependent on microeconomic and macroeconomic variables, it is likely that the performance and associated risks of green bonds vary depending on the region's economic activity or the investors' uncertainty evaluation and risk aversion. A second rationale for this hypothesis comes from the difference in the inherent characteristics of financial markets, depending on the region. In particular, the financial sector in Asia and the Pacific is dominated by traditional banking, with venture capitalists being

Table 7.6 Regional characteristics of green bonds

Item	Asia and the Pacific	Europe	North America
Risks	High	Low	Moderate
Return	High	Low	Moderate
Homogeneity between bonds	Heterogeneous	Homogenous	Heterogeneous
Sector of issuance	Dominated by banking and finance	Well-balanced between public, utilities, and banking and other issuers	Well-balanced, between public, utilities, and banking and other issuers
Size	Large	Large	Small
Maturity	Long-term	Medium-term	Medium-term

Source Authors' compilation

quite scarce (Peimani 2019). However, Yoshino et al. 2019) highlighted that traditional banking is not necessarily an appropriate source of funding for green bonds due to maturity mismatch the conservative approach of banking. Indeed the study argued that maturity mismatch occurs as bank liabilities are short to medium-term while infrastructure projects are more long-term oriented, leading to risk overvaluation. Therefore, this study aimed to provide a comparative analysis of regional characteristics and green bonds' performance.

Using data from both BNEF and CBI, we gathered panel data composed of a total of 1174 observations, and divided them into regional subsamples. Then, the study combined summary statistics as well as mean–variance and regression analysis to reach its conclusion. The results of this research are summarised in Table 7.6.

Based on the empirical results, we were able to show that green bonds issued in Asia and the Pacific had different characteristics from those issued in Europe and North America. Specifically, Asian bonds proved to have higher returns, but also higher associated risks, as these bonds showed higher levels of heterogeneity than their European or North American counterparts. In the sample, bonds from Asia and the Pacific were generally issued in the long term, as their time to maturity was almost twice as long as that of bonds issued in other regions. However, the summary statistics revealed the dominance of the banking and finance sector in Asia—a trend that is not found in other regions. The empirical analysis proved that bonds issued by banks in Asia consistently showed lower returns; hence, there is an urgent need for diversification of issuers in Asia and the Pacific.

7.5.2 Policy Implications

A major takeaway from this study is the relatively high risk and return associated with bonds issued in Asia and the Pacific. Most importantly, the research showed that bonds issued by banks in Asia were associated with lower returns. Thus, the study proposes several policy recommendations to address each of the weaknesses of Asian bonds, and eventually encourage their issuance, as green bonds are useful tools against climate change.

First, this study proposes using tax spillover to increase the rate of return of green bonds issued by banking and finance. Since this sector represents 60% of issuance in Asia, it is likely that traditional banking will keep playing a decisive role in green finance in the region. While green infrastructure requires high up-front costs, these projects create employment and revenue in the long term. Subsidising green bonds in the early stages of project development could be a solution, as in the long term, these subsidies could be repaid to the public sector through tax spillover generated by employment and increased economic activity. A similar idea is developed in Taghizadeh-Hesary and Yoshino (2020), although not applied to green bonds in particular. Figure 7.5 displays how an increase in the rate of return can directly impact investors' portfolios and contribute to making Asian green bonds more attractive. Detailed calculations behind this policy recommendation are in Appendix 3.

Since bonds issued by the banking and finance sector in Asia are shown to have lower returns, another solution to increase their attractiveness would simply be to encourage the diversification of issuers, and generally by promoting the involvement of the public sector. As shown in Fig. 7.4, bonds issued by the public sector in Asia have high associated risks and relatively high returns. Diversification is not necessarily limited to the sector of issuance, however, and Yoshino et al. (2020) highlighted the possibility of increased financial connectivity between Asian and European public institutions in financing green infrastructure.

Finally, a last remedy to increase the amount of green bonds issued in Asia and the Pacific is to reduce the risks associated with these instruments. Several studies have highlighted the risks associated with green infrastructure projects and proposed

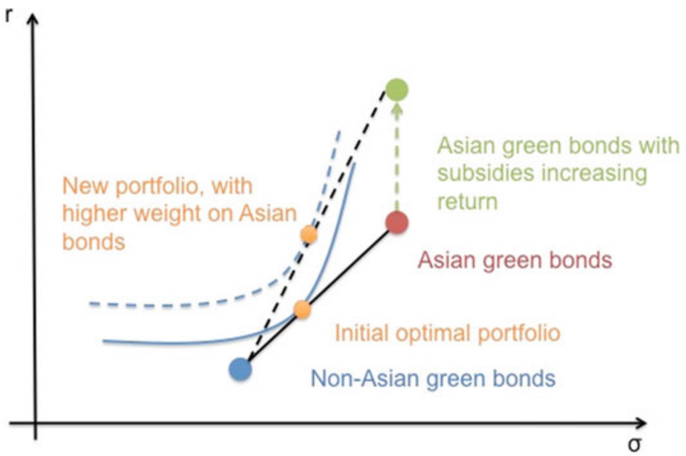

Fig. 7.5 Effect of tax spillover on rate of return of green bonds. *Source* Authors' depiction

de-risking approaches for policymakers. Komendatova et al. (2019) suggested a simplification of administrative procedures linked with project developments. They also proposed the establishment of agreements with local governments or companies, as green infrastructure projects are often more oriented towards the long term. Carafa et al. (2016) also proposed a wide array of de-risking solutions—ranging from general measures such as the unbundling of the electricity market, corruption control mechanisms, or reforms of fossil fuel subsidies, to financial de-risking measures such as credit guarantees or guaranteed power prices and the establishment of public–private partnerships to reduce political risks generally associated with green policies. Specifically, Taghizadeh-Hesary and Yoshino (2019) proposed a model green credit guarantee scheme, where a public entity absorbs the risks related to green infrastructure projects by providing a credit guarantee. As many companies involved in green projects tend to be small and medium-sized enterprises, credit guarantee schemes can allow these firms to receive higher funding, as the public entity acts as a form of collateral.

Utilising tax spillover to increase the rate of return of green bonds, diversifying sectors and regions, and de-risking policies—together—could surely contribute to increasing the attractiveness of Asian green bonds, and help to accelerate the fight against climate change in the region.

Acknowledgements This chapter results from a research project titled 'Energy Sustainability and Climate Change in ASEAN and East Asia' for the Economic Research Institute for ASEAN and East Asia (ERIA). The authors are grateful to Fukunari Kimura and Jun Arima and all members of the working group in the aforementioned project for their valuable comments and inputs, which significantly contributed to improving the quality of this study. The authors are also grateful to the Climate Bonds Initiative (CBI) for providing part of the data used in this research.

Appendix

Appendix 1: Summary Statistics with the Reduced Sample, Using Data from Bloomberg New Energy Finance

See Tables 7.7, 7.8 and 7.9.

Appendix 2: Summary Statistics by Sector

See Tables 7.10, 7.11 and 7.12.

Table 7.7 Asian subsample

Item	Observations	Mean	Std. dev	Min	Max
Rate of return	366	3.515615	3.595249	−0.216	48.955
Days to maturity	760	1806.713	1212.08	145	11,217
Amount issued	760	4.38e+08	5.52e+ 08	9.98e + 07	4.33e + 09
Coupon rate	760	3.425405	2.185087	0	15.5
Private	760	0.9052632	0.293044	0	1
Banking	760	0.5578947	0.4969639	0	1
Manufacturing	760	0.0578947	0.2336981	0	1
Power/Utilities	760	0.1263158	0.3324237	0	1
Others	760	0.1631579	0.369753	0	1

Std. dev. = standard deviation
Source Authors' compilation

Table 7.8 European subsample

Item	Observations	Mean	Std. dev	Min	Max
Rate of return	603	0.9731144	3.362978	−0.572	80.075
Days to maturity	1140	5578.874	30,351.63	147	36,6305
Amount issued	1140	6.66e+08	4.68e+08	1.00e+08	4.46e+09
Coupon rate	1140	1.162737	0.9079918	0	7.125
Private	1140	0.7894737	0.4078614	0	1
Banking	1140	0.322807	0.4677548	0	1
Manufacturing	1140	0.0210526	0.1436228	0	1
Power/Utilities	1140	0.2877193	0.4528983	0	1
Others	1140	0.1578947	0.3648023	0	1

Std. dev. = standard deviation
Source Authors' compilation

Appendix 3: Theoretical Framework for Policy Recommendation

Policy implications for this research are based on a theoretical framework, detailed below. Since Asian bonds are characterised by higher relative risks and returns, we derive the optimal portfolio of a theoretical investor, who can choose to assign a weight α on green bonds not issued in Asia and a weight $(1-\alpha)$ on Asian bonds.

The rate of return and associated variance of this portfolio is given by Eqs. (C.1 and C.2), respectively:

$$r = \alpha r_{NA} + (1-\alpha) r_A \tag{C.1}$$

Table 7.9 North American and other issuers subsample

Item	Observations	Mean	Std. dev	Min	Max
Rate of return	205	2.666659	1.306911	−0.3	7.72
Days to maturity	432	4122.398	3229.278	245	13,655
Amount issued	432	5.26e+08	3.72e+08	9.51e+07	2.25e+09
Coupon rate	432	2.958718	1.474915	0	8
Private	432	0.7222222	0.4484225	0	1
Banking	432	0.1388889	0.3462315	0	1
Manufacturing	432	0.0555556	0.229327	0	1
Power/Utilities	432	0.3333333	0.4719511	0	1
Others	432	0.1944444	0.3962313	0	1

Std. dev. = standard deviation
Source Authors' compilation

$$\sigma^2 = \alpha^2\sigma_{NA}^2 + (1-\alpha)^2\sigma_A^2 + 2\alpha(1-\alpha)\sigma_{NA/A} \tag{C.2}$$

where r, r_{NA}, and r_A denote the rate of return of portfolio, non-Asian bonds, and Asian bonds respectively; σ^2, σ_{NA}^2, σ_A^2, and $\sigma_{NA/A}$ denote the variance of portfolio, non-Asian bonds, Asian bonds, and covariance between Asian and non-Asian bonds.

Then, the theoretical investor aims at maximising the utility derived from their portfolio. This study assumes that their utility function is given by:

$$U(r, \sigma, \alpha) = r - \beta\sigma \tag{C.3}$$

Thus,

$$U(r, \sigma, \alpha) = \alpha r_{NA} + (1-\alpha)r_A - \beta\left\{\alpha^2\sigma_{NA}^2 + (1-\alpha)^2\sigma_A^2 + 2\alpha(1-\alpha)\sigma_{NA/A}\right\} \tag{C.4}$$

The investor's utility maximisation problem is given by Eq. (C.5)

$$\max_{\alpha} U(r, \sigma, \alpha) \tag{C.5}$$

The first order condition, with respect to α, is:

$$\frac{\partial U}{\partial \alpha} = (r_{NA} - r_A) - \beta\left\{2\alpha^*\sigma_{NA}^2 - 2\left(1-\alpha^*\right)\sigma_A^2 + \left(2-4\alpha^*\right)\sigma_{NA/A}\right\} = 0 \tag{C.6}$$

Solving this equation for α^*, we obtain the optimal weight the investor can put on non-Asian bonds.

Table 7.10 Asian subsample

Item		Obs	Mean	Std. dev	Min	Max
Public sector	Rate of return	40	2.78625	1.938086	−0.216	9.03
	Days to maturity	72	2501.5	1105.893	555	4815
	Amount issued	72	6.47e+08	4.60e+08	1.10e+08	2.24e+09
	Coupon rate	72	2.273056	1.815014	0	7.125
Banking/Finance	Rate of return	221	3.086752	1.548352	−0.059	6.95
	Days to maturity	424	1466.811	820.2578	145	4797
	Amount issued	424	5.05e+08	6.85e+08	1.02e+08	4.33e+09
	Coupon rate	424	3.296255	1.611012	0	6.5
Manufacturing	Rate of return	17	3.903	7.30048	– 0.184	26.092
	Days to maturity	44	1914.045	939.1773	472	4305
	Amount issued	44	2.69e+08	1.71e+08	1.00e+08	7.05e+08
	Coupon rate	44	2.105455	2.437531	0	7.5
Power/Utilities	Rate of return	37	5.32027	7.92042	0.744	48.955
	Days to maturity	96	1922.677	1069.983	218	4723
	Amount issued	96	2.85e+08	1.42e+08	9.98e+07	5.90e+08
	Coupon rate	96	3.845875	1.855951	0.85	7.9
Others	Rate of return	51	4.507686	3.735481	0.231	17.395
	Days to maturity	124	2437.669	1938.155	174	11,217
	Amount issued	124	2.67e+08	1.44e+08	1.00e+08	6.00e+08
	Coupon rate	124	4.678968	3.273824	0.09	15.5

Std. dev. = standard deviation
Source Authors' compilation

$$\alpha^* = \frac{\frac{1}{\beta}(r_{NA} - r_A) - \left(2\sigma_{NA/A} - 2\sigma_A^2\right)}{2\sigma_{NA}^2 + 2\sigma_A^2 - 4\sigma_{NA/A}} \tag{C.7}$$

To change this optimal weight, policymakers in Asia and the Pacific can act on parameters of this utility maximisation problem, namely on r_A and σ_A^2.

For instance, one can increase the weight put on Asian bonds by increasing the rate of return r_A, by subsidising bonds through tax spillover, denoted by θ_{tax}. The new rate of return of this subsidised portfolio, denoted by $r_{spillover}$, is given by Eq. (C.8):

$$r_{spillover} = \alpha r_{NA} + (1 - \alpha)(r_A + \theta_{tax}), where \theta_{tax} \geq 0 \tag{C.8}$$

Then, the investor's utility becomes:

$$\begin{aligned} U(r, \sigma, \alpha)_{spillover} &= \alpha r_{NA} + (1 - \alpha)(r_A + \theta_{tax}) \\ &\quad - \beta\left\{\alpha^2\sigma_{NA}^2 + (1 - \alpha)^2\sigma_A^2 + 2\alpha(1 - \alpha)\sigma_{NA/A}\right\} \end{aligned} \tag{C.9}$$

Table 7.11 European subsample

Item		Obs	Mean	Std. Dev	Min	Max
Public sector	Rate of return	153	0.9720131	1.020399	−0.556	3.263
	Days to maturity	240	2667.183	1878.802	147	11,266
	Amount issued	240	8.56e+08	7.43e+08	1.16e+08	4.46e+09
	Coupon rate	240	1.16585	0.8552492	0	3.3
Banking/Finance	Rate of return	184	0.4063315	0.5703005	−0.572	2.615
	Days to maturity	368	2601.359	1844.092	151	12,251
	Amount issued	368	6.35e+08	3.32e+08	1.06e+08	1.74e+09
	Coupon rate	368	0.6791848	0.5777155	0	2.5
Manufacturing	Rate of return	11	9.553909	23.62808	0.221	80.075
	Days to maturity	24	2298.333	1084.292	753	4692
	Amount issued	24	3.65e+08	2.55e+08	1.08e+08	8.37e+08
	Coupon rate	24	2.371333	2.296941	0.5	7.125
Power/Utilities	Rate of return	176	0.9256023	0.6572373	−0.224	3.602
	Days to maturity	328	12,709.1	55,942.4	473	366,305
	Amount issued	328	6.79e+08	3.68e+08	1.09e+08	1.93e+09
	Coupon rate	328	1.374195	0.7278362	0	4.496
Others	Rate of return	79	1.206405	0.8654128	−0.202	4.732
	Days to maturity	180	2993.033	1406.762	888	9954
	Amount issued	180	4.93e+08	2.89e+08	1.00e+08	1.14e+09
	Coupon rate	180	1.600711	0.9940294	0.1	5

Std. dev. = standard deviation
Source Authors' compilation

Solving the utility maximisation problem, we obtain the new optimal weight for this investor:

$$\alpha^*_{spillover} = \frac{\frac{1}{\beta}(r_{NA} - (r_A + \theta_{tax})) - \left(2\sigma_{NA/A} - 2\sigma_A^2\right)}{2\sigma_{NA}^2 + 2\sigma_A^2 - 4\sigma_{NA/A}} \tag{C.10}$$

Note that

$$\alpha^*_{spillover} \leq \alpha^* \tag{C.11}$$

where the equality holds if and only if $\theta_{spillover} = 0$.

Since α^* denotes the optimal portfolio weight attributed to bonds not issued in Asia and the Pacific, policymakers can make green bonds more attractive for investors by using spillover from tax returns.

Table 7.12 North American and other issuers subsample

Item		Obs	Mean	Std. dev	Min	Max
Public sector	Rate of return	59	1.973627	1.518473	−0.3	7.72
	Days to maturity	120	3083.367	2605.471	265	12,148
	Amount issued	120	4.47e+08	3.33e+08	1.00e+08	1.20e+09
	Coupon rate	120	2.060917	1.905424	0	8
Banking/Finance	Rate of return	27	2.594	1.033445	−0.004	4.205
	Days to maturity	60	2,902.767	2,313.379	245	10,886
	Amount issued	60	7.24e+08	6.14e+08	1.10e+08	2.25e+09
	Coupon rate	60	2.847733	1.344723	0.25	5.25
Manufacturing	Rate of return	13	2.812	1.428624	0.05	5.219
	Days to maturity	24	3279.167	1107.982	1140	5422
	Amount issued	24	9.77e+08	3.39e+08	4.50e+08	1.50e+09
	Coupon rate	24	2.633333	1.938997	0	5.5
Power/Utilities	Rate of return	67	2.92809	0.9791559	0.068	4.512
	Days to maturity	144	5643.694	3752.187	705	12,103
	Amount issued	144	4.31e+08	1.68e+08	9.51e+07	7.50e+08
	Coupon rate	144	3.449056	0.7427922	1	4.6
Others	Rate of return	39	3.267821	1.166826	0.789	7.079
	Days to maturity	84	4110.881	3026.646	894	13,655
	Amount issued	84	5.33e+08	5.33e+08	1.00e+08	1.23e+09
	Coupon rate	84	3.572952	0.8995293	1.625	5.875

Std. dev. = standard deviation
Source Authors' compilation

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Chapter 8
Potential Green Hydrogen from Curtailed Electricity in ASEAN: The Scenarios and Policy Implications

Han Phoumin, Fukunari Kimura, and Jun Arima

Abstract The power generation mix of the Association of Southeast Asian Nations (ASEAN) is dominated by fossil fuels, which accounted for almost 80% in 2017 and are expected to account for 82% in 2050 if the region does not transition to cleaner energy systems. Solar and wind power is the most abundant energy resource but contributes negligibly to the power mix. Scalable electricity production from wind and solar energy faces tremendous challenges due to system integration practices in ASEAN. Investors in solar or wind farms face high risks from electricity curtailment if surplus electricity is not used. Technologies for battery storage (lithium-ion batteries) have been developed to handle surplus electricity production from wind and solar energy but they remain costly. Hydrogen produced from electrolysis using surplus electricity, however, has numerous advantages that complement battery storage, as hydrogen can be stored as liquid gas, which is suitable for many uses and easy to transport. Employing the policy scenario analysis of the energy outlook modelling results, this paper examines the potential scalability of renewable hydrogen production from curtailed electricity in scenarios of high share of variable renewable energy in the power generation mix. The study intensively reviewed potential cost reduction of hydrogen production around the world and its implications for changing the energy landscape. The study found many social and environmental benefits as hydrogen can help increase the share of renewables in decarbonising emissions in ASEAN.

Keywords Energy transition · Renewables · Hydrogen · Fossil fuels · System integration

JEL Codes O20 · Q30 · Q2 · Q35 · Q40

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H. Phoumin et al. (eds.), *Energy Sustainability and Climate Change in ASEAN*, Economics, Law, and Institutions in Asia Pacific,
https://doi.org/10.1007/978-981-16-2000-3_8

8.1 Introduction

The economic, social, and political dynamics of the Association of Southeast Asian Nations (ASEAN) have made it one of the fastest-growing regions. However, Southeast Asia faces great challenges in matching its energy demand with sustainable energy supply as the region transitions to a lower-carbon economy. The transition requires development and deployment of green energy sources. Growing energy demand can be met by energy supply produced by renewables and other clean energy alternatives such as hydrogen and by clean technologies. Whilst Organisation for Economic Co-operation and Development (OECD) countries have quickly reduced greenhouse gas emissions in response to the commitments of the Paris Climate Conference or the 21st Conference of the Parties (COP21), developing Asia has some way to go to balance economic growth and affordable and available energy. Much of the future energy mix of emerging ASEAN countries will rely on fossil fuel to power economic development. However, they can follow a renewable energy path to economic growth, social well-being, and environmental sustainability.

Increasing the share of renewables is hindered by the trade-off between political issues, energy affordability, and affordable technologies. Although countries have rich wind and solar resources, production of scalable electricity is greatly encumbered by system integration practices. Investors in solar or wind farms will face high risks from electricity curtailment when they produce too much electricity and grid cannot absorb it. In this case, the curtailed electricity poses risks to solar or wind projects' revenue if there is no technology to utilise or store the surplus electricity. Many countries have recently developed technologies for battery storage (lithium-ion batteries) for surplus electricity produced from wind and solar energy, but battery storage remains costly. Hydrogen produced from electrolysis using surplus electricity, however, has numerous advantages that complement battery storage, as hydrogen can be stored as liquid gas, which is suitable for many uses and easy to transport.

In the past 10 years, renewable energy proponents have rarely mentioned hydrogen although it is frequently used in the ammonia, petrochemical, and oil refining industries. The use of hydrogen has been accelerating, however, as it is versatile and can be produced from many energy sources. Hydrogen fuels have untapped potential as clean energy. About 120 million tonnes[1] of hydrogen are produced globally, of which two-thirds are pure hydrogen and one-third mixed with other gases (IEA 2020). Hydrogen can be produced from either fossil fuels or from renewables. About 95% of hydrogen is produced from coal and gas without carbon capture, sequestration, and storage (CCS) ('grey' hydrogen), with only small amounts produced with CCS ('blue' hydrogen). About 5% of total hydrogen production uses renewables ('green' hydrogen [H2]). Reducing greenhouse gas emissions is high on the global agenda under COP 21 and the upcoming COP26, which will require leaders to pursue alternative fuel pathways, shifting from fossil fuel–based to clean energy systems. Although

[1]Tonne = metric ton. 1 metric ton = 1000 kg.

its share remains small in global energy consumption, hydrogen fuel represents positive growth potential as world leaders start to see the great benefit and promise of its use to abate climate change. Hydrogen fuel enjoys political support in many advanced countries, including Germany, the Netherlands, and several other OECD countries. In many ASEAN countries, hydrogen as an alternative fuel is not yet on the policy agenda. The ASEAN Plan of Action for Energy Cooperation (APAEC) Phase 2, however, will include policy measures to encourage emerging and alternative technologies such as hydrogen and energy storage.

The potential use of hydrogen in transport, power generation, and industry has been proven by projects around the world. Renewable hydrogen has attracted leaders' attention as an option to increase the share of renewables in electrical grids amidst the falling cost of renewable electricity from wind and solar energy. The International Renewable Energy Agency (IRENA 2018) predicted that the cost of electrolysers, the devices used to produce hydrogen from water, will halve from US$840 now to US$420 per kilowatt by 2040. Renewable hydrogen production could be the cheapest energy option in the foreseeable future. The cost-competitiveness of producing renewable H2 is key for the wide adoption of hydrogen. Renewable H_2 production costs dropped drastically from US$10–US$15/kilogram (kg) in 2010 to US$4–US$6/kg in 2020 (Hydrogen Council 2020). Costs are expected to decrease to US$2.00–US$2.50/kg of H2 in 2030, which is competitive with hydrogen production using natural gas through steam methane reforming with CCS.

Hydrogen is a clean energy carrier and can be stored and transported for use in hydrogen-run vehicles, synthetic fuels, upgrading of oil and/or biomass, ammonia and/or fertilizer production, metal refining, heating, and other end uses. Developing hydrogen, therefore, is an ideal pathway to sustainable clean energy systems and can help scale renewables such as solar and wind energy. Adopting renewable hydrogen would bring more renewables into the energy mix and could be a game changer in the transition from fossil dependence to a cleaner energy system. Hydrogen could help integrate the current electricity system with wind and solar energy. Solar and wind penetration of the electrical grid is hindered by the high intermittency of electricity from wind and solar energy, and many grid operators around the world are, therefore, hesitant to include a large share of it. For ASEAN Member States (AMS) that can afford to invest more in renewable energy, an important concern is the need for electricity storage and smart grids to support higher renewable energy penetration levels. Smart grid technologies already significantly contribute to electricity grids in some OECD countries. However, these technologies are continually being refined and are vulnerable to potential technical and nontechnical risks. Renewable energy growth is constrained by weak infrastructure development and the slow deployment of technology, including the capacity to assess and predict the availability of renewable energy sources in many developing countries. Hydrogen can provide an unlimited supply of electricity from wind and solar energy. How it works is simple. On-site electrolysers convert electricity excess from wind and solar energy into hydrogen, which can be stored for a longer time and used to produce electricity, industrial heat, vehicle fuel cells, and fertilizers such as ammonia, and to power petrochemical processes.

8.2 The Study's Objectives and Structure

The study investigates the potential of renewable hydrogen as a clean energy source for ASEAN's energy mix, which will need huge investment in hydrogen energy–related industries. The paper aims to do the following:

(i) Use energy modelling scenarios to explore policy options of increasing the share of renewables, particularly wind and solar energy, in the power mix, and explore the possibility of electricity curtailment resulting from the high share of renewables that can be converted to hydrogen production.
(ii) Estimate the potential emission abatement resulting from the introduction of hydrogen produced using curtailed renewable electricity.
(iii) Review scalable renewable electricity from wind and solar energy from a cost reduction perspective, considering global experience.
(iv) Review technologies and cost perspectives of hydrogen produced using curtailed electricity.
(v) Review a hydrogen policy and road map that can be applied to ASEAN.

Hydrogen adoption and development could be highly beneficial for ASEAN. Renewable hydrogen will enable the deployment of variable renewable energy (VRE) and will be a game changer by breaking the barrier of integrated traditional power systems, which cannot absorb a high share wind and solar energy. The paper highlights how public awareness and participation in promoting hydrogen use, especially willingness to pay and public financing of renewable hydrogen production, will promote investment. Section 8.2 reviews the literature. Section 8.3 explains the methodological approaches. Section 8.4 discusses the study's results. Section 8.5 draws conclusions and recommends policy.

8.3 Literature Review

8.3.1 Hydrogen Adoption and Development

The Economic Research Institute for ASEAN and East Asia's research on hydrogen energy since 2017 has identified the significant potential of hydrogen energy supply and demand in East Asia. By 2040, the cost of hydrogen will decrease by more than 50% if it is adopted in all sectors. The target price of US$2.00–US$2.50/kg of H2 in 2040 is competitive with the price of gasoline. The cost of supplying hydrogen is about 3–5 times higher than that of gas, mainly due to limited investment in hydrogen supply chains and the lack of a strategy to widely adopt hydrogen usage. The wide adoption and usage of hydrogen will need time to ensure cost-competitiveness and safety, especially for automobiles. The large-scale hydrogen-based energy transition from 'grey' and 'blue' to 'green' hydrogen will happen concurrently with a global shift to renewables. 'Green' hydrogen can face current system integration challenges that have blocked increasing the share of wind and solar energy.

Hydrogen uptake will happen in several ways. The European Union's ambition to make Europe the first climate-neutral continent by 2050 includes a large role for hydrogen fuel. Many OECD hydrogen projects will come online by 2023, including electrolysers and pipelines to distribute hydrogen to end users. Since hydrogen is a clean energy carrier, it has the best prospect of accelerating hydrogen storage in island countries such as Indonesia, Malaysia, the Philippines, Brunei, Australia, and New Zealand. In East Asia, China is one of the biggest potential producers and consumers of hydrogen energy. China has recently accelerated hydrogen investment support to local industries, where about $2 billion is expected to be invested in the next few years. China plans to put in place 300 hydrogen fuelling stations in 2025 and scale up to 1000 by 2030 to support the deployment of 50,000 to 1 million fuel cell electric cars from 2025 to 2030 (Hydrogen Council 2019). Japan is promoting the global adoption of hydrogen for vehicles, power plants, and other potential uses. Japan had planned to provide the 2020 Olympics with fuel cell shuttle buses.

In the United States (US), more than 10 million tonnes of hydrogen are produced annually to meet demand mainly in oil refining and in ammonia production for fertilizer. About 95% of hydrogen produced in the US comes from natural gas feedstock (DOE 2020c). The US has about 1600 miles of hydrogen pipeline, more than 26,000 hydrogen fuel cell forklifts in use, more than 30 hydrogen fuel cell buses, and more than 40 public stations supporting more than 7500 fuel cell cars. California alone has about 40 hydrogen stations for passenger cars; other states with such stations include Connecticut, Hawaii, Massachusetts, Michigan, and South Carolina. On 23 January 2020, the US Department of Energy announced up to US$64 million in funding to advance innovations that will support transformational research and development (R&D), and innovative hydrogen concepts that will encourage market expansion and increase the scale of hydrogen production, storage, transport, and use.

In ASEAN, Brunei Darussalam leads in the hydrogen supply chain and has supplied liquefied hydrogen from Muara port to Japan since late 2019. However, the liquefied hydrogen process consumes a great deal of energy to cool gaseous hydrogen into liquid hydrogen at temperatures of –253 °C and lower. The hydrogen supply chain demonstration project, in cooperation with Japan's government, explored an alternative way of shipping hydrogen using a new technology called liquid organic hydrogen carrier. If the technology is economically viable, it will pave the way for market access worldwide and overcome hydrogen supply chain barriers.

The use of hydrogen is expanding in transport and gaining momentum. For example, India is starting to call for foreign investment in fuel cell vehicles and hydrogen transport infrastructure development in some pilot cities. In Japan, the Tokyo metropolitan government will increase the number of hydrogen buses to 100 in 2020, and in Malaysia, the Sarawak government will soon start to operate hydrogen buses. Singapore is working closely with Japanese companies to explore developing hydrogen fuel to decarbonise emissions.

Japan is pioneering the renewable hydrogen economy, in which producing hydrogen through electrolysis of renewable electricity from wind, solar, and nuclear energy could be a game changer in decarbonising emissions. Japan is the first country in East Asia to adopt a basic hydrogen strategy to make sure that hydrogen production will reach cost parity with gasoline fuel and power generation in the long term. A 2019 Fuji Keizai market survey of potential hydrogen demand in Japan indicated that hydrogen demand will increase 56-fold by 2030, needing investment estimated at more than JPY400 billion. Although Japan's government and businesses are making efforts to kick-start hydrogen adoption and usage, realising a hydrogen society will largely depend on whether the cost of hydrogen production is competitive and whether society is willing to pay. The Republic of Korea has set a bold target for hydrogen use: 10% of total energy consumption by 2030 and 30% by 2040 to power selected cities and towns.

In many ASEAN countries, hydrogen is not yet on the policy agenda as an alternative fuel. However, APAEC, which is under preparation for endorsement at the ASEAN Ministers on Energy Meeting in November 2020, will include policy measures to promote emerging and alternative technologies such as hydrogen and energy storage. APAEC will help AMS increase their adoption of hydrogen to enlarge the share of hydrogen in the energy mix.

8.3.2 Selected Pathways of Hydrogen Production Processes

Hydrogen emits zero emissions when used in combustion for heat and energy. If pure hydrogen (H_2) combusts by reacting with oxygen (O_2), it will form water (H_2O) and release energy that can be used as heat, in thermodynamics, and for thermal efficiency. Hydrogen is the most abundant chemical substance in the universe, but it is rarely found in pure form (H2) because it is lighter than air and rises into the atmosphere. Hydrogen is found as part of compounds such as water and biomass and in fossil fuels such as coal, gas, and oil (DOE 2020a). Several ongoing researches use two processes to extract hydrogen fuel: steam methane reforming, mainly applied to extract hydrogen from fossil fuels, and electrolysis of water, applied to extract hydrogen from water using electricity.

Steam methane reforming extracts hydrogen from methane using high-temperature steam (700–1000 °C). The product of steam methane reforming is hydrogen, carbon monoxide, and small amount of carbon dioxide (DOE 2020b). Most hydrogen is produced through this process, which is the most mature technology. Given how cheap natural gas is in the US and other parts of the world, hydrogen is one pathway to transition to a cleaner economy if steam methane reforming can be augmented with CCS. Technically, the chemical reaction process can be written as follows.

Steam methane reforming reaction (heat must be supplied through an endothermic process):

$$CH_4 + H_2O\,(+heat) \rightarrow CO + 3H_2$$

Applying water–gas shift reaction produces more hydrogen:

$$CO + H_2O \rightarrow CO_2 + H_2 \ (+small\ amount\ of\ heat)$$

At this stage, carbon dioxide and other impurities are removed from the gas stream, so the final product is pure hydrogen.

Instead of steam methane reforming, partial oxidation can be applied to methane gas to produce hydrogen. However, the partial oxidation reaction produces less hydrogen fuel than does steam methane reforming. Technically, partial oxidation is an exothermic process, producing carbon monoxide and hydrogen and giving off heat:

$$CH_4 + \frac{1}{2}O_2 \rightarrow CO + 2H_2 \ (+heat)$$

Applying a water–gas shift reaction produces more hydrogen:

$$CO + H_2O \rightarrow CO_2 + H_2 \ (+small\ amount\ of\ heat)$$

Electrolysis can produce hydrogen by splitting water into hydrogen and oxygen in an electrolyser, which consists of an anode and a cathode. Electrolysers may have slightly different functions depending on the electrolyte material used for electrolysis.

The polymer electrolyte membrane (PEM) electrolyser is an electrochemical device to convert electricity and water into hydrogen and oxygen. The PEM electrolyte is solid plastic. The haft reaction that takes place on the anode side forms oxygen, protons, and electrons:

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^-$$

The electrons flow through the external circuit and the hydrogen ions move across the PEM to the cathode, in which hydrogen ions combine with electrons from the external circuit to form hydrogen gases:

$$4H^+ + 4e^- \rightarrow 2H_2$$

PEM electrical efficiency is about 80% in terms of hydrogen produced per unit of electricity used to drive the reaction. PEM efficiency is expected to reach 86% before 2030.

Another method is alkaline water electrolysis, which takes place in an alkaline electrolyser with alkaline water ($pH > 7$) with an electrolyte solution of potassium hydroxide (KOH) or sodium hydroxide (NaOH). In the alkaline electrolyser, the two electrodes are separated. Hydroxide ions (OH^-) are transported through the electrolyte from cathode to anode, with hydrogen generated on the cathode side. This method has been commercially available for many years, and the new method of using solid alkaline exchange membrane is promising as it is working in a laboratory environment.

8.4 Methodology and Scenario Assumptions

Hydrogen is used mainly to produce petrochemicals and ammonia. The potential of hydrogen, however, clearly remains untapped in ASEAN countries because it is a clean energy carrier that can be produced from various sources using fossil fuel and renewable energy. To build a hydrogen society, the cost of producing hydrogen must be competitive with that of conventional fuels, such as gas, for transport and power generation.

Renewable or ‘green’ hydrogen must be produced using renewable electricity from wind, solar, hydropower, and geothermal energy. Excess electricity from nuclear power, however, could be used to produce hydrogen as nuclear power plants provide base-load power and cannot be easily ramped up and down. During low demand, electricity from nuclear energy and VRE could be used to produce hydrogen. To produce renewable hydrogen using VRE, it is important to know the predicted available curtailed electricity resulting from power system integration challenges due to higher share of renewables.

Two components determine the cost to produce ‘green’ hydrogen: electricity cost from renewables and the cost of electrolysis. If these costs could be reduced significantly to allow the cost of hydrogen production to be competitive with that of natural gas, then hydrogen adoption and usage could be accelerated. This study reviews the falling cost of VRE and electrolysis to see how their current and future cost could allow competitive hydrogen production cost. High VRE penetration of the electrical grid is the biggest challenge for the grid operator as electricity from VRE is variable and intermittent. Upgrading the grid system with the Internet of Things to create a smart grid could allow more penetration by VRE; otherwise, VRE electricity would be greatly curtailed due to a weak power grid system. This study calculates potential renewable hydrogen production and potential emission abatement under various scenarios assuming the following:

(i) Under current grid system integration, curtailment is likely to be 20–30% if the VRE share in the power mix exceeds more than 10%. Given the large potential of hydropower, geothermal, wind, and solar energy, increasing the share of renewables is technically possible using hydrogen storage. The study assumes the following scenarios: replacement by renewables of total combined fossil fuel generation (coal, oil, and gas) by 10, 20, and 30% by 2050, or Scenario1 = 10%, Scenario2 = 20%, and Scenario3 = 30%.

(ii) In Scenario1, Scenario2, and Scenario3, renewable hydrogen producing using curtailed electricity is calculated based on assumptions of curtailed electricity generated from renewables at the rate of 20–30% of total generation from renewables. Potential renewable hydrogen produced using curtailed electricity in Scenario1, Scenario2, and Scenario3 is expressed as Scenario1 H_2, Scenario2 H_2, and Sceario3 H2.

(iii) The formulas to calculate potential renewable hydrogen production in the renewable scenarios are as follow:

Scenario1H_2 (Mt-H2) = [Scenario1 (TWh) X (Percentage of curtailed electricity)/48 (TWh)

Scenario2H_2 (Mt-H2) = [Scenario2 (TWh) X (Percentage of curtailed electricity)/48 (TWh)

Scenario3H_2 (Mt-H2) = [Scenario3 (TWh) X (Percentage of curtailed electricity)/48 (TWh)

Mt-H_2 stands for million tonnes of hydrogen; TWh is terawatt-hour; percentage of curtailed electricity is 20–30% of total generation from renewables. The study also applies the conversion factor of 48 kilowatt-hours (kWh) of electricity needed to produce 1 kg H2 (ISES 2020).

(iv) The potential emission abatement is the difference between (a) the business as usual (BAU) scenario and (b) the alternative policy scenario (APS) and other high-renewable-share scenarios such as Senario1, Scenario2, and Scenario3.

To estimate potential hydrogen produced using curtailed electricity, the power generation mix for the BAU and APS is estimated using ASEAN countries' energy models by applying the Long-range Energy Alternative Planning System (LEAP) software, an accounting system to project energy balance tables based on final energy consumption and energy input and/or output in the transformation sector. Final energy consumption is forecast using energy demand equations by energy and sector and future macroeconomic assumptions.

In the modelling work applying LEAP, the baseline of 10 AMS was 2017, the real energy data available in 2017, which are the latest that the study employed. Projected demand growth is based on government policies, population, economic growth, and other key variables, such as energy prices used by the International Energy Agency energy demand model (IEA 2017). BAU is in line with current energy policy in the baseline information, which is used to predict future energy demand growth. However, APS differs from BAU in policy changes and targets, with a greater share of renewables, including possible nuclear uptake based on an alternative policy for energy sources and more efficient power generation and energy in final energy consumption.

For electricity generation, experts from 10 AMS specified assumptions based on their national power development plans and used the assumptions to predict ASEAN's power generation mix. For renewable hydrogen production, the study applies a conversion factor of 48 kWh of electricity needed to produce 1 kg of hydrogen (ISES 2020).

8.5 Results and Discussion

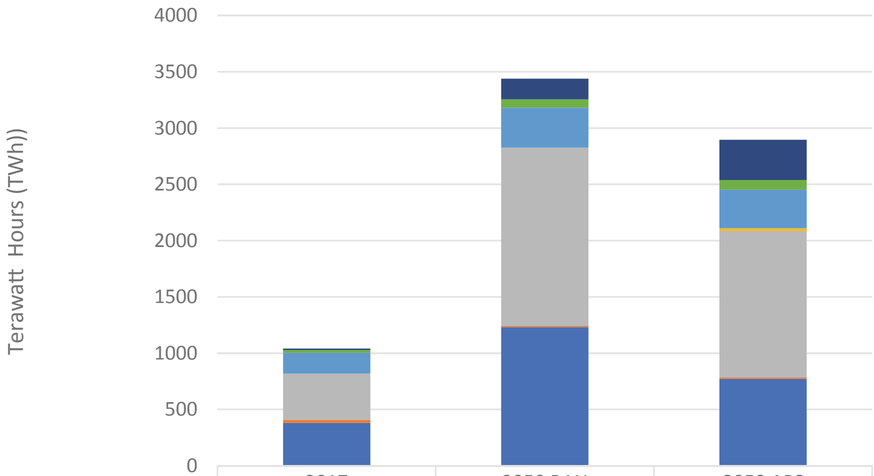
The potential of renewable hydrogen produced using curtailed electricity in Scenario1, Scenario2, and Scenario3 is quantified according to a renewable curtailment rate of 20–30% for the high share of renewables in 2050. Emission abatement—the difference between (i) BAU and (ii) APS, Scenario1, Scenario2, and Scenario3—is calculated. The higher share of renewables under Scenario1, Scenario2, and Scenario3 could only happen if hydrogen is developed as energy storage by utilising curtailed renewable electricity. The study discusses hydrogen as an enabler of higher shares of renewables, the need to reduce the cost of renewable hydrogen production by reducing the cost of electrolysis and renewables, and the need to develop a hydrogen road map for ASEAN to guide industry and key investors in renewable hydrogen development. The road map will help create a large-scale ASEAN hydrogen society.

8.5.1 Potential Renewable Hydrogen from Curtailed Electricity

ASEAN's power generation is dominated by fossil fuel (coal, oil, and gas), the share of which in the power mix was 79% (equivalent to 1041 TWh) in 2017 and is predicted to be 82% (2826 TWh) and 72% (2087 TWh) in 2050 for BAU and APS, respectively (Fig. 8.1). The share of combined fossil fuel (coal, oil, and gas) in the power generation mix is expected to reduce drastically from 82% in BAU to 65, 58, and 51% in Scenario1, Scenario2, and Scenario3, respectively, in 2050 (Fig. 8.2). The share of combined renewables is expected to increase from 18% in BAU to 35, 42, and 49% in Scenario1, Scenario2, and Scenario3, respectively, in 2050. The higher share of renewables in the power generation mix is desirable to decarbonise emissions in ASEAN's future energy system. However, the high share of renewables can only happen with bold policy actions to develop and deploy renewable hydrogen to support the power integration system, which has a higher penetration of renewables. Utilizing unused electricity and/or curtailed renewable electricity to produce hydrogen could be ideal to tap the maximum potential pf renewables.

Scenario1, Scenario2, and Scenario3 assume the replacement of combined fossil fuel (coal, oil, and gas) power generation in 2050 with 10, 20, and 30% of power generation from renewables. Renewable power generation amounts in 2050 are 1016, 1224, and 1433 TWh for Scenario1, Scenario2, and Scenario3, respectively (Table 8.1).

In Scenario1, Scenario2, and Scenario3, the shares of renewables in the power mix will be 35%, 42%, and 49%, respectively, in 2050. Because of higher shares of renewables in the power mix, renewable energy generation will be highly curtailed. The curtailed electricity rate could vary from 20 to 30%, depending on the power grid infrastructure in AMS. Based on this curtailed electricity, with varying shares of



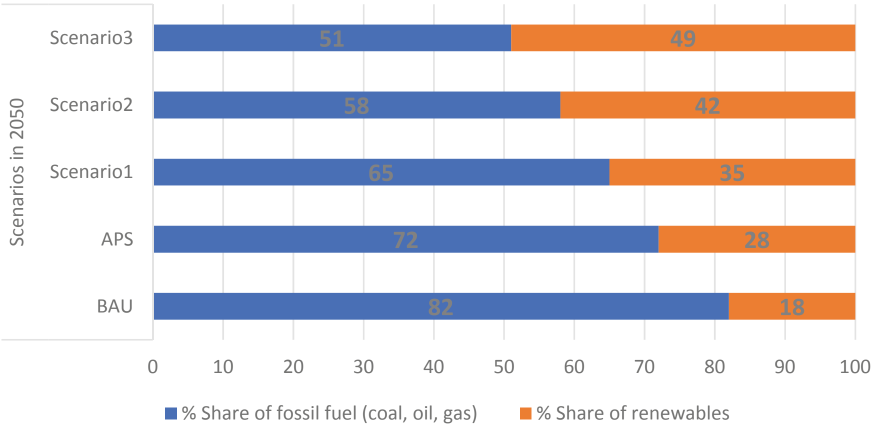
	2017	2050 BAU	2050 APS
Solar, Wind, Biomass	14	185	356
Geothermal	23	73	86
Hydro	183	356	344
Nuclear	0	0	21
Natural gas	414	1582	1303
Oil	26	12	12
Coal	381	1232	772

BAU = business as usual, APS = alternative policy scenario.
Source: Authors.

Fig. 8.1 ASEAN's power generation mix in business as usual and alternative policy scenario by source

renewables in Scenario1, Scenario2, and Scneario3, hydrogen production scenarios are created—Scenario1H_2, Scenario2H_2, and Scenario3H_2. Potential renewable hydrogen from curtailed electricity in scenarios in AMS range from 4.23 to 8.96 million tonnes hydrogen (Table 8.2).

The higher share of renewables under various scenarios such as APS, Scenario1, Scenario2, and Scenario3 will see a large reduction in carbon dioxide emissions (CO_2), which could resu lt in decarbonising emissions and contribute to COP commitments. Potential emission abatement ranges from −340 million tonnes carbon (Mt-C) in APS to −648 Mt-C, −710 Mt-C, and −774 Mt-C in Scenario1, Scenario2, and Scenario3, respectively (Table 8.3). Emissions were cut by 28% from BAU to APS, 53% from BAU to Scenario1, 58% from BAU to Scenario2, and 64% from BAU to Scenario3.



APS= alternative policy scenario, BAU = business as usual.
Note: Scenario1, Scenario2, and Scenario3 envision replacing combined fossil fuel (coal, oil, and natural gas) power generation with renewables (mainly variable renewable energy) at 10%, 20%, and 30%, respectively, in 2050.
Source: Authors.

Fig. 8.2 Share of combined fossil fuels (coal, oil and gas) versus renewables under various scenarios. APS = alternative policy scenario, BAU = business as usual.

Table 8.1 ASEAN's power generation mix under various scenarios of share of renewables (TWh)

	2050 APS	Replacement of coal, oil, and natural gas by renewables		
		Scenario1 = 10%	Scenario2 = 20%	Scenario3 = 30%
Coal	772	698.8	618	540
Oil	12	11	10	8
Natural gas	1303	1173	1042	912
Renewables (wind, solar, hydro, geothermal, andiomass)	807	1016	1224	1433

APS = alternative policy scenario
Note Scenario1, Scenario2, and Scenario3 envision replacing combined fossil fuel (coal, oil, and natural gas) power generation with renewables (mainly variable renewable energy) at 10%, 20%, and 30%, respectively, in 2050
Source Authors

8.5.2 Hydrogen, an Enabler to Scale up Variable Renewable Energy

In ASEAN, power generation is dominated by coal, gas, and hydropower. Intermittent renewables from solar and wind energy contributed a negligible amount (14.47 TWh) or about 1.4% in 2017. However, the most optimistic prediction is that ASEAN will increase the share of wind and solar energy in the power generation mix to about

Table 8.2 ASEAN's potential renewable hydrogen from curtailed electricity

Hydrogen production	Potential renewable hydrogen production		
	Scenario1 H_2 (million tonnes H2)	Scenario2 H_2 (million tonnes H2)	Scenario3 H_2 (million tonnes H2)
Of 20% curtailed renewables	4.23	5.10	5.97
Of 30% curtailed renewables	6.35	7.65	8.96

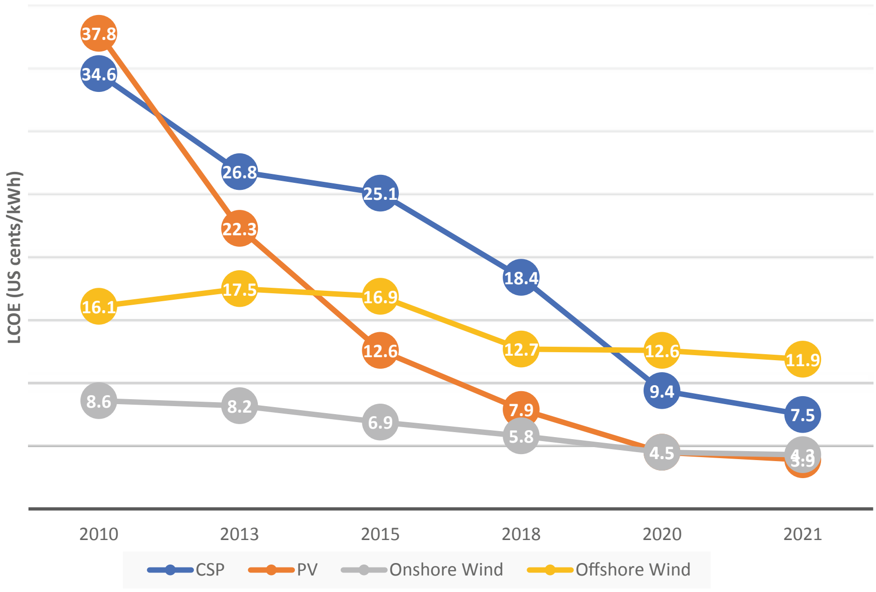
H2 = hydrogen, Scenario1 H_2 = hydrogen production in Scenario1, Scenario2 H_2 = hydrogen production in Scenario2, Scenario3 H2 = hydrogen production in Scenario3
Note 20–30% curtailed electricity applied for combined renewable power generation in 2050. The study applied a conversion factor of 48 kilowatt-hours (kWh) of electricity needed to produce 1 kg (kg) H2 (ISES 2020); 1 kg of H2 could generate 33.3 kWh (ISES 2000)
Source Authors

Table 8.3 Potential emission reduction under various scenarios (Mt-C)

	2017	2050	2050	2050
	Baseline	Emissions under various scenarios	Emission abatement potential	% emission reduction from BAU (%)
BAU	376	1216		
APS	376	876	−340	28
Scenario1	376	568	−648	53
Scenario2	376	506	−710	58
Scenario3	376	442	−774	64

APS = alternative policy scenario, BAU = business as usual, Mt-C = million tonnes carbon
Note Emission abatement potential is change of emissions from BAU to APS and other scenarios in 2050 under high renewables in Scenario1, Scenario2, and Scenario3
Source Authors

12.3% by 2050 (calculated from Fig. 8.1). The inclusion of the share of hydro (17.6%) and geothermal (2.2%) energy in the power generation mix contributed to the overall renewable share of 21.2% in 2017. However, future abundant resources are wind and solar energy, the current share of which is negligible. Grid operators had many misperceptions of VRE such as wind and solar energy, although its production cost has drastically dropped in recent years; solar photovoltaic farms' levelized cost of electricity (LCOE) dropped from US$0.378/kWh in 2010 to US$0.043/kWh in 2020 in some places. Similarly, all LCOE cost trends for wind energy and concentrated solar power dropped drastically in 2010–2020 and will continue to drop in 2021 (Fig. 8.3), but their share in the power generation mix remains small. Misperceptions stemmed from the concern that VRE production is variable and intermittent, and that its higher share in the grid will add costs as it will require backup capacity from conventional gas power plants (NREL 2020).



CSP = concentrated solar power,kWh = kilowatt-hour, LCOE = levelized cost of electricity, PV = photovoltaic.
Source: IRENA (2020).

Fig. 8.3 Falling costs of renewables. CSP = concentrated solar power, kWh = kilowatt-hour, LCOE = levelized cost of electricity, PV = photovoltaic.

Technically, VRE power production output varies within a few seconds depending on wind or sunshine. However, the risk of variable energy output can be minimised if the power system is largely integrated within the country and within the region. The aggregation of output from solar and wind energy from different locations has a smoothing effect on net variability (NREL 2020). However, the ASEAN power grid is progressing slowly and the integrated ASEAN power market might be far off because of several reasons, such as regulatory and technical harmonisation issues within ASEAN power grids and utilities.

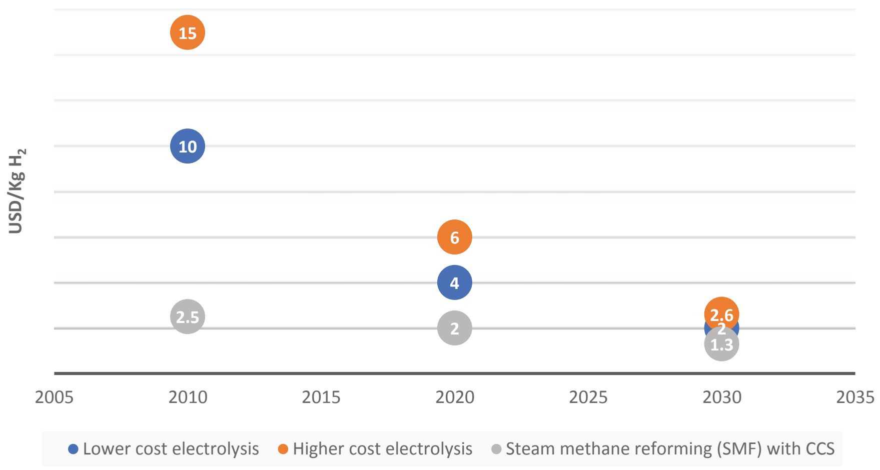
Scalable electricity production from wind and solar energy faces tremendous challenges from the current practice of system integration in ASEAN. Investors in solar or wind farms will confront high risks from electricity curtailment if surplus electricity is not used. Many countries have advanced research and technologies for battery storage (lithium-ion batteries) for surplus electricity produced from wind and solar energy, but advanced battery storage remains costly. Produced from electrolysis using surplus electricity, hydrogen has many advantages as it can be stored as liquid gas, which is suitable for numerous uses and easy to transport. Many ASEAN countries could produce wind, solar, hydropower, or geothermal electricity. Their resources, however, are far from demand centres and developing the resources would require large investments in undersea transmission cables. A solution would be to turn renewables into easily shipped hydrogen.

Hydrogen is a potential game changer for decarbonising emissions, especially in sectors where they hard to abate, such as cement and steel. Scalable resources from wind and solar energy and other renewables can be fully developed by widely adopting the hydrogen solution. The more electricity produced from wind and solar energy, the higher the penetration by renewables of the grid; at the same time, surplus electricity during low demand hours can be used to produce hydrogen. The more power generated from wind and solar energy and other renewables, the greater the possibility to increase the efficiency of electrolysis to produce hydrogen. On-site hydrogen production from wind and solar farms will solve the issue of curtailed wind and solar electricity. To increase the efficiency of electrolysis and allow further penetration by renewables of grids, a hybrid energy system including hydropower, geothermal, or nuclear plants, for example, would be the perfect energy choice. Since hydrogen is a clean energy carrier and can be stored and transported for use in, amongst others, hydrogen vehicles, synthetic fuels, upgrading of oil and/or biomass, ammonia and/or fertilizer production, metal refining, heating, and other end uses, hydrogen development is an ideal pathway to a sustainable clean energy system and enables scalable VRE such as solar and wind energy.

8.5.3 Need to Reduce Renewable Hydrogen Production Cost

Cost-competitiveness of producing renewable hydrogen is key for the wide adoption of hydrogen uses. The upfront costs of renewable hydrogen such as electrolysers, transport infrastructure, and storage, and the varying costs of electricity tariffs are key factors contributing to the high production cost of renewable hydrogen (Fig. 8.4). ‘Green’ hydrogen production costs dropped drastically from US$10–US$15/kg of H_2 in 2010 to US$4–US$6/kg of H_2 in 2020, with varying assumptions of lower and higher upfront costs of electrolysers with 20 megawatts and producing capacity of 4,000 normal cubic metres per hour (IRENA 2019a; Hydrogen Council 2020). The costs are expected to reduce to US$2.00–US$2.60/kg of H2 in 2030, which is competitive with steam methane reforming with CCS.

Considering the electricity tariffs of up to US$0.10/kWh with varying load factors of 10–50%, the cost of producing hydrogen ranged from US$0.90–US$5.50/kg of H_2 to US$4.20–US$8.90/kg of H_2 (Fig. 8.4), meaning that electricity tariff is the major cost of producing hydrogen using electrolysis. At zero electricity tariff or when VRE is expected to be curtailed, the cost of producing hydrogen can be as low as US$0.90/kg of H_2 at an electrolyser’s load factor of 50%, and US$5.50/kg of H_2 at an electrolyser’s load factor of 10%. The International Renewable Energy Agency’s target of cost-competitiveness of producing renewable hydrogen is US$2.00–US$2.50/kg of H2 (IRENA 2019b). In this case, an electricity tariff of US$0.03/kWh with an electrolyser’s load factor of 30% is the most practical given all the constraints.



CCS = carbon capture, sequestration, and storage, , SMF = steam methane reforming. H_2 = hydrogen.
Note: Assumption: 4,000–normal cubic metre per hour (20-megawatt) polymer electrolyte membrane electrolysers connected to offshore wind. The lower-cost electrolysis case is US$200/kilowatt (kW). The middle-cost electrolysis case is US$400/kW. The higher-cost electrolysis case is US$600/kW.
Source: Authors, based on Hydrogen Council (2020), DOE (2014), and IRENA (2019a).

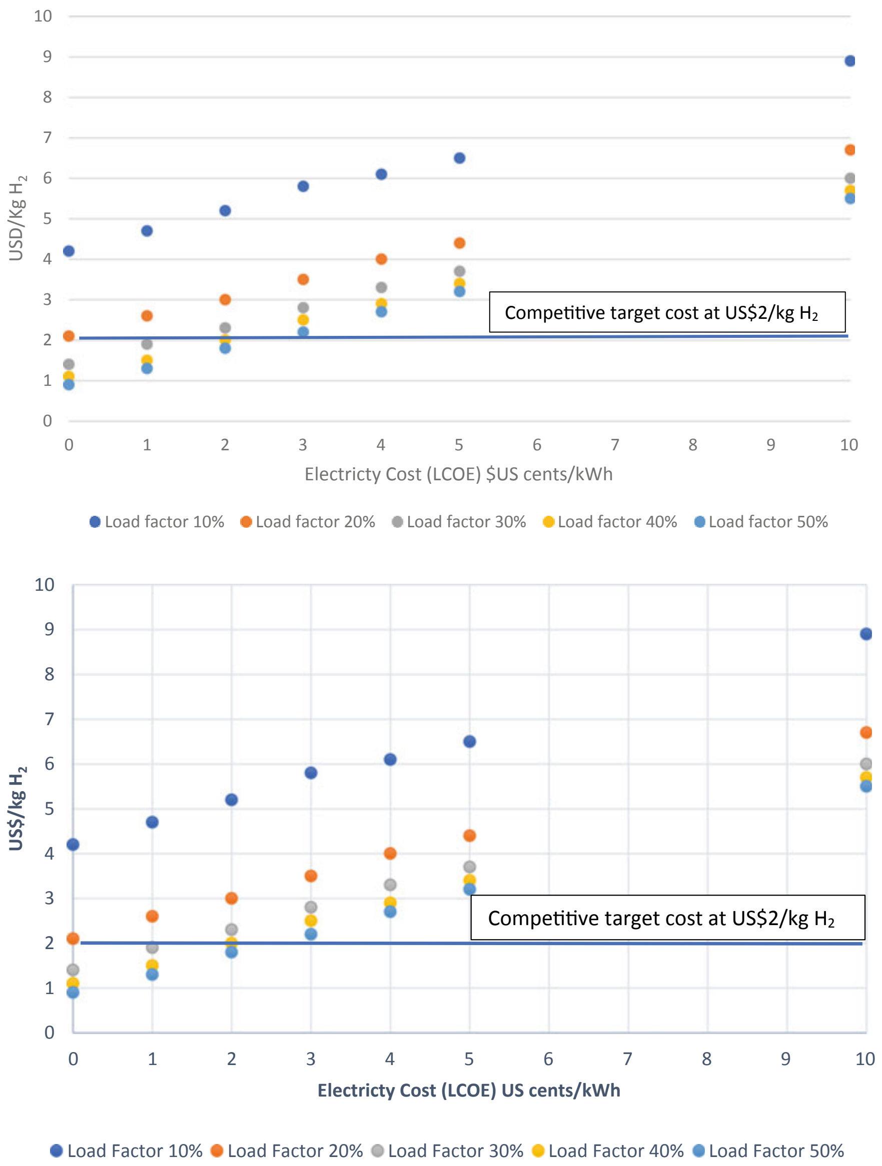
Fig. 8.4 Hydrogen production cost trends with upfront cost of electrolysers. CCS = carbon capture, sequestration, and storage, SMF = steam methane reforming. H2 = hydrogen

The solar photovoltaic farm and onshore wind already cost US$0.02–US$0.03/kWh in some locations (IRENA 2019b). Even the target cost of US$2.00–2.50/kg of H2 to produce 'green' hydrogen, however, would not be competitive with low-cost natural gas at US$5 per gigajoule (GJ)[2] (US$0.018/kWh), but would be with natural gas, which costs US$10–US$16/GJ (US$0.036–US$0.057/kWh).

Technically, if renewable hydrogen production uses only curtailed electricity from renewables, the operating load factor of electrolysis, which contributes the most to the cost of producing hydrogen, will likely be low at 10% or less. Based on Hydrogen Council (2020), the electrolyser will need to run at a load factor of at least 30% or more to lower the cost of producing hydrogen to US$2.00–2.50/kg of H2, which is competitive with the natural gas grid price (Fig. 8.5).

Electrolysis facilities must have a load factor above 30% to ensure the cost-competitiveness of producing renewable hydrogen, and other capital expenditures such as the electrolyser's upfront cost must be reduced by 50% from US$840 today to US$420 per kilowatt by 2040. As wind and solar energy is expected to increase its share in the power generation mix, expected curtailed electricity from renewables will be higher by 10–30%. By 2030, the share of VRE curtailment will be 10–30% in Sweden, which provides the most incentives for renewable hydrogen (IRENA 2019b). In 2020, Chile, Australia, and Saudi Arabia have achieved the target cost of US$2.50/kg to produce 'green' hydrogen because of cheap access to electricity

[2]Conversion factor: US$0.01/kWh = US$2.80/GJ.



H_2 = hydrogen, kWh = kilowatt-hour, LCOE = levelized cost of electricity.
Note: Assumption: The polymer electrolyte membrane electrolyser is connected with the grid.
Source: Authors, based on Hydrogen Council (2020), DOE (2014), and IRENA (2019a).

Fig. 8.5 Hydrogen production cost with varying electricity cost and electrolysis load factors from wind and solar energy. The cost is expected to drop further to US$1.90/kg in 2025 and to US$1.20/kg in 2030, which is highly competitive with the cost of 'grey' hydrogen production.

Effective policies and incentives to develop and adopt hydrogen can promote economies of scale and cost-competitiveness in producing hydrogen, encouraging investors to manufacture electrolysers; improve their efficiency, operation, and maintenance; and use low-cost renewable power such as hydrogen to enable scaling VRE penetration of the power grid. 'Green' hydrogen production cost could decline even faster and go even lower than US$2/kg of H2 if governments, business, and stakeholders join hands to adopt the wider use of 'green' hydrogen and increase investment and R&D in hydrogen fuels. Australia, Chile, and Saudi Arabia have achieved cost-competitiveness in wind and solar energy generation.

The energy transition will largely depend on the clean use of fossil fuel leading to a clean energy future. Although hydrogen is a clean fuel, the way it is produced matters. Almost 95% of hydrogen production is from natural gas with or without CCS. The gasification of coal can be used as feedstock for producing hydrogen, but it emits roughly four times more CO2/kg of H_2 produced than natural gas feedstock does. The production cost of low-carbon or blue hydrogen depends on feedstock cost and suitable geographical CCS storage. IRENA (2019a) estimated that 'blue' hydrogen production in China and Austria with current CCS infrastructure could realise a production cost of about US$2.10/kg of H2 for a cost of coal of about US$60 per ton. In the US, where natural gas is below US$3 per million British thermal units and has large-scale CO_2 storage such as depleted gas fields and suitable rock formations, 'blue' hydrogen cost could drop below US$1.50/kg in some locations. If the carbon cost of about US$50 per ton of CO_2 is considered, low-carbon hydrogen could reach parity with 'grey' hydrogen. 'Blue' hydrogen cost in the US and the Middle East could drop further to about US$1.20/kg in 2025 if economies of scale prevail.

World leaders need to provide a clear policy to develop and adopt hydrogen. The right policy will enable economies of scale for producing hydrogen cost-competitively, inducing investors to explore electrolyser manufacturing; improve electrolyser efficiency, operation, and maintenance; and use low-cost renewable power. With the full participation of governments, business, and stakeholders, hydrogen can become the fuel that enables scaling up renewable energy penetration in all sectors, decarbonising global emissions.

8.5.4 Need for Renewable Hydrogen Development Policies in ASEAN

Until 2020, ASEAN did not have a hydrogen road map. APAEC, however, mentions alternative technologies and clean fuels such as hydrogen and energy storage. APAEC will help AMS increase the share of hydrogen in the energy mix. An ASEAN hydrogen road map is needed to guide national road maps. Based on the analysis of the drastic drop in the cost of VRE and electrolysers, opportunities to introduce 'green' hydrogen produced using curtailed electricity will be plentiful. The hydrogen road map should include hydrogen development and penetration in transport, power generation, and industry. To guide investment, hydrogen penetration policies and targets must be set up. This study, however, can only suggest policies to develop, adopt, and use hydrogen. The study adopts Australia's hydrogen road map, especially its key polices (Bruce et al. 2018), and tailors them to ASEAN's energy landscape (Table 8.4).

ASEAN needs a comprehensive hydrogen road map that includes a policy framework supporting hydrogen production, storage, and transport, and hydrogen utilisation in power generation, transport, heat production, industrial feedstock, and import and export. In developing the hydrogen road map, governments should consult industry, financial, and banking stakeholders and cultivate people's willingness to support a hydrogen society.

Table 8.4 Suggested key polices for renewable hydrogen development in ASEAN

Financing	Regulations	RD&D	Social Acceptance
Provide access to lower-cost financing for hydrogen development and low-emission projects Provide fiscal policy incentives for local manufacturing for hydrogen development Provide financing incentives for low-emission electricity	Set up targeted policies to stimulate hydrogen demand Develop hydrogen-specific regulations across AMS to support hydrogen development in power generation, transport, and industry Allow grid-firming services from electrolysers to be compensated Allow for on-site hydrogen production and, where possible, position plants close to where the hydrogen will be used Review gas pipeline regulations to consider including gaseous hydrogen	Set up demonstration projects for mature hydrogen technologies Set up a hydrogen centre of excellence as a research body to bring in all parties to work on technologies and policy coordination Conduct R&D in plant efficiency and safety, and in hydrogen shipment, pipeline, and storage	Develop a public engagement plan and strategy to support clean fuels such as hydrogen and ensure that communities understand all aspects of its use Promote willingness to pay for clean fuels

RD&D = research and development and deployment
Source Authors, based on Bruce et al. (2018)

8.6 Conclusion and Policy Implications

ASEAN's energy transition will largely depend on increasing the share of renewables and clean fuels such as hydrogen and the clean use of fossil fuel to create a clean energy future. Fossil fuel (coal, oil, and gas) accounted for almost 80% of ASEAN's energy mix in 2017, a share that is expected to rise to 82% in BAU. Transitioning from a fossil fuel–based energy system to a clean energy system requires drastic policy changes to encourage embracing renewables and clean fuels whilst accelerating the use of clean technologies in employing fossil fuel (coal, oil, and natural gas). The study uses energy modelling scenarios to explore policy options to abate emissions in ASEAN by giving wind and solar energy a high share of the energy mix, and using electricity curtailment to promote renewable hydrogen production. The study reviews the potential cost reduction of renewables and hydrogen around the world and hydrogen road maps that might help ASEAN create its own strategy. Hydrogen will be an enabler, allowing wind and solar resources to be used to their maximum potential, without concern for electricity curtailment. 'Green' hydrogen will be important in increasing the share of renewables in the power generation mix by breaking the traditional barriers of power system integration, which cannot absorb a high share or intermittent electricity from solar and wind energy. Hydrogen enables increasing the share of other renewables such as geothermal, hydropower, and biomass energy. In the US, Japan, the Republic of Korea, and other OECD countries, renewable hydrogen will play a big role in using nuclear power–based load during low demand hours to produce 'green' hydrogen.

Hydrogen is not yet on the policy agenda in many ASEAN countries as an alternative fuel, but APAEC includes policy measures to utilise emerging and alternative technologies such as hydrogen and energy storage. APAEC will help AMS adopt the use of hydrogen. Hydrogen production in AMS is mainly used in the refining, fertilizer, and petrochemical industries. However, the energy landscape will see hydrogen fuels used more in many sectors as clean fuels and as an enabler of increasing renewables in the energy mix.

The findings suggest that ASEAN has high potential to produce renewable hydrogen using curtailed electricity. The higher share of renewables under various policy scenarios will see a large reduction in CO_2 emissions, which could lead to decarbonising emissions and contribute to abating global climate change. The potential emission abatement ranges from −340 Mt-C in APS to −648 Mt-C, −710 Mt-C, and −774 Mt-C in Scenario1, Scenario2, and Scenario3, respectively. Emissions will be cut by 28% from BAU to APS, 53% from BAU to Scenario1, 58% from BAU to Scenario2, and 64% from BAU to Scenario3. The study found that OECD countries are accelerating toward the hydrogen society, which will have a big impact on the world's energy landscape. ASEAN needs to catch up.

Hydrogen development is ideal for bringing sustainable clean energy to ASEAN and the rest of the world. Major policy reforms are needed to ensure that clean fuels such as hydrogen and renewables and clean technologies will gradually replace traditional fuels and technologies. The study's findings have policy implications for hydrogen adoption:

(i) ASEAN leaders must strongly commit to promoting a hydrogen society. ASEAN Ministers on Energy Meetings, facilitated by the ASEAN Secretariat, are an excellent platform for drafting a clear and actionable hydrogen development road map.
(ii) ASEAN energy leaders must develop a clear strategy to promote hydrogen use in transport; power generation; and other sectors where emissions are hard to abate, such as the iron and steel industries. Singapore, Malaysia, Thailand, Indonesia, and the Philippines could take the lead by investing in R&D on hydrogen produced from renewables and non-renewables and by setting investment targets adapted from OECD countries. Investment in industries that can adopt hydrogen energy has strong potential, but to realise it ASEAN must accelerate its plans and strategies to embrace hydrogen use.
(iii) Leaders in ASEAN and around the world must provide a clear investment policy to develop and adopt hydrogen as a fuel. The policy must enable economies of scale in cost-competitive production of hydrogen to induce investors to consider electrolyser manufacturing; improvements in electrolyser efficiency, operation, and maintenance; and the use of low-cost renewable power. With the full participation of governments, business, and stakeholders, hydrogen can become the fuel that enables scaling up renewable energy penetration in all sectors, decarbonising global emissions.
(iv) Governments must engage the public, build its awareness of the many benefits of a hydrogen society, and ensure that the public is willing to pay for them. The success of introducing hydrogen on a large scale needs the participation of all stakeholders, including governments and public and private companies. Financing mechanisms such as banks must create favourable conditions to finance facilities such as electrolysers. Governments must provide financial incentives to invest in developing hydrogen.
(v) Improving the electricity governance system in ASEAN developing countries will help reduce the cost of managing energy systems, allow the uptake of clean energy technology investment, and upgrade the grid system to bring in more renewables. The energy sector must be reformed; rules and procedures must allow more advanced and competitive technologies to enter the market. Electricity reform will attract foreign investment to modernise electricity infrastructure, including by making power systems more efficient and phasing out inefficient power generation and technologies.
(vi) Unbundling of ownership in the electricity market, non-discriminatory third-party access to transmission and distribution networks, and the gradual removal of subsidies for fossil fuel–based power generation are key to ensure market competition. Other policies to attract foreign investment include tax holidays; reduction of market barriers and regulatory burdens; and plans to reduce the upfront cost investment, such as a rebate payment system through government subsidies and government guarantees that investment will be feasible and low risk.

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Chapter 9
Green Technology Development and Deployment in the ASEAN—Lessons Learned and Ways Forward

Rabindra Nepal, Han Phoumin, and Abiral Khatri

Abstract Southeast Asia faces one of the fastest growths in energy demand in the world, driven by increasing incomes, urbanisation, and industrialisation. The development and deployment of green energy technologies offer a natural conduit to meet the growing energy needs in the Association of Southeast Asian Nations (ASEAN). This chapter undertakes a case study approach in reviewing green energy deployment in the context of green growth and energy transition and discusses the current status of renewable energy development in ASEAN. The study aims to formulate policy lessons for the ASEAN economies in facilitating the development and deployment of green technologies and alternative energy options based on a case-study approach for delivering sustainable economic growth and in combating climate change in the region. The review suggests that carbon capture and storage (CCS) technologies will allow ASEAN to continue to use fossil fuels whilst achieving sustainable economic growth as coal demand increases in the region. The deployment of CCS technologies is also an enabler of hydrogen energy as a green energy solution in the region in the longer term. The shorter-to-medium-term policies include boosting public acceptance to nuclear energy, implementing energy efficiency improvement policies, and

This research paper was carried out under the funding from the Economic Research Institute for ASEAN and East Asia. We also acknowledge the valuable comments received from Fukunari Kimura, Jun Arima, and participants at the First Working Group Meeting—Energy Sustainability and Climate Change in ASEAN—held on 14 September 2020. This book chapter is also an alternative version of a paper published in the journal Sustainability, cited as: Nepal, R., H. Phoumin, A. Khatri (2021), 'Green Technological Development and Deployment in the Association of Southeast Asian Economies (ASEAN)—At Crossroads or Roundabout?', *Sustainability*, 13(2), p. 758. https://doi.org/10.3390/su13020758.

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https://doi.org/10.1007/978-981-16-2000-3_9

eliminating fossil fuels consumption subsidies. Increasing both public and private sector energy investments and the development of CCS technologies in the longer-term are necessary complementary policies for maximising the benefits of greater deployment of renewable energy sources in the region.

Keywords Green technology · Sustainability · Climate change · Southeast Asia · Energy policy

9.1 Introduction

Sustainable development is about achieving a more sustainable global future and holds significant importance as a powerful development concept as it integrates economic, societal, and environmental aspects. Developing sustainably ensures the availability of critical resources, such as energy, water, and food, be available to both present and future generations but also emphasises mitigating the risks posed by planetary boundaries (Steffen et al. 2015). However, the transition towards sustainability is still at an early stage in developing economic regions, whilst economies around the world have been struggling to balance their economic growth without depleting the natural resources. The coronavirus disease (COVID-19) pandemic brings further uncertainty in adapting sustainability reforms given the economic downturn and border closures in many regions affecting resource mobility. Whilst the COVID-19 pandemic has pushed back the immediate urgency to tackle climate change as global emissions have decreased in the short term, the role of green technology has always been crucial in providing a new perspective on sustainable development.

Southeast Asia currently faces paramount challenges as well as opportunities in matching its increasing energy demand due to rising incomes, industrialisation, and urbanisation with a sustainable energy supply considering the transition to a lower-carbon economy. In recent decades, greenhouse gas emissions have been rapidly rising at an average annual rate of 5% amongst major Southeast Asian economies, such as Indonesia, Malaysia, the Philippines, Thailand, and Viet Nam (Raitzer et al. 2015). The region is poised to become a net energy importer of fossil fuels, such as oil, due to growing populations, industrialisation, and urbanisation despite the slowdown in economic growth (IEA 2019a). The total population in the Association of Southeast Asian Nations (ASEAN) region will increase to 715 million by 2025 with the economy growing by more than 5% per year, therefore explaining the rapid rise in energy demand of at least 4% annually (IRENA 2016). The overall growth in energy demand of more than 80% since 2000 has been met by a doubling in fossil fuel use, engendering severe energy security concerns, such as rising import dependence and environmental concerns due to an increase in energy-related carbon dioxide (CO_2) emissions (IEA 2019b). For instance, the share of this geographic region to global emissions increased to 4% in 2018 (3% in 2010), whilst the number of deaths linked to outdoor and household air pollution in Southeast Asia is expected to spike to more than 650,000 a year by 2040, up from around 450,000 in 2018 (IEA 2019c).

Nevertheless, the energy usage is expected to have a much sustainable approach. Moreover, the average temperature in ASEAN has been rising by 0.1–0.3 °C per decade in the last 50 years and is projected to reach 2–4 °C by the end of the twenty-first century (International Resources Group 2010). The electricity demand in the region is growing at an average of 6% and remains amongst the fastest in the world whilst the region's demand for electricity is projected to double by 2040 (IEA 2019a). In 2016, the ASEAN economies set a target of 23% of its primary energy supply to be secured from renewable sources by 2025 (IRENA 2016). However, it is also likely that the overall energy demand will grow by almost 50%, whilst power generation will double by 2025 (IEA 2019a). Although some countries will have to at least double their share of renewable energy every year, this alone may not be enough to combat climate change. The rising energy demand and related CO_2 emissions in ASEAN, therefore, implicate the heightened need for transitioning towards the development and deployment of greener energy sources in the region.

There is also an ongoing discourse in ASEAN to devise policy strategies to mitigate and adapt to climate change threats and balance the trade-offs between economic development and environmental sustainability. Policymakers across Southeast Asia are intensifying their efforts in achieving a common goal of a secure, sustainable, and affordable energy sector even though the region is diverse and dynamic (IEA 2019b). The diversity in the energy mix in the region also offers a viable opportunity to accelerate regional physical interconnections of power grids and make greater use of the resource and demand complementariness (Singh et al. 2018). Boosting regional power grids in ASEAN has also been well advocated in the energy policy agenda (Halawa et al. 2018). Within this context, the need for developing, deploying, and adopting green technologies is imminent for Southeast Asia to address the twin challenges of rising energy demand and increasing emissions in ensuring energy sustainability as well as to mitigate the adverse impacts of climate change. However, the progress towards the adoption of green technology, such as renewables, in Southeast Asia is slower than the anticipated potential. Renewable energy only meets around 15% of demand with the rapid increase in hydropower and modern use of bioenergy in heating and transport (Louis 2020). In addition, countries in ASEAN should increase their share of renewables in the energy mix to 70% by 2040 to meet their Sustainable Development Goals (SDGs). The large potential for the sustainable use of modern bioenergy remains untapped in the region, although electricity from hydropower production almost tripled to 44 gigawatts (GW) in 2016 compared to 16 GW in 2000 (IRENA 2018b). Southeast Asian economies are yet to perform globally in renewable energy deployment due to various challenges despite having huge potential for sustainable energy sources (Erdiwansyah et al. 2019).

The objective of this chapter is to analyse and review the energy–economy–environment interrelationships in ASEAN from an energy sustainability perspective in the context of green energy development and deployment. In doing so, the study recognises the inevitable economy–environment trade-off between regional economic growth and adverse climate change impacts as a policy tool for policymakers to emphasise. Based on our impartial and unbiased analysis, we propose that policymakers need to formulate and implement proper policies that are of short-term, medium-term, and long-term nature for the scaling of renewable energy deployment; focus on energy efficiency improvements; discourage the use of fossil fuels by undertaking energy pricing reforms; and embrace carbon capture, utilisation, and storage technologies. However, significantly accelerating the deployment of renewable energy in the region requires higher levels of investment. This chapter uses a case study approach as case studies are suitable for examining policy problems that do not easily lend themselves to rigorous quantitative analysis or that cannot be analysed due to the unavailability of disaggregated data (Nepal and Jamasb 2015).

The remainder of the chapter is structured as follows. Section 2 portrays the current status of renewable energy deployment in ASEAN. Section 3 discusses green energy innovation and alternative energy options for ASEAN. The three major policy recommendations are discussed in Sect. 4. Section 5 concludes the chapter.

9.2 Current Status of Renewable Energy Deployment in ASEAN

It is projected that the ASEAN region will have accelerated economic growth over the next decade and experience a 50% rise in energy demand. Importantly, the region has targeted sourcing 23% of its primary energy from renewable sources (IRENA 2016). Global economic and energy indicators show an indication that the ASEAN region is becoming a net importer of fossil fuels given its rapidly growing economies and increasing population size. Southeast Asian countries have a geographic advantage in terms of their diverse natural resource endowments. For example, Indonesia and the Philippines have substantial potential for geothermal energy, whilst Vietnam, Cambodia, the Lao PDR, and Myanmar have mass-scale hydropower potential. Similarly, most areas in these countries have at least 12 h of sunshine on average, which is suitable for solar electrification. Global renewable energy generation capacity stood at 2179 GW by the end of 2017, with the hydro sector holding the largest share with an installed capacity of 1271 GW. In 2019, Asia alone accounted for 54% of the new capacity in renewables, increasing by 95.5 GW to 1.12 TW. The majority of this growth was driven by new installations of solar and wind energy covering 85% of all new renewable capacity installed. Thailand was one of the distinguishable countries from the ASEAN region with the second-highest share in the region in terms of bioenergy capacity at 430 megawatts (MW). The other was Indonesia, which topped the list in expanding its geothermal energy capacity to 306 MW and is soon approaching 2 GW (IRENA 2018a). Similarly, Malaysia is the third-largest producer of photovoltaic cells in the world.

Likewise, the Lao PDR has around 80% of its primary energy demand sourced through renewable energy, and the country has realised its potential. Biomass from forestry and agricultural waste comprises 68% and is used for household cooking and small-scale rural production, whilst the other 12% is from the hydropower sector. The Lao PDR has taken advantage of the 300 days of sunlight it has every year to equip 13,000 rural homes with solar panels. In Indonesia, the government took the initiative to build its largest solar power plant by 2019 with an investment of $300 million (Kurniawan 2020). The country has huge potential for wind, and a 100-ha wind farm was opened in South Sulawesi with the capacity to power around 70,000 households (Hajramurni 2018).

The Philippines has the largest potential for wind energy in Southeast Asia, although a significant proportion of the population does not have access to electricity, compelling them to use alternate methods for cooking and lighting. Green start-ups have played a major role in the Philippines by benefitting from the natural energy resources. A Filipino start-up named Sustainable Alternative Lighting came up with a saltwater solution-powered lamp that retains power for up to 8 h. Furthermore, the disposable component of the lamp lasts for 6 months and is not expensive to replace. Around 51% of people use firewood or charcoal in the Philippines, and a green-start up named Hi-Gi Energy came up with an alternative cooking fuel by changing water hyacinths, a commonly found plant, into compressed blocks of coal dust, known as briquettes (Clean Cooking Alliance 2020).

However, about 120 million people do not have access to electricity in Southeast Asia, and the rural areas face critical challenges in receiving power (Charlotte Trueman 2018). There are about 45 million people in the region who rely on biomass as a fuel for cooking (Louis 2020). There is a tremendous potential for renewable energy, but it only accounts for 15% of the energy demand. On one hand, hydropower has increased fourfold since 2000 along with the increase in the use of bioenergy in heating and transport (IEA 2019a). On the other hand, the share of solar photovoltaics and wind is small, although the costs have been declining in recent years. An efficient market-based energy efficiency framework could strengthen their deployment.

Based on a stated policies scenario developed by the International Energy Agency (IEA) in 2019, by 2040 Southeast Asia's overall energy demand is expected to grow by 60%. This also implies that the size of the economy will double over the period and the majority of the population will be concentrated in urban areas, with an increase of 120 million (ASEAN Secretariat 2012). A structural economic shift towards less-energy-intensive manufacturing and services sectors is expected along with greater efficiency, which will lower the rate of energy demand compared to previous decades, representing 12% of the global energy rise by 2040. The oil demand will exceed 9 million barrels per day (mb/d) by 2040 from the current 6.5 mb/day (IEA 2019a).

Given the little progress made by countries and major multinational companies in the world on their pledge for net zero carbon by 2050, it is likely that oil will continue to dominate road and transport demand in ASEAN. Similarly, coal demand driven by strong policy settings by countries to meet the economic growth targets set by policymakers will increase. In the case of natural gas, the IEA estimated that industrial consumers drive demand more than power plants, whilst the increase in imports of oil is making sources such as liquified natural gas (LNG) less price-competitive for power plants.

In Fig. 9.1, inferences can be made as a result of having policy targets where the region's energy demand is expected to rise to 60% by 2040. Compared with the energy demand of the previous decades, the growth rate is far lower, which reflects a

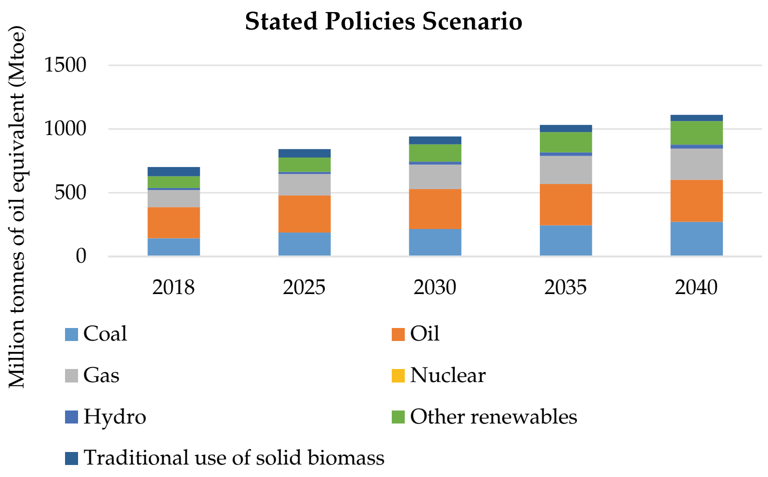

Fig. 9.1 Primary energy demand in ASEAN, 2018–2040. *Source* Adapted from IEA (2019a)

systemic economic shift towards less- energy-intensive sectors along with increasing efficiency. In addition, the renewable share in power generation is expected to rise from 24% today to 30% by 2040. However, this is still short of levels reached by other emerging economies, such as China and India, under the stated policies scenario. The hydropower sector, which accounts for almost 80% of the renewable share, is the cornerstone of ASEAN's energy portfolio, and the rise of wind and solar energy, as well as biofuels and bioenergy from waste products, is likely to deliver promising growth. Furthermore, innovation in hydrogen carbon technologies could change the energy landscape and bring a positive change in the energy landscape of ASEAN.

Figure 9.2 portrays how Southeast Asia has been shaping several aspects of the global economic and energy outlook. Whilst the region remains highest in the world in terms of electricity demand at an average of 6% per year, a number of power systems in the region need major financial support. The use of overall energy demand cannot be undermined either, as the overall energy demand has grown by more than 80% with a doubling of fossil fuel use. This reflects the region's development and industrial growth, but also the negative consequences in terms of public health and environment as a result of air pollution and CO_2 emissions, respectively. As can be observed in the figure, the renewable energy capacity in Southeast Asia is significant enough and is continuously growing. Nevertheless, only 15% of the region's energy demand is met at present, which provides a huge opportunity for the future. Especially for the small economies in the region, such as Myanmar, Cambodia, Viet Nam, and the Lao PDR, the falling costs of solar photovoltaics and wind could be encouraging news for supporting their deployment.

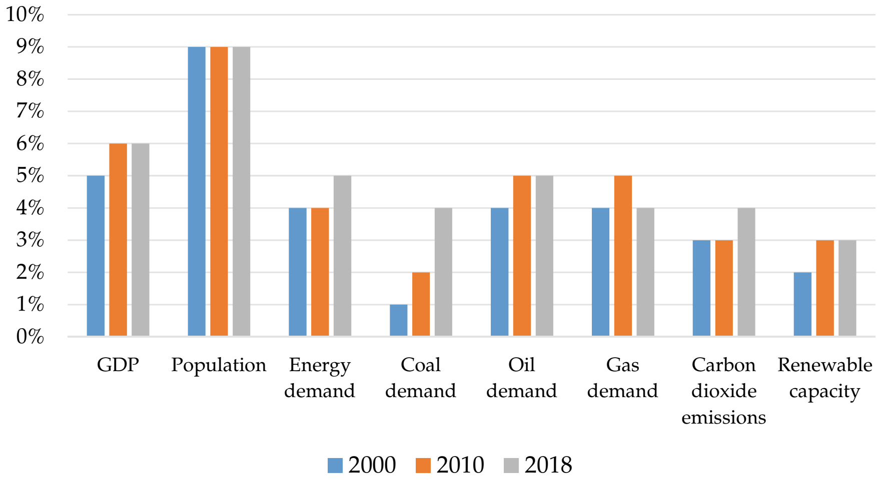

Fig. 9.2 Global economic and energy indicators (growth rates) in ASEAN, 2000–2018. GDP = gross domestic product. *Source* Adapted from IEA (2019a)

9.3 Green Innovation and Alternative Energy Options in ASEAN

Meeting the energy SDGs in ASEAN requires deploying multiple technologies and policy approaches in the energy sector. As there are no silver bullets, international experiences of energy transitions can offer valuable guidance and insights in the development and deployment of green energy technologies in ASEAN considering that fossil fuels have dominated the planet for centuries and will continue to do so. Whilst the replacement of carbon is urgent, innovative solutions should be adopted considering the environmental, technological, and economical aspects. Policymakers need to have a practical orientation towards the frameworks that are being developed internationally for the deployment of green technologies so that the energy transition becomes smooth. A report by IRENA showed that Southeast Asia has the highest share of jobs in renewable energy (83%), but it is lowest in terms of energy efficiency jobs (only 7%) (IRENA 2020a). Renewable energy technology varies significantly across the member states in ASEAN, although there has been some significant progress made in renewable energy development.

9.3.1 Nuclear Energy

Nuclear power systems are comparatively clean and an abundant source of energy with the potential to contribute to the hydrogen economy. Many countries in Southeast Asia have also expressed increasing interest in nuclear energy given its economic benefits as well as its low carbon emissions for electricity supply (Nian and Chou 2014). In addition to renewables, the technological advancement of nuclear reactors is considered to have the capacity to transform the clean energy sector in Southeast Asia (Nian and Hari 2017). The substantial possibility for the cost-effective, efficient, and large-scale production of hydrogen utilising heat derived from nuclear power station already exists. For example, the US Department of Energy introduced the Advanced High-Temperature Reactor technology built for hydrogen production with high-temperature water electrolysis or thermochemical cycles (Zink 2003). Several studies on the thermochemical cycle have delivered thermal-to-hydrogen energy efficiencies, such as the adiabatic UT-3 cycle with 50% and sulphur-iodine cycle of 52% (Brown et al. 2003). Hence, economically sound and technologically superior hydrogen production capacities could be sourced from nuclear energy. The nuclear energy sector has also gained favour from international organisations like the Intergovernmental Panel on Climate Change as an important energy option for attaining 'zero emissions'. However, cases like the Fukushima nuclear incident in Japan have changed the political environment, and commitments to mitigating greenhouse gases have been revised. Although Japan committed to a 25% reduction in emissions from the 1990 levels by 2020, it only decreased them by 3.8% from 2005 levels, translating to a 3.1% increase in greenhouse gases from the 1990 levels (Thornhill and Roston 2020). The nuclear reactors in Japan also restarted their operations in 2015 despite a lack of public acceptance.

About an 80% increase in global nuclear power production is required by 2040 to achieve the sustainability target, where 85% of the global electricity needs to come from clean sources by 2040 compared with the existing 36%. The use of nuclear power has reduced CO_2 emissions by over 60 gigatons, which is equivalent to 2 years' worth of global energy-related emissions (IEA 2019a). Hence, it would be much harder to achieve a sustainable energy system without proper nuclear investment. Furthermore, nuclear plants also help to keep the power grids stable by limiting the seasonal fluctuation impact from other renewables and reduce dependence on imported fuels, which has been prevalent in major ASEAN countries. However, public acceptance and trust needs to be garnered by informing the public about the importance of the energy source as a viable energy technology to address societal needs.

9.3.2 Carbon Capture and Storage

Achieving long-term economic growth in ASEAN will involve the continued use of fossil fuels. Increasing demand for coal is expected to cause around a 66% rise in emissions by 2040 (IEA 2019b). How can the ASEAN region continue to use fossil fuels to accelerate economic growth without hurting the environment? Carbon capture and storage (CCS) offers a viable pathway to use cheaper energy sources, such as fossil fuels, whilst minimising their environmental impacts as the technology can prevent around 90% of CO_2 from entering the atmosphere by capturing the emissions produced from fossil-based electricity generation and use. CCS technology is also an enabler to produce clean hydrogen from fossil fuels as the emitted carbon gets captured and is geologically stored. Almost all of the world's hydrogen is sourced from gas and coal, and producing clean hydrogen using CCS technology can be more cost-effective than producing clean hydrogen from renewables using electrolyses. If combined with renewable biomass, CCS allows CO_2 to be taken out of the atmosphere and is carbon negative.

Southeast Asia provides good opportunities for harnessing CCS technology as the region has plentiful geological storage resources. Countries like Indonesia, Viet Nam, the Philippines, and Thailand have 54 gigatons of storage capacity (Zhang 2020), reflecting the sufficient capacity to conceal CO_2. However, countries in the ASEAN region are developing CCS at different speeds. For instance, CCS technologies have gained much attention in Singapore across both the public and private sectors since 2017. Indonesia is also considering the development of large gas projects with high CO_2 concentrations even though there is a need to further codify the CCS legal framework. Malaysia, on the other hand, has been focusing on developing CCS in the power and oil/gas sectors by undertaking capacity development and storage assessments alongside running legal and regulatory workshops. The Asian Development Bank (ADB) has also been promoting carbon capture, utilisation, and storage in Asia since 2009 (ADB 2019). In a report on carbon capture and storage in Southeast Asia, economic analysis by ADB showed that natural gas processing and power plants are the best capture source as they are the lowest-cost option for CCS (ADB 2013). However, the development and deployment of CCS in the ASEAN region need to overcome significant challenges, such as generating investment and attracting climate financing and regional and international collaboration as well as establishing regulatory frameworks for CO_2 storage. Effective stakeholder engagement, especially through a smooth public dialogue, could enhance CCS development, which could increase the commercial viability.

9.3.3 Hydrogen Energy

Hydrogen is the most abundant chemical element available in the atmosphere and can be a viable source to electrify homes and for transport and industry. Hydrogen is being pursued as a potential form of clean energy given its wide use in areas such as ammonia production, petrochemical and oil refining industries, and many others. Currently, around 95% of hydrogen is produced from coal and gas, also called 'grey hydrogen', and a small portion is produced by CCS, called 'blue hydrogen'. Less than 5% of the total hydrogen production is produced from renewables, also known as 'green hydrogen' (Phoumin 2020). Green hydrogen obtained through the electrolysis of water could be a non-polluting alternative for energy. It could be adopted in sectors such as transport, power generation, building construction, and energy storage as it can make a remarkable contribution to clean energy transitions. Hydrogen has the characteristics of being light, storable, and energy-dense, and it has no direct emissions of greenhouse gases, making it an important part of a clean and secure energy future. It has been found out that if all the current hydrogen production is to be transformed from green sources, electricity demand would reach 3600 TW h, surpassing the total annual electricity generation of the whole of the European Union (Evwind 2020).

Hydrogen fuel has the huge potential to combat climate change by facilitating the transition to low-carbon energy sources despite its low share in global energy consumption. The increase in scope for renewable energy and the continuous decrease in costs will strengthen innovative green technologies, such as storage facilities developed from hydrogen. Furthermore, research has shown that blending hydrogen with natural gas could provide a smooth transition from the current hydrocarbon-based economy to a hydrogen carbon economy (Muradov and Veziroğlu 2005). In a long-term transition towards a clean and sustainable energy future, hydrogen provides a flexible option and a more distributed energy system in the energy system which ensures a clean and sustainable hydrogen future (Barreto et al. 2003). For many countries in ASEAN with infrastructure and high energy demand, the system brought by hydrogen economy could provide an easy transition towards a renewables-based future.

The cost of hydrogen will also decline by over 50% by 2040 if adopted across all sectors making it as competitive as the price of gasoline (Bermudez and Hasegawa 2020). The current cost of supplying renewable is about five times higher than gas, but the cost will come down with investment in hydrogen supply chains. As the world is shifting towards a green economy, green hydrogen will serve as a catalyst to address the integration challenges facing wind and solar. By 2023, many hydrogen projects in Organisation for Economic Co-operation and Development (OECD) countries are expected to be launched and include major pipelines for distribution to end users and electrolysers (IEA 2010). Island countries, especially in the ASEAN region, will benefit substantially as hydrogen will accelerate carbon capture and storage technologies, which are a form of clean energy carrier.

The ASEAN region has not yet included hydrogen in its policy agenda in many countries as an alternative fuel. Nevertheless, policy measures on emerging and alternative technologies, such as hydrogen and energy storage, are likely to be addressed by the ASEAN Plan of Action for Energy Cooperation (APAEC) Phase 2, which is under preparation for endorsement at the ASEAN Ministers on Energy Meeting. The OECD's action plan to increase the share of hydrogen in the energy mix could indeed be fulfilled with support from the APAEC. The energy leaders in ASEAN could also develop a clear strategy on ways to promote hydrogen use in the transportation and power sectors, not limited to the refining, fertiliser, and petrochemical industries. Countries such as Singapore, Malaysia, Thailand, Indonesia, and the Philippines could learn lessons from OECD countries, China, and countries in Europe to guide investment in research and development for hydrogen produced from both renewables and non-renewables.

Southeast Asian countries can learn from neighbouring economies like China, which has already accelerated hydrogen investment support to local industries, and around US $2 billion is being injected. Similarly, Japan has been promoting the global adoption of hydrogen for vehicles, power plants, and other usages. Brunei Darussalam in the ASEAN region, too, has taken a lead in the supply chain of hydrogen as it has supplied liquefied hydrogen to Japan since last year. However, more energy is consumed by the liquefied hydrogen as it needs a temperature of −253 °C in order to transform the cooled gas into a liquid form (Phoumin 2020).

Japan has been pioneering the renewable hydrogen economy, in which the production of hydrogen through the reformatting process of renewable electricity such as solar and nuclear is likely to bring a breakthrough in decarbonising emissions. By adopting a basic hydrogen strategy, Japan also became the first country in East Asia to ensure that production will reach cost parity with gasoline fuel and power generation in the long term. Society's willingness to pay is also a major factor despite the efforts by governments and private sectors to adopt hydrogen practices. The Republic of Korea (henceforth, Korea) is another country which set a target for hydrogen usage at 10% of total energy consumption by 2030 and 30% by 2040 in order to power selected cities and towns (Phoumin 2020). The Korean government has also made an announcement to create three hydrogen cities by 2022 where hydrogen will be used for major urban functions, such as cooling, electricity, heating, and transportation.

New research efforts are also underway with regards to investigating new methods for chemical-based liquid hydrogen carriers. Lee et al. (2013) introduced a methodology to quantitatively analyse the energy system by looking into the relationship between green car technology and greenhouse gas reductions in the regions of Korea. The research suggested that technology such as de-carbonisation should be enhanced in the production of hydrogen to replace existing fossil fuel sources in the foreseeable future.

9.4 Policy Recommendations

The development and deployment of green technologies are viable and necessary in Southeast Asia to address the critical issues of climate change and adaptation in the context of increasing energy demands. The development and deployment of green energy technologies will improve environmental quality and human welfare and overall help developing economies to achieve the SDGs. ASEAN as a regional multinational organisation has a pivotal role to play not only to fulfil its global commitments of the United Nations Climate Change Conference (COP 21) but also to facilitate cross-sectoral partnerships for sustainable economic development. This is important for achieving the ASEAN Community Vision 2025, too, which aims to sustain the momentum of regional integration (ASEAN 2015).

There seems to be lack of adequate experience and expertise in some ASEAN Member States, such as Viet Nam, Malaysia, and Indonesia, when it comes to the evaluation of the risk of renewable energy investments, and this has translated into a lack of financial support and public capital immobility for renewable energy investment. The cost of deploying the renewable energy sector has been continuously falling, which has increased prospects for its investment by shifting investors away from fossil

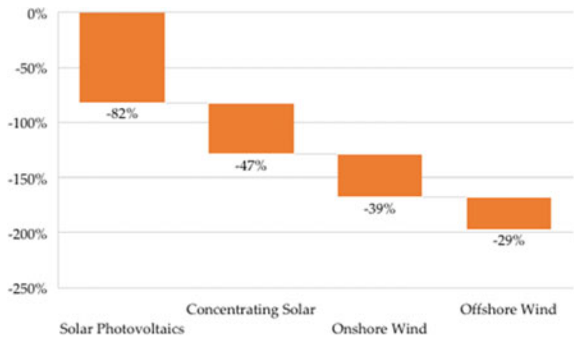

Fig. 9.3 Decline in renewable energy costs, 2010–2019. *Source* Adapted from IRENA (2020b)

fuels. Green technologies, such as hydropower, geothermal, and hydrogen carbon technologies, become substantially competitive. Figure 9.3 shows how renewable energy costs have declined in the past 10 years.

Some 56% of capacity additions for utility-scale renewable power achieved lower electricity costs in 2019 than the cheapest new coal plant. Annual potential costs could be cut by US $23 billion if the existing coal of 500 GW were to be replaced by solar photovoltaic and onshore wind (Creamer 2018). This global trend is an indication for policymakers in ASEAN to also emphasise renewable energy and exploit the huge benefits it can bring.

9.4.1 Transitioning Towards a Hydrogen-Carbon Economy

The development and deployment of certain green technologies like carbon capture, utilisation, and storage require an appropriate institutional and policy set-up as a prerequisite. There are traditional raw materials widely used in infrastructure in the construction, aerospace, and automotive sectors that can be replaced by carbon-based materials, such as carbon composites and manufactured graphite. These materials can absorb enormous amounts of carbon products, and several bridges in Canada, Japan, the United Kingdom, and the United States have already been constructed and developed using such mechanisms (IEA 2019d). One major advantage of carbon-composites in comparison to traditional materials, such as steel, is that they do not erode and are five times stronger than the mainstream heavy construction equipment (Brown et al. 2003).

By replacing concrete with carbon materials, there could be a significant decrease in CO_2 emissions, which would in turn discontinue the cement-manufacturing plants. There has been good progress made in terms of using carbon-based products as additives for substituting cements. Moving towards a hydrogen-carbon economy, ASEAN countries could emphasise the efficient interplay between energy, the environment, and the economy.

Hydrogen has major implications in various sectors, such as transport. Countries like India have welcomed foreign investment in fuel cell vehicles and hydrogen transportation infrastructure has already started in some pilot cities. Similarly, in Japan, the Tokyo Metropolitan Government increased the number of hydrogen buses to 100 in 2020 (Deloitte China 2019). As for the ASEAN region, the Sarawak Local Government in Malaysia is starting to operate hydrogen buses soon. Singapore also seems to be collaborating with companies from Japan to explore the development of hydrogen as a new clean fuel to decarbonise emissions.

It can be observed that support investment for hydrogen technologies has increased recently in many countries, with around 50 targets, mandates, and several policy incentives especially focused on transport. Hydrogen production mostly comes from natural gas as it comprises 70 million tons, or around three-quarters of the annual global share, or 6% of natural gas use. Coal also has an equal contribution as countries like China have a major stake, whilst only some production of hydrogen comes from oil and electricity (Bermudez and Hasegawa 2020).

There is not a 'one size fits all' when it comes to hydrogen policy. The production of both 'blue' and 'green' hydrogen includes several opportunities and risks for the countries following the respective approaches, even though there are options available to deploy hydrogen products from both fossil fuels and low-carbon sources, such as renewable electricity. On one hand, fossil fuel-based hydrogen may enable scale-up in the short term; however, there remain minimal environmental benefits and need for carbon capture or low-carbon hydrogen in the long term. On the other hand, the substantial application of hydrogen in big sectors, such as transport and chemicals, can bring efficiency in the energy system. This could bring numerous opportunities to exploit energy resources that are currently underutilised. ASEAN governments should align their ambitions and approaches for the use of hydrogen by considering international practices as well as the market scope where it can be widely applied.

Despite the wide spectrum of opportunities for hydrogen with its industry application, there still remains a considerable gap in realising its potential. As support for the clean energy transition is growing amongst policymakers in ASEAN, an action-oriented plan and vision are required both for the near future and to make hydrogen feasible for the longer term. An intelligible policy is essential to meet the long-term goals on hydrogen as there are various risks associated in investments which could be detrimental to many stakeholders given the complexity of hydrogen value chains. Standard regulations are required across the ASEAN countries to mitigate uncertainties and coordination problems. The IEA stated four key value chains as opportunities in the coming decade to accelerate the speed of hydrogen deployment focusing on different regions of the world. ASEAN is part of the fourth value chain as a part of Asia–Pacific along with the Middle East, North Africa, and Europe. It has been recommended to establish 'first shipping routes' in order to commence international hydrogen trade for the ultimate goal of setting-up a global low-carbon market (Bermudez and Hasegawa 2020) (Fig. 9.4).

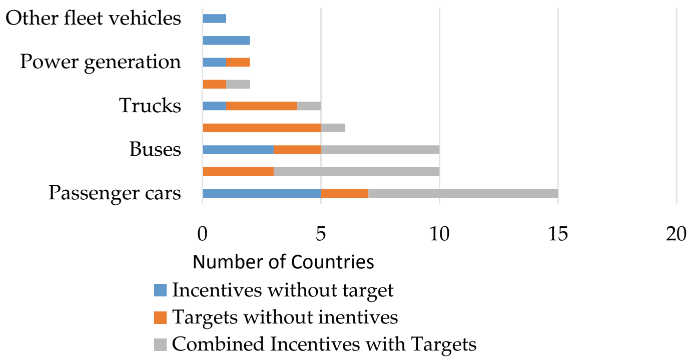

Fig. 9.4 Support policies for hydrogen development, 2018. *Source* Adapted from Bermudez and Hasegawa (2019)

9.4.2 Adapting Green Energy Financing for Green Deployment

Finance is the engine of development for renewable energy projects, whilst the financing of investments that provide environmental benefits through new financial instruments such as green bonds, green banks, carbon market instruments, fiscal policy, green central banking, fintech, and community-based green funds are necessary to achieve the SDGs (Sachs et al. 2019). ASEAN and Southeast Asian governments should adopt these targeted funding channels, also known as green energy financing, for the greater deployment of green technologies in the region. A geographical mismatch between resource endowments and demand centres provides an incentive for the regional integration of power grids in order to bridge the gap but requires investments in physical interconnectors. Therefore, the hindrances to renewable energy development do not only include technological capacity and access to finance (Shi 2016). It is difficult for policymakers to determine ways to make the transition towards a green economy from the existing coal generation in the absence of financing projects when, generally, financial institutions show more interest in fossil fuel projects rather than in green projects. The cross-sector policy framework can enable the integrative financing and development of renewable energy, fostering energy efficiency and replacing fossil fuels.

The Southeast Asia region has played a significant role under the agenda of 'one community for sustainable energy', with initiatives such as the ASEAN Power Grid interconnection, the trans-ASEAN natural gas pipeline, energy efficiency, renewables, and regional policy and planning (Shi and Malik 2013). All these initiatives require costly investments in capital expenditure and, hence, appropriate financing. The breakthroughs in technology in the renewable sector can provide a resilient model for a low-carbon energy system. The stronger regional framework on green project financing can serve as an extensive development plan and ensure a sustainable energy transition roadmap moving forward. Both regional coordination and cooperation with a strong political will from all the countries in the region will be vital for integrated economic development.

The Belt and Road Initiative introduced by China also has some major implications for Southeast Asian economies, such as promoting infrastructure projects in the region that relate to water resources and transboundary rivers. However, several positive and negative impacts may pertain, creating political issues on the social and environmental fronts (Williams 2019). Therefore, similar concerns should be raised whilst deploying green technology projects, especially when international collaborations take place. A regional governing institution focused on energy and the use of market-based instruments can provide a platform for strengthening energy dialogues and facilitating the mobilisation of green technologies to boost the energy infrastructure. Furthermore, the role of the private sector is also equally important and will not only ensure civic engagement but also support the leveraging of public funds. Policymakers in ASEAN have been increasingly trying to ensure reliable and affordable sustainable energy solutions. It is equally important to focus on efficiency whilst developing investment infrastructure for fuel and power supply.

Since 2000, hydropower output has quadrupled in Southeast Asia (IEA 2019a). The costs for solar PV have been falling over time, but the share in total energy remains small. Market-based instruments along with a better framework are crucial to support their deployment. IEA data also show that there has been a shift towards low energy-intensive manufacturing and services given the projected rate of energy demand growth is lower than it was in the past 2 decades, holding a 12% share of the projected rise in global energy use to 2040.

Achieving a clean energy future in ASEAN also requires electrifying the transport sectors by deploying green technologies like electric vehicles. However, the congested roads and lack of proper infrastructure make it difficult to scale up and replace oil consumption. The rise of middle-income consumers and the increasing demand for household space cooling has increased the energy use of air conditioners in ASEAN by 7.5 times in the past 30 years as revealed in Fig. 9.5. Indonesia, which is the most populated country in ASEAN, only has about 10% of its households with air conditioning, and less than 20% of households in the whole ASEAN region have air conditioning. However, these numbers are likely to keep growing, and an additional 200 GW of capacity needs to be added by ASEAN countries by 2040, which will increase the demand by 30% (IEA 2018). At the same time, there are opportunities to increase efficiency policies, which could in turn enhance efforts to improve building and equipment efficiency. Policymakers must understand that hydrogen is one of the many alternatives available to fossil fuels. It is highly significant for energy storage, long-distance driving, and faster filling.

Figure 9.5 shows that higher levels of investment are required in order to meet Southeast Asia's energy needs and policy priorities. The fastest-growing use of electricity to 2040 is space cooling, which is driven by high cooling needs and rising incomes. Commitments for funding from both public and private entities are crucial. For example, public sources have played an important role in financing thermal power plant projects and large-scale renewables, such hydropower, whilst most wind and

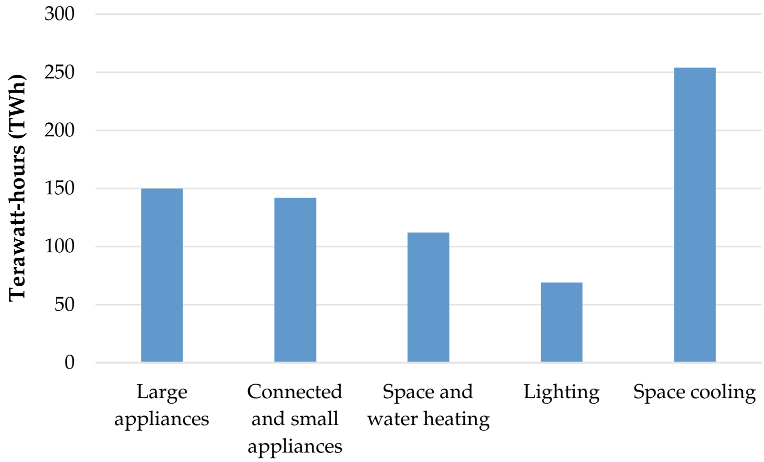

Fig. 9.5 Household electricity demand growth to 2040 in ASEAN by appliance source. *Source* Adapted from IEA (2019a)

solar PV projects have relied on private finance supported by policy incentives. Civic engagement and initiatives from investors and companies also play an equally vital role. Finding by the Korean government showed how both aid and other public finance are deployed.

Figure 9.6 indicates that more investments should be channelled towards sustainable energy, and the deployment of renewables should be scaled up, although notable progress has been made towards disincentivising the consumption of fossil fuels. Technologies to reduce emissions from the power sector, such as carbon capture,

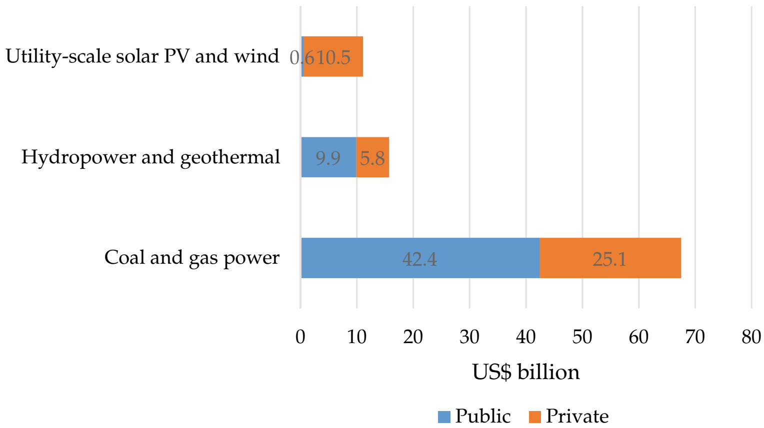

Fig. 9.6 Sources of finance for power generation investment in ASEAN, 2014–2018. PV = photovoltaic. *Source* Adapted from IEA (2019b)

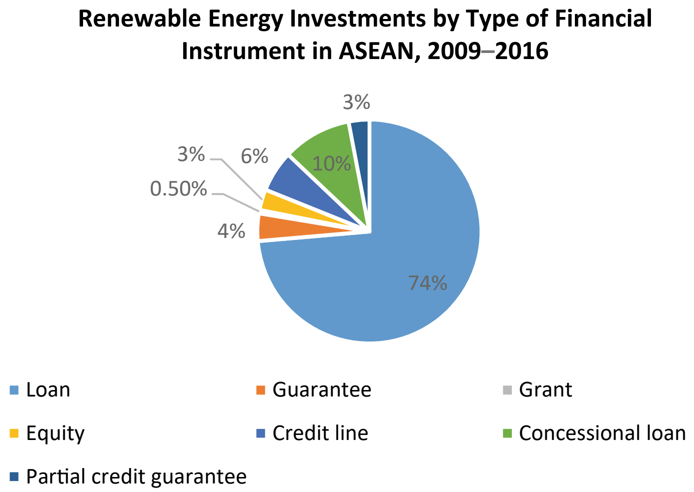

Fig. 9.7 Share of renewable energy investments in ASEAN by Type of Financial Instrument, 2009–2016. *Source* Adapted from IRENA (2018b)

utilisation, and storage, are essential, and efficiency must be achieved in sectors such as vast cooling and road transport. The gasification of biomass and solar-thermal technology create alternatives for producing hydrogen from renewable energy sources. Similarly, surplus wind electricity can also be used for hydrogen production as a means for storing energy (Fig. 9.7).

9.4.3 Managing Risks

Green projects are associated with risks pertaining to new technologies and their relatively lower rates of return. The rapid rise in energy demand in Southeast Asia is poised to bring several risks to the region from an energy financing perspective. The region has been forecast by the IEA to register a net deficit in energy trade of US $300 billion per year due to increasing imports of oil by 2040 (IEA 2019a). Government budgets will likely remain tightened as increases in subsidies for renewable energy can disincentivise market-based energy prices. Setting energy prices based on market signals by reducing fossil fuel consumption subsidies will entice more sustainable energy consumption and investments in ASEAN. Whilst the progress in eliminating fossil-fuel subsidies is notable, the process still remains incomplete. From the standpoint of energy security, the current dependence on imports of oil is 65% and is expected to rise to 80% in 2040, and this overdependence is a serious concern for the region (IEA 2019b). The high carbon-intensive power sector in Southeast Asia especially due to the rise in coal demand is expected to increase CO_2 emissions to almost 2.4 Gt in 2040, an increase by 42% from the current level (IEA 2019b). This will negatively impact the environment, adding to already existing poor urban air quality and congested transportation infrastructure.

The governments of ASEAN need to address the energy security risks by taking into account the financial, environmental, and social viability of the projects. For this, various frameworks could be developed for the process of procurement and contracting mechanisms in renewable areas. Support for the financial system and the enhancement of sustainability utilities could also strengthen the market. The challenge of limited infrastructure, particularly in the Philippines and Indonesia, which are archipelagic in nature, has obstructed effective renewable energy deployment as the countries have fragmented electricity grids when it comes to transmission. Similarly, the lack of regulatory frameworks on green technology development and deployment brings major challenges. Countries like Brunei do not have a specific policy framework in place to regulate the development of renewable energy, although it has been reported to be in progress. There was major devastation in the Lao PDR due to a lack of coordination creating human risk, as the failure of an auxiliary dam raised heavy water that washed out 13 villages, affecting around 11,000 people (Gnanasagaran 2020). Despite the huge potential for hydropower, with an unrealized power potential of 22.3 GW, the high-risk nature of dam construction should not be underestimated.

Viet Nam is another major player in the hydropower sector, with an estimated capacity of 16.68 GW, but the lessons from the Lao PDR have allowed the country to focus on less intrusive sources of renewable energy. The revised master plan of Viet Nam has not focused on the development of large-scale hydropower as a renewable source of energy but promotes increasing capacity to 21.6 GW in 2020 and approximately 27.8 GW by 2030 with small and multipurpose projects (Greening et al. 2020). Viet Nam has a heavy reliance on coal-fired power as in 2020 alone the country's capacity stood at 49.3%. Despite efforts by the government's revised master plan to reduce reliance on coal, coal's share is expected to reach 53.2% by 2030 as the demand for development projects in the country demands more energy (Vietnam Electricity News 2016). Given the cheaper costs associated with renewables and wind and solar, sources from coal could be shifted and current imports of coal of around 30 million tons could be reduced (Vu and Gloystein 2019).

Proper coordination amongst government agencies and the private sector is crucial for prioritising renewable energy policies for implementation. Awareness amongst the public about the benefits of using green technologies can boost energy efficiency as well as environmental conservation. Multilateral power trading agreements will be crucial along with the expansion of cross-border transmission, which can lower the building and operating costs of ASEAN power systems. The Lao PDR exports 67% of its electricity generated from hydropower, which is almost 30% of all its total exports, with the main buyers being ASEAN countries such as Thailand, Viet Nam, and Cambodia (Gnanasagaran 2020). Regional integration could facilitate the growing demand for energy by deploying green technologies, such as wind and solar PV, and most importantly, the application of hydrogen carbon-based instruments.

9.5 Conclusions

The purpose of this study was to formulate the policy lessons and frameworks in ASEAN economies for facilitating the development and deployment of green technologies and alternative energy options. In doing so, the study reviewed the literature around green energy deployment in the context of green growth and energy transition and discussed the current status of renewable energy development in ASEAN. Alternative energy options such as nuclear and hydrogen energy prospects were discussed, with the study proposing hydrogen fuel as a way forward in meeting the energy and environmental objectives in the ASEAN. The nuclear prospects in ASEAN are complicated by political factors, and public acceptance of nuclear energy needs to be boosted. Likewise, carbon capture, utilisation, and storage will be a vital technology in ASEAN to reduce emissions from the power sector and from industry whilst allowing the use of fossil fuels to achieve economic growth. The study proposes transitioning to a hydrogen-carbon economy, adapting green energy finance for development, and managing financial risks in promoting green energy development. The decreasing costs for renewable electricity, especially from solar PV and wind, seem to support the production of electrolytic hydrogen, making it a low-cost supply technology option for hydrogen. Similarly, increasing pressure from international agreements such as COP21 will demand countries to deploy alternative fuel pathways in their energy mix.

The IMF has forecast the global economy to grow negatively at 4.9% in 2020, and policymakers will need to come up with major economic stimulus packages to combat the COVID-19 crisis (IMF 2016). Investment in clean energy with technological solutions will not only be an ideal option from an environmental standpoint but will also fulfil the unemployment gap that is been created, especially in emerging regions like ASEAN. In addition, the falling costs of renewables can also provide policymakers with the perspective to revisit policy planning documents and create a long-term vision for the deployment of green technologies. It is a crucial time for batteries, hydrogen, and carbon capture as they have the potential to be deployed on a mass scale, which could help in achieving the global clean energy transition. According to a recent analysis done by the IEA, governments are believed to be driving 70% of global energy investments (Birol 2020). Proper government coordination and leadership to engage multiple stakeholders is important to achieve climate goals with the right deployment of green technologies.

Implementing policy for energy efficiency improvements in ASEAN through policy measures such as attracting foreign direct investment and reducing energy consumption in public goods provisions, such as streetlights, is desirable (Nepal 2020). Cross-sectoral partnerships and international power connectivity in the ASEAN region should be the way forward. The European Union provides a perfect example of this case whereby their partnership in renewable energy lowered the energy supply from coal by 3% (Louis 2020). This will not only enable the sustainable sourcing of energy but also increase the share of renewable energy. Future areas of research should investigate the policy frameworks needed to better support the wider deployment of green technologies, such as carbon capture, utilisation, and storage in the region. The scope for energy efficiency improvements in the region within the context of the push towards greener technology development and deployment also needs to be thoroughly studied. The role of cross-sectoral partnerships between the governments, businesses, and non-governmental organisations in ASEAN to facilitate green financing and investments to help mitigate the threats of climate change also needs to be studied.

Acknowledgements This research paper was carried out under the funding from the Economic Research Institute for ASEAN and East Asia. We also acknowledge the valuable comments received from Professor Fukunari Kimura, Professor Jun Arima, and participants at the First Working Group Meeting—Energy Sustainability and Climate Change in ASEAN held on 14 September 2020.

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Chapter 10
Innovation Management and Productivity in Sustainable Energy—The Case of Biomass Fuel Manufacturers in Malaysia and Thailand

Sufian Jusoh, Norasikin Ahmad Ludin, and Mohd Adib Ibrahim

Abstract The high price of fossil fuels and increased demand for more sustainable and environmentally friendly sources of energy have caused firms and consumers to search for alternatives sources, like from biomass. This study examines innovations in biomass-powered and -led products introduced by three firms, Firm A and Firm B, which are based in Malaysia, and Firm C, based in Thailand. Firm A produces pulverised biomass fuel and biomass combustion systems to generate power and heat for heat-treatment factories in the area. Firm B produces lubricants from palm oil and vegetable oil residue. Firm C uses cassava biomass to produce biogas to generate electricity supplied to the grid. The study argues that the three firms have intentionally or unintentionally employed effective innovation management in ensuring sustainability in their business, which is challenged by the volatility in oil prices and competing demands for feedstocks. By developing innovative products and/or services, the three firms differentiate themselves from their competitors and have a competitive advantage in the market.

Keywords Innovation management · Sustainability · Biomass · Feedstock · Oil price volatility · Economic shocks

10.1 Introduction

With the world becoming more aware of climate change and environmental sustainability, a more responsible production of energy is in high demand, thus leading to more private sector-led innovations. Firms have begun to innovate and to produce new sources of energy, as from biomass, which forms part of the circular economy.

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H. Phoumin et al. (eds.), *Energy Sustainability and Climate Change in ASEAN*, Economics, Law, and Institutions in Asia Pacific,
https://doi.org/10.1007/978-981-16-2000-3_10

In addition, countries around the world, including Association of Southeast Asian Nation (ASEAN) members, are working towards reducing the use of fossil fuels by encouraging more use of renewable energy from various sources. According to Otaka et al. (2019), full-fledged biomass utilisation is a key issue for ASEAN members.

As most ASEAN members are producers of agriculture products, they have begun to examine agriculture waste, or biomass, as a source of renewable energy, either for generating heat or electricity. Most agriculture residue is treated as waste either through incineration or landfills, which may cause environmental degradation if continued (Otaka et al. 2019). Biomass resources, which are seasonal in nature, can become a promising renewable fuel for small-scale power generation, while addressing the issues of carbon dioxide (CO_2) emissions reduction and rural electrification that are crucial to rural development.

Types of biomass differ throughout the ASEAN region. Indonesia, Malaysia, and Thailand have large plantations, so the types of available biomass include those from oil palms, rice, rubber trees, and cassava. Biomass residues in other ASEAN members may be limited to rice, corn, and cassava. Junginger et al. (2020) found that in the world's largest producers of palm oil—Malaysia and Indonesia—palm kernel shell (PKS) is the most traded type of biomass, with high demand from Japan and the Republic of Korea. Other residues are less competitive due to logistic costs, and biogas production from palm oil mill effluent is still underutilised.

Biomass as an important component of renewable energy depends on various factors, such as the availability of the biomass, ability of private sector firms to transform the biomass into potential use, incentives offered by governments to encourage biomass utilisation, and technology upgrading and innovations that help an industry replace fossil fuels with biomass energy. Firms also must find new methods for industries and the public to access the technology that allows utilisation of the biomass as a source of energy for heating, transport, or electricity generation.

This study examines innovations on biomass by three firms in the ASEAN region, two from Malaysia and another from Thailand. It analyses innovations in biomass-related technology that is leading to utilisation of biomass in the heat-generating industry and transport in Malaysia and the power-generating industry in Thailand. The first Malaysian firm, Firm A, produces pulverised biomass fuel to generate power and heat for heat-treatment factories in the area. The second Malaysian firm, Firm B, produces lubricants from palm oil residue. The Thai firm, Firm C, uses anaerobic digestion technology to produce biogas from cassava biomass to generate electricity supplied to the grid.

This study argues that these firms had to employ effective innovation management to ensure sustainability in their businesses, which are challenged by oil price volatility. Innovation is a key contribution to a firm's ability to succeed in a competitive environment. By developing innovative products and/or services, these firms were able to differentiate themselves from their competitors and to acquire a competitive advantage in the market. A reduction in the oil price, however, may have a negative impact on the demand of a biomass substitute fuel. Moreover, in a highly competitive world, these firms will still have to compete to move up the economic ladder.

The study further argues that the innovation demonstrated by the three firms to produce energy from biomass must be linked to the overall objective of ASEAN to develop alternative sources of energy. Innovative firms are also important to ASEAN as part of the plan to adopt a circular economy in the region and to encourage more domestic and foreign direct investment in renewable energy. This, in return, will lead to higher-quality foreign direct investment while contributing to responsible production and consumption in the ASEAN region.

The study also shows that, with innovation and innovation management, these small firms are able to contribute to more utilisation of biomass as a source of renewable energy, especially at the local level. This is consistent with the latest finding by Dhar (2020) that corporations, whether privately held or state-owned, focused or diversified, captured 43% of the share of leading innovators. However, these firms still face various challenges, which may require government intervention. In addition to the challenge posed by oil price fluctuation, they may also face competing demands for the biomass, especially regarding PKS.

The firms also need better access to financing to meet customer demand. The study shows that for firms A and B in Malaysia, benefits accrued from research grants provided by the government. Hence, governments should consider policy interventions, such as restricting the exports of certain types of raw biomass, especially PKS, and increasing access to finance through specialised funding schemes beyond research grants. Moreover, bioenergy is not currently cost-competitive with fossil fuels and remains reliant on government support to create enough demand (Vivid Economics 2019).

10.2 ASEAN, Biomass, and Sustainable Energy Development

Sustainable sources of energy are important for ASEAN, and this is reflected in the amount of renewable energy in the electricity mix. The ASEAN Centre for Energy (2017) projected that between 2016 and 2040, the energy mix in the region will continue to rely heavily on fossil fuels. However, ASEAN has demonstrated its commitment towards sustainable sources of energy through the *ASEAN Plan of Action for Energy Cooperation, 2016–2025* (ASEAN Centre for Energy 2016) and *ASEAN Vision 2025: Forging Ahead Together* (ASEAN Secretariat 2015).

10.2.1 Biomass Potential in ASEAN

Of the 10 ASEAN members, Indonesia, Malaysia, Singapore, and Thailand are estimated to become greatly reliant on renewable energy in near future based on their current 2013 business-as-usual (BAU) scenario (ADB 2013). The use of renewable energy is expected to increase by 2040 based on the BAU. These ASEAN members are known for their live tree carbon stocks, including tropical equatorial forests, tropical seasonal forests, and tropical dry forests (IRENA 2018).

ASEAN has abundant bioenergy resources, as its countries are large producers of agriculture and wood products (Tun and Juchelková 2019), where biomass residues generated from sugar, rice, and palm oil mills total more than 230 million tons per year, with a potential energy generation of 16–19 GW. It is estimated that biomass energy could provide about 26% of the total primary energy supply or 87% of the renewable energy supply (Tun and Juchelková 2019).

Sources of biomass fall into two categories of countries (Otaka et al. 2019). One group, consisting of Indonesia, Malaysia, and Thailand, produce agriculture resources from big plantations such as oil palms. The other, consisting of Cambodia, the Lao People's Democratic Republic (Lao PDR), the Philippines, Myanmar, and Viet Nam, have biomass resources mainly from rice, corn, and sugar cane. Oil palm wastes include kernel shells, fibres, empty fruit bunches, and trunks; coconut waste includes fibres and kernel shells; and rice waste includes rice husks and straw.

ASEAN biomass energy potential is high (Fig. 10.1). This potential is calculated based on the reported live tree stocks, crops, and forest availability, whereas the energy potential is based on the energy content in biomass live stocks (Tun et al. 2019).

Table 10.1 displays the available live tree stock species status%age as well as live tree carbon. Indonesia's vast lands, covered in forests, recorded 36.02% of tree

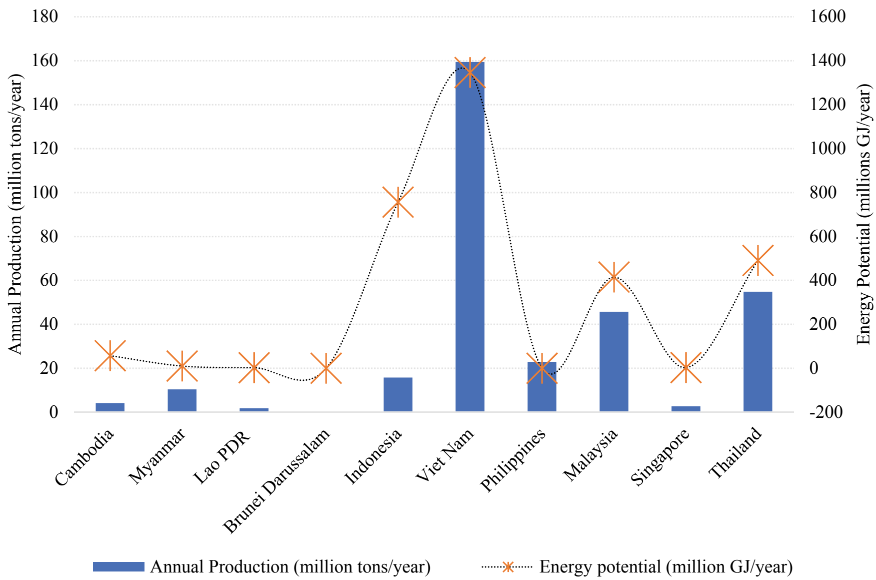

Fig. 10.1 ASEAN biomass energy potential and annual production. GJ = gigajoule, Lao PDR = Lao People's Democratic Republic. *Source* Tun et al. (2019)

Table 10.1 ASEAN biomass carbon stock and life tree carbon

Country	Biomass carbon stock (million tons carbon)	Tree species number	Tree species status (%)
Cambodia	957–1914	67	2.55
Myanmar	–	48	1.83
Lao PDR	718–1870	22	0.84
Brunei Darussalam	40–115	–	–
Indonesia	10,252–25,542	947	36.02
Viet Nam	–	111	4.22
Philippines	–	640	24.34
Malaysia	240–4821	769	29.25
Singapore	–	1	0.04
Thailand	–	24	0.91
ASEAN	*Live tree carbon (tons of carbon per hectare)*		
Tropical equatorial forest	180/225		
Tropical seasonal forest	105/169		
Tropical dry forest	78/96		

Source Hoefnagels et al. (2017), Besar et al. (2020), ACE (2020) and Abanades et al. (2005)
ASEAN Association of Southeast Asian Nations, *Lao PDR* Lao People's Democratic Republic

species status and have more that could increase its biomass energy potential even further. The biomass carbon stock reported by the International Panel on Climate Change (IPCC) showed that both Indonesia and Malaysia dominate the above-ground biomass carbon concentration in the ASEAN region.

10.2.2 Biomass Policy Issues and Challenges

In developing renewable energy, ASEAN members face many challenges relating to policymaking and policy implementation, such as domestic energy policy technology, permitting and licensing mechanisms and technical standards to facilitate grid interconnection, obtaining raw materials, pricing of power and renewable energy, international trade law, and environmental and sustainability concerns (Jusoh 2017; IRENA 2018).

One concern raised by IRENA (2018) is the need to communicate the policies with stakeholders. IRENA (2018) suggested that adaptations to the policy and regulatory landscape be well-communicated and managed, particularly to minimise investment uncertainty and risk perception. IRENA (2018) also found that there is a lack of comprehensive frameworks for the end-use sectors (i.e., heating, cooling, and transport). The region has enormous potential to scale up modern bioenergy for sustainable, efficient cooking; industrial heat generation; and co-generation of power and heat. It has been identified that the transport sector currently has the lowest share of renewable energy in the region.

Producers of renewable energy, especially from biomass, also face issues with raw material. For non-plantation industry players, such material must be obtained from third-party suppliers or developed by the project developers themselves (Jusoh 2017). For example, any project using palm waste must secure the material from palm-processing mills, mainly owned by large plantation conglomerates such as FGV Holdings Berhad and Sime Darby Berad. These conglomerates may compete for the use of biomass for boilers, animal feed, and export to markets that offer a better price, such as Japan and Korea.

Moreover, the commoditisation of waste or biomass results in competing demands from export markets, creating a shortage for domestic green electricity. A domestic green electricity generator would stand to gain from any restrictions on the export of raw materials, as this could secure the supply and help keep prices down as demand falls from export markets. Based on the World Trade Organization Appellate Body decision in China—Measures Related to the Exportation of Rare Earths, Tungsten, and Molybdenum,[1] export restrictions could be imposed under Article XX (g) of the General Agreement on Tariffs and Trade (GATT), measures related to the conservation of natural resources.

10.3 Innovation Management in Biomass Technology

To allow for effective and easy use of biomass as a source of energy, related industries have developed biomass-conversion technologies, including combustion, thermochemical, electrochemical, and biochemical. These conversion technologies can turn biomass into alternative sources of fuel such as solid energy sources, liquid biofuels, and gaseous fuels (Faaij 2006; Vivid Economics 2019). Thermochemical conversions include combustion, gasification, and pyrolysis liquefaction, leading to use in heat and electricity generation. Biochemical conversion also involves digestion and fermentation, which lead to electricity generation and fuel production. These technologies and innovations contribute to development in renewable and environmental sustainability.

The utilisation of biomass energy is an important element towards achieving the Sustainable Development Goals set by the United Nations. As biomass can originally be considered organic waste, the utilisation of biomass energy can be classified as part of the process of shifting waste into an economic source, which forms part of the circular economy. Private sector participation and innovation in biomass energy is an important component of the waste-to-wealth value chain. The involvement of

[1] WT/DS431/AB/R, WT/DS432/AB/R, WT/DS433/AB/R, 7 August 2014.

the private sector in producing sustainable biomass energy forms part of responsible production, whereas the utilisation of biomass energy, either by businesses or consumers, is part of responsible consumption.

Private firms may also improve the traditional way of using biomass in the ASEAN region, where biomass is often used for heating and cooking through direct burning. With innovation, innovation management, and a modern way of adopting renewable energy—such as biomass—in household heating, the health of the population in the ASEAN region could be improved. Taghizadeh-Hesary and Taghizadeh-Hesary (2020) found that the increasing use of renewable energy in the total energy consumption of the ASEAN region will result in fewer harmful emissions and contribute to lower lung cancer rates.

Innovation management is key for those involved in biomass-conversion technologies and biomass energy by-products. However, there is little correlation between research and development and revenue, or the need to develop an innovation strategy and to recognise that improving innovation requires transformation of an organisation, culture, and business processes (Accenture 2011). In other words, to remain competitive, biomass-related firms require a strategic approach towards innovation and must employ techniques of innovation management.

Innovation management focuses on transforming uncertainties into knowledge, where firms have to examine and to reassess innovation projects at different levels or stages (Berchicci 2009; Brandtner et al. 2014; Tidd et al. 2005; Van de Ven et al. 1999). Innovation management involves a firm's capability to conduct internal and external management (Lengrand and Chartrie 1999; Hidalgo 2004; Thomke 2006); deal with both growth and efficiency; manage and integrate different components, capabilities, and resources; and implement relevant technical and relational tools (Aggeri and Sagrestin 2007; Bessant and Tidd 2007).

Firms must be able to acquire and to utilise new information and communication technologies, including artificial intelligence, to process and to manage innovation (Haefner et al. 2021). Practitioners of innovation management may need to be outward-looking, in addition to inward-looking for firm-level issues. Among the external factors requiring attention are the highly volatile and changing environments, competitive global markets, rival technologies, and dramatically changing political landscapes. In fact, the Covid-19 pandemic has probably contributed to the way that innovation is being managed, as firms are now looking for more technology collaborations and sustainable outcomes of their products and services (George et al. 2020).

To manage innovation, firms require an entire set of innovative practices involving developing innovation culture; harmonising business strategy; and expanding the strategy to all organisational levels, market tendencies, competitor acts, and technologies (Sanchez et al. 2011). Innovation culture deals with a constant approach to innovation, which links to creativity, openness, and acceptance of new ideas, absorbing the calculated risks to change and cultivating an entrepreneurial mentality. Innovation culture also affects the performance of product launches, where it is found that ventures scoring high in all innovation culture dimensions had higher new product

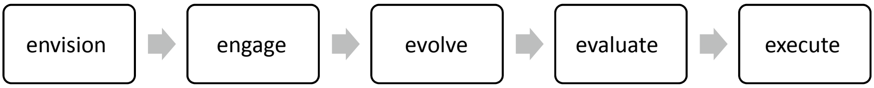

Fig. 10.2 Subprocesses of innovation management. *Source* Microsoft (2013)

profits, and the result revealed no significant moderation between developed and less-developed countries (Michaelis et al. 2018).

In dealing with market tendencies, innovation management allows firms to develop techniques that satisfy existing customers and to focus on the mainstream of the organisation, while cultivating new customers by focusing on a new stream of the market (Lawson and Samson 2001; Michaelis et al. 2018). Innovation in mainstream activities may also help firms reduce costs by eliminating waste, errors, defects, and poor product delivery. New stream activities encourage dynamism to introduce new products and services to create new demand amongst existing customers, generate new customers, and apply new knowledge (Lawson and Samson 2001). In addition, innovation also means that firms are able to partner with suppliers and customers in creating a new stream of products or services by sharing ideas and risks (Von Hippel 2005; George et al. 2020).

Microsoft (2013), in association with some of its customers, developed a process flow for innovation to take effect, involving five subprocesses (Fig. 10.2).

Under the envision process, a firm will put in place a strategy to achieve innovation goals. The vision should contain high-level goals—high-level areas to be funded for innovation that will drive ideas and the portfolio management process. The vision should also involve co-creation, open innovation, collaboration, and social approaches.

In the second stage—engage—ideas are generated. Companies engage employees, customers, and partners in the innovation community to create new ideas. The goal is to generate ideas that will drive new business value for higher income and profit margins. To generate high-value innovations, firms may develop a digital innovation environment; create a branding strategy; pre-populate the process with some ideas; and develop profiles, capabilities, and communities to provide access to expertise and evaluation of new ideas.

In the third stage—evolve—firms take the output to the next level to increase quality and value. At this stage, firms seek to improve ideas and to resolve any issues. The evaluation process then involves providing filtering and search mechanisms; tracking ideas with the most attention, views, and comments; rating the ideas; and undertaking a secondary review process in which a panel of experts can provide more detailed feedback and develop a business case for those ideas.

Finally, firms will execute the ideas. At this stage, they must overcome the three biggest challenges of timely delivery, budget constraints, and quality. Firms need to adopt a faster-to-market view and ensure that resources are used efficiently. To ensure effective execution, firms must follow a standard product development process, develop different project templates for various types of projects to adjust to levels of governance and risk, and associate project tasks with standardised project deliverables. Some firms may encounter ‘development risk’ at one stage, involving product defects not discovered when the product was put into circulation (O’Rourke 1999); risk of failure or nonacceptance by the market; risk of technology becoming obsolete at the end of the innovation process; and risk from substitutes, such as an oil price drop, which may pose market risks to the producers of biofuels.

10.4 Case Study: Innovation Management

10.4.1 Firms and Their Innovations

Biomass does not carry much value, as it is just agriculture waste. To carry any value, it must be converted to a potential source of energy or fuel through biomass conversion technologies as discussed previously. This subsection examines three innovations related to biomass conversion technology, two in Malaysia and one in Thailand. To protect confidentiality, the study will not reveal the names of the innovative firms. The study adopted the case study approach of innovation of management; Goffin et al. (2019) proposed that, as managing innovation is fast moving, exploratory research with a theory-building perspective is needed, and, in such situations, case study research is highly appropriate. The summary of innovations of and activities of the three firms are shown in Table 10.2.

Firm A, incorporated in 2006, is based in the small town of Chemor, in the state of Perak, Malaysia. It developed a biomass combustion system. Firm A’s main business activity is the processing of biomass from PKS into pulverised powder, which is used as powdered fuel in the combustion system, also developed and supplied by Firm A, either for heat exchange or boilers. Firm A’s biomass combustion system is based on the needs of production processes and can be tailored to customer needs. Typical components include an oil tank for the fossil fuel to be used as starter, a feeder that acts as a ‘tank’ for the pulverised biomass fuel, an air controller, a blower, and a burner. The system is patented in Malaysia (No. PI 20071494), Thailand (0801004493), China (200880006258.5), and under the World Intellectual Property Organization Patent Cooperation Treaty (PCT/MY2008/00091).

Firm A obtains a supply of PKS from palm oil mills around the country, with whom it typically signed long-term supply contracts. In purchasing PKS, Firm A must ascertain the interactions between moisture contents, dry matter losses in storage over time, heating values, and bulk density, as they affect the overall costs of transport, storage, and conversion of the energy.

The customers install the biomass combustion system as an alternative to fossil fuel-powered heat treatment systems, and buy the pulverised biomass solid fuel from Firm A through an annual contract. The biomass combustion system is generally made to measure, and is designed and fabricated at Firm A’s factory, in the same complex where the pulverised fuel is processed. It is designed with the latest

Table 10.2 Biomass innovations of firms A, B, and C

Firm and origin	Innovation	Biomass source	Type of firm	Sources of research fund	Target customers
A: Malaysia	Pulverised biomass as solid fuel Patented biomass combustion system Green technology certified	Oil palm kernel shell)	Small	Own source R&D funding through Techno Fund under the Ministry of Science, Technology and Innovation Special loan under the Green Technology Financing Scheme	Heat treatment companies Heat exchange Boilers
B: Malaysia	Advanced biofuel (lubricant)	Oil palm residue Palm oil methyl esther	Small	Own source R&D funding through Techno Fund under the Ministry of Science, Technology and Innovation	Transport companies (engine oil)
C: Thailand	Biogas production for electricity using anaerobic digestion	Cassava biomass	Small	Own fund	Electricity grid

Source Authors
R&D research and development

CATIA software, which helps Firm A's designers and engineers simulate the biomass combustion system to meet client requirements.

To enhance the technology and efficiency of the biomass combustion system, Firm A obtained a research grant from the Techno Fund under the Ministry of Science, Technology and Innovation (MOSTI). It also obtained a green technology certification under the Green Technology Funding Scheme supported by the Government of Malaysia. Further, Firm A received special funding to expand its business under the Green Technology Funding Scheme, where the government provided an interest rate subsidy of 2% over the commercial interest charged by the banks.

Using research and development funds obtained through the Techno Fund, Firm A has developed a third product, a biomass-powered fire-tube boiler system that comes in a package of a biomass-powered burner, specially adapted fire-tube boiler that can use different fuels, biomass ash-traps, and pulverised biomass solid fuel. The development took place for 2 years between 2013 and 2015 at Firm A's facility.

Firm B, incorporated in 2006, is based in the small industrial town of Mentakab, in the state of Pahang, Malaysia. Firm B is involved in developing high-quality lubricants, known as high-density biofuels (HDBFs) using a mix of vegetable oil and palm oil methyl ester. HDBF is categorised as part of advanced biofuels, as the raw material is from non-food-grade feedstock. The European Industrial Bioenergy Initiative in 2014 defined advanced biofuel as produced by advanced processes from non-food feedstocks (e.g., waste, agricultural and forestry residue, energy crops, and algae) (EIBI 2014). Firm B also received research and development support from the Government of Malaysia through the Techno Fund. Firm B has not applied for any incentive under the Green Technology Funding Scheme and therefore does not carry any green certification.

Firm C is based in Ubon Ratchathani, in north-eastern Thailand. It produces biogas from cassava residue. The cassava residue is converted to biogas in anaerobic digestion ponds within Firm C's area, which also includes a generator to generate electricity connected to the grid, up to 2 megawatts (MW) of power. Firm C has a 5-year electricity supply contract to the grid, up to a maximum of 5 MW.

10.4.2 Analysis of the Adoption of Innovation Management

This part examines how the three firms directly apply the innovation management theory.

10.4.2.1 Management

For small firms, both Firm A and Firm B are structured as the leading firm dealing with biomass-powered heat systems and advanced biofuels, respectively. Each has a lean management structure, which may also pose a risk to their sustainability and continuity. Both are family owned and led by their founder-directors.

Firms A and B also engage external experts as advisors. Firm A engages an associate professor from Universiti Teknologi Malaysia who is an expert in thermal engineering. The associate professor leads the research and development team, which also consists of a young design engineer and an external expert in boiler technology and thermal technology from a firm based in Taiwan. Firm B works with an expert in advanced biofuels from Italy. Instead of engaging an external strategy advisor like Firm A, Firm B runs business strategy by having in-house directors of business development and marketing in Kuala Lumpur. Firm A runs all of its business, research and development, and marketing from its office in Chemor, which is more than 200 kms north of Kuala Lumpur.

Firm C is the smallest of the three firms. It is run by a husband and wife, with a small technical team to support work at the digestion ponds and to handle maintenance of the electricity generator at the same site.

10.4.2.2 Market Tendencies

Both Firm A and Firm B can be considered first movers in their own subsectors. Firm A products are mainly for heat-producing needs, such as heat exchange, steam production, and heat treatment. The subsectors include the brass-smelting industry; die-casting industry; premix and asphalt plants; boiler industry; cement industry; painting and dyeing industry; glass-making industry; roasting, baking, and cooking in the food sector; and porcelain and pottery industry. Up to the end of 2019, Firm A was supplying up to 3000 metric tons of pulverised biomass fuel to eight customers per month, which have biomass combustion systems. Firm A even tested its biomass combustion technology for a potential market in China.

Firm B's advanced biofuels have a wider market potential. As advanced biofuels contribute significantly to energy security in the transport sector, reducing greenhouse gas emissions and providing a long-term sustainable alternative to fossil fuels, Firm B's products appeal to the road transport, shipping, maritime transport, and aviation sectors.

Firm C has a captive market—the electricity grid. It has a 5-year electricity supply contract to the grid, up to a maximum of 5 MW. Currently, Firm C is only able to supply up to 2 MW of electricity to the grid, however.

10.4.2.3 Carbon Savings

Carbon savings to Firm's A clients are shown in Table 10.3.

Firm A's clients may also save on fuel costs when using biomass fuel. Table 10.4 shows the equivalent usage in kilograms of biomass fuel for every litre of fossil fuel.

For example, for every litre of diesel, the customer must purchase 2.1 kg of biomass fuel. The customer will pay RM1.26 ($0.32) for every equivalent of 1 L of diesel at RM2.70 ($0.68) at the highest and RM2.05 ($0.51) at the lowest price (on 10 January 2019) (MDTCA 2021). This shows that a consumer using diesel fuel can

Table 10.3 Carbon savings of firm A's biomass fuel

No	Customer	Original fuel type	Consumption of biomass fuel per year, average 2013–2019 (million tons)	Carbon dioxide emission savings per year, average 2013–2019 (kilograms)
1	A (Clay)	Light fuel oil	4800	10,312
2	B (Clay)	Light fuel oil	2160	5810
3	C (Clay)	Light fuel oil	310	670
4	D (Steel)	Light fuel oil	18,000	38,678
5	E (Kaolin)	Recycled oil	1100	2592
6	F (Kaolin)	Recycled oil	1600	3291
7	G (Steel)	Diesel	17,630	33,900

Sources Authors

Table 10.4 Consumption of firm A's biomass per Kilogram to biofuel per Litre

No	Alternative fuels	Highest industrial unit price (RM)	Lowest industrial unit price (RM)	Usage	Biomass (kg)	Unit price biomass (RM)
1	Diesel	2.70 ($0.68)	2.05 ($0.51)	1 L	2.100	0.60 ($0.15)
2	Recycled oil	1.20 ($0.30)		1 L	1.166	0.60 ($0.15)
3	Light fuel oil	1.50 ($0.375)		1 L	1.400	0.60 ($0.15)
4	LPG	4.00 ($1.00)		1 kg	1.800	0.60 ($0.15)
5	LNG	7.50 ($1.875)		1 mmbtu	38.400	0.60 ($0.15)

Source Firm A, author's analysis
LNG liquified natural gas, *LPG* liquified petroleum gas, *mmbtu* one million British thermal units

save RM0.85 per litre of diesel at the lowest ($0.21). Customer G, a steel mill, stated that it is able to save 45% of its fuel cost when using biomass fuel.

For Firm B, its products have been tested on two engine manufacturers, X and Y. These two companies are amongst the largest manufacturers of big engines in the world. X, based in Finland, manufactures and services power sources and other equipment in the marine and energy markets. The core products of X include large combustion engines used in cruise ships and ferries. X also focuses on environmental services, including reducing emissions, as it works with different types of renewable fuels such as advanced biofuels. Y is a German engineering company with primary outputs of heavy trucks using diesel engines, as well as engines and marine systems for the shipping industry. The results of the tests are shown in Table 10.5.

The tests show that HDBF produces 39.59 megajoules per kilogram of energy value, which is higher than other biofuels but slightly lower than low-sulphur diesel and gasoline. It also means that HDBF is able to offer savings to customers.

Table 10.5 Firm B high-density biofuel test with engine manufacturers

Parameter	Unit	X	Y
Kinematic viscosity at 40 °C at injection	Centistokes	100 max 24	60 max
Density	kilograms per cubic metre	991 max	990–930
Flash point	°C	60 min	60 min
Carbon residue at 10% distillate	% weight	3	nil
Ash content	% weight	0.05 max	0.01 max
Acidity	mgKOH/g	5 max	4 max
Sulphur content	parts per million	500 max	nil
Calorific value	megajoule per kilogram	nil	35 min

Source Firm B, authors' calculations

Firm C has not been able to provide the amount of carbon savings offered to the electricity grid. Hence, there is a need to refer to the literature on the similar use of cassava biogas in Thailand. Tran et al. (2015) showed that using biogas as a source of energy in cassava starch-processing plants in Thailand could save up to 40% of the carbon footprint.

10.4.2.4 Product Development Management

Although both companies did not formally introduce the innovation management concept into their daily operations, the development of the biomass-powered boilers and HDBF biofuel went through the five innovation management steps as discussed by Microsoft (2013), (Table 10.6).

10.4.2.5 Risk Management of the Innovation

Although the firms may have taken steps to adopt complete innovation management as discussed above, they had to undertake risk assessment of the innovation project during the development and commercialisation stages. This involves risk assessment, risk management, and risk communication. A SWOT analysis of the firms' innovative products is shown in Table 10.7.

Strengths

Both Firm A and Firm B have strengths. One, both firms can be considered early players in the fields in which they focus. Firm A was an early leader in biomass combustion systems and solid pulverised fuel to industries that utilise heat exchange and boilers. Firm B was the first supplier of lubricants based on Italian technology. Its move to HDBF biofuel is part of the synergy to expand its business from fossil fuel-based to biofuel-based lubricants.

Moreover, both firms own intellectual property rights for their respective products and processes. Firm A's combustion system is patented in China, Malaysia, and Thailand under the name of its managing director. In addition, Firm A has also conducted several environmental tests to ensure that all emissions are within environmental standards. The company is pleased that all of its products, combustion system, and pulverised biomass fuel do not pollute the environment and that emissions from the burning of the biomass fuel does not contain hazardous gases or heavy metals. In addition, Firm B retained their formulations as trade secrets and holds an ISO 9001 certificate for quality management system.

Both firms have also built up their market base with ready customers. Firm A has eight factories using their combustion systems in Ipoh and Klang Valley. The customers range from pottery businesses to smelters. Some customers have shown a willingness to continue expanding with Firm A by issuing letters of intent to place

Table 10.6 Innovation management process in product development in firms A, B, and C

Category	Firm A	Firm B	Firm C
Envision	The biomass combustion system is based on in-house technology The biomass boiler system is developed using Taiwanese boiler technology, with the support of an in-house team led by a lead researcher from Universiti Teknologi Malaysia	HDBF biofuel is based on in-house research, led by the CEO, in collaboration with a partner in Italy The HDBF is based on an Italian technology, which was adjusted to suit Malaysian conditions	The project is based on the Government of Thailand's efforts to increase utilisation of biomass as a source of energy Cassava biomass is abundant in Ubon Ratchathani
Engage	In developing the biomass combustion system and biomass boiler system, Firm A engaged with an R&D team as well as some potential customers, such as glove makers and a paper factory, from the beginning. Firm A wanted to assurance from the market that the product would be useful for certain types of heat treatment and heat exchange facilities. Firm A also discussed the project with the boilermakers in Taiwan to ensure project viability	In the same way as Firm A, Firm B engaged with an R&D team and potential customers	Firm C engaged with the Government of Thailand for the technology and the Thai electricity company for the contract to supply to the grid
Evolve	In all cases, the projects evolved from an idea. Firms began looking at the costing and prepared the necessary team, financing, and grant application		
Evaluate	All firms evaluated the project during the engagement process. The firms sought opinions from various groups, including employees, customers, suppliers, financiers, and government authorities, on how to proceed with the project		

(continued)

Table 10.6 (continued)

<table>
<tr><th>Category</th><th>Firm A</th><th>Firm B</th><th>Firm C</th></tr>
<tr><td>Execute</td><td colspan="2">Both companies received government research grants from the MOSTI Techno Fund. The funds were approved on a reimbursable basis, meaning that both companies were in strong financial positions to carry out the projects
As with most Techno Fund recipients, both companies executed the pre-commercialisation project based on agreed milestones. Both companies completed their respective projects within the agreed time frame with MOSTI, i.e., within 24 months from the date of the Techno Fund agreement</td><td>Firm C obtained a loan from a commercial bank to initiate the project. There is no special government R&D grant in Thailand
The commercial loan is secured by the electricity supply agreement and Firm C's shareholder assets</td></tr>
</table>

Source Authors
CEO chief executive officer, *HDBF* high-density biofuel, *MOSTI* Ministry of Science, Technology and Innovation, *R&D* research and development

Table 10.7 SWOT analysis of firms A, B, and C

<table>
<tr><th>Strengths</th><th>Weaknesses</th><th>Opportunities</th><th>Threats</th></tr>
<tr><td>Firms A and B are early players in the field with ready customers</td><td rowspan="2">Firms are involved in capital-intensive sectors, hence requiring major investment</td><td>Firm A and B can expand their markets in the region</td><td>The firms cannot ensure a constant supply of raw material</td></tr>
<tr><td>Firm A has patents and is green technology certified. Firm B is ISO 9001 certified</td><td rowspan="2">The governments of Malaysia and Thailand are committed to green technology</td><td rowspan="2">The biggest threat for firms A and B is a reduction in the price of fossil fuel</td></tr>
<tr><td>Firm C has a secure 5-year electricity supply contract to the national grid</td><td>As a small family firm, there is a lack of technical staff</td></tr>
</table>

Source Authors

orders for a new combustion system as well as additional pulverised biomass fuel with the new combustion engines.

Firm B has exported its lubricants to different international markets outside of Malaysia, including China, Fiji, Papua New Guinea, and Singapore. It is also exploring new markets in Myanmar and Timor-Leste. At the same, Firm B has been working with its early customers, including major automotive and shipping engine manufacturers.

Firm C's strength is its ability to secure cassava biomass from the nearby cassava starch factory in Ubon Ratchathani as well as a 5-year contract for the electricity to the grid. Compared to firms A and B, Firm C does not have any specific intellectual property, proprietary information, or trade secrets. The digestion technology for the biomass anaerobic ponds was provided by the government.

Weaknesses

Firm A's main weakness is the limited skilled labour available in its area, limiting the ability of its technical team towards production, fabrication, marketing, and after-sale services to customers. Second, the existing business operation can only supply a limited number of combustion systems and amount of pulverised biomass fuel, restraining company growth. Acknowledging this weakness, Firm A plans to hire more technical staff who will be able to contribute to technical growth, including those who can handle digital design and simulation of the system. The increase in demand means the company has to build new factories to produce the pulverised biomass fuel and combustion engines as well.

Moreover, to expand production, the firm has to seek more funding from banks, which is challenging. Some financiers may refuse funding projects due to their inability to comprehend Firm A's technology and business model. Although the firm has been able to obtain additional funding from a bank specialising in supporting small and medium-sized enterprises, the bank charges higher interest rates than normal. The higher interest rates practically eliminate any gain from the interest rate subsidies provided by the Green Technology Financing Scheme.

Firm B does not face the technical labour issue, as its technical team is led by a qualified technical production director. Firm B also has its own dedicated marketing office based in Subang Jaya near Kuala Lumpur to market the relevant products to Malaysian and international customers. Firm B works closely with its international partner Polilube Italia, which provides technical expertise. It is innovative with funding arrangements, as it is working with the government venture fund, Malaysian Technology Development Corporation (MTDC), to provide commercialisation funding for HBDF. The venture fund was keen on the product potential, as it has a broader market and appeals to the automotive industry. However, the fund is limited to early-stage commercialisation, hence the need to engage with more financiers at the next stage of product commercialisation.

Firm C's main weakness is a lack of technical support to maintain the generators, facilitate the logistics of the cassava biomass, and ensure online delivery of the biomass to the power-generating site. On a visit to the site in February 2020, it was found that the generators had frequent breakdowns, which affected the constant supply of electricity to the main grid. The firm is run by a husband and wife, and both work only part time. Firm A and Firm B are fully managed by an innovating team, with full-time professional teams to support research and development, technical tasks, and sales and marketing.

Opportunities

Both Firm A and Firm B are making the ASEAN region their next target market. Both firms visited several ASEAN members to identify market expansion and investment opportunities, as renewable energy is fast gaining acceptance. For example, the oil price in Cambodia, Lao PDR, and Viet Nam is about three times more expensive than in Malaysia; thus, the industry needs to search for alternative fuels. The opportunities in the area of alternatives to fossil fuels is also expanded by the increased commitment of many governments, creating more opportunities for the company to supply the pulverised biomass fuel to neighbouring countries.

However, market expansion is not easy, as both are small firms with limited financial and technical resources. Firm A must look for local sources of biomass, either PKS or wood-based biomass, which can produce the same amount of energy as what it has been producing. To secure adequate biomass raw material, Firm A has to compete with other industrial users in the new market. It also must begin to invest in localised fabrication plants to construct the tailor-made biomass combustion systems.

Importing PKS from Malaysia may not be the best option due to potential non-tariff measures, however. Pulverised PKS is classified both as an agriculture product and energy product. It is subject to non-tariff measures applicable to all agriculture products, such as the need to obtain phytosanitary certificates, subject to fumigation and other sanitary and phytosanitary requirements imposed by the importing country. An attempt to export to the pulverised PKS to China as part of the initial attempt to test the biomass combustion technology in the country hit an obstacle when Customs in Xiamen and Shanghai would not allow importation due to the lack of phytosanitary certification, as China considered the product agriculture and not an energy product.

Firm B may find it easier to expand its market and customer base beyond Malaysia. The products, bio-based lubricants, are packed like traditional lubricants, making it is easier to ship to new destinations. Nevertheless, in seeking market expansion in the ASEAN region and elsewhere, Firm B faces competition from the traditional fossil fuel-based lubricants with more established international brands and distribution networks.

Firm C is very localised in its business model, which is based on the supply of the electricity to the grid, where the electricity is generated through biogas from cassava biomass. Business expansion relies on Government of Thailand policy to encourage small power producers. As explained in Han et al. (2019), the government established the Small Power Producer programme in 1992, which aims to promote power generation by using alternative fuels and waste, including cogeneration, to efficiently employ domestic alternative resources and by-product energy. The government also established the Very Small Power Producers scheme for those producing power of 1 MW and below. This scheme received an additional rate of B0.30 for every kilogram-hour.

Threats

One of the threats facing all three firms is a constant supply of raw material at a reasonable price. For Firm C, it must ensure a constant supply of the cassava biomass from the nearby biomass ethanol and starch factories. The author visited the different locations in Ubon Ratchathani in February 2020 and found that the owners of Firm C had a very good working and business relationship with at least two cassava starch and bioethanol factories in the area. Firm C has supply contracts with these factories, and they deliver the biomass to Firm C's site.

For firms A and B, good-quality palm kernel is in short supply, and the price is rising. Despite general data showing the huge stock of palm oil-based biomass—80 million tons of biomass per year (Agensi Inovasi Malaysia 2020)—obtaining and keeping a long-term supply of this biomass is difficult. Large palm oil mills normally use about 50% of the biomass in-house, such as for their own boilers. With the increased usage, palm oil mills realise that PKS is no longer waste but a commodity that could generate additional revenue. This is consistent with the views of Otaka et al. (2019); because it has a low moisture content, relatively high calorific value, and low chlorine and potassium content, demand for PKS is increasing in Japan and Korea. This biomass fuel is also mixed with other types of fuel to reduce carbon emissions from coal-fired power plants. Furthermore, large palm companies in Indonesia purchase PKS from other mills and use it as fuel in related facilities other than palm oil mills. As a result, demand for PKS is increasing, thus intensifying the competition in the procurement market, making it difficult to obtain.

Another obstacle faced by Firm A is the inability to secure long-term large contracts for the supply of PKS, which limits its ability to supply the solid fuel, which is an integral part of the biomass combustion system. To secure long-term supply contracts, Firm A visited two of the largest plantation companies in Malaysia, which has more 100 mills between them. However, they refused any long-term engagement with Firm A, instead asking the firm to enter bids through competitive tenders.

To ensure a consistent supply of PKS, Firm A has entered into supply agreements with independent palm oil mills throughout the country. It has also embarked on research and development of alternative sources of biomass such as river tamarind or *Leucaena leucocephala,* which has comparable calorific value to PKS. Similarly, Firm B has diversified its raw material sources to include palm sludge oil, off-spec crude palm oil, palm fatty acid distillate, all types of animal fat, and used cooking oil.

The biggest threat to the Firm A and B remains the price of fossil fuels. Both firms managed to expand their businesses during a period of high fuel prices. However, with the reduction in the price of fossil fuels, Firm A's main advantage has greatly been reduced, as it can no longer offer savings. Therefore, all three firms have to leverage on being the suppliers of carbon–neutral products that could reduce reliance on fossil fuels. For example, HDBF emits less particulate pollution and about 60% less carbon monoxide than other fossil fuels with practical non-sulphur content.

10.5 Conclusions and Recommendations

This study shows that, when intentionally or unintentionally applied, innovation management is important for all innovative firms, including those involved in biomass-related technologies. With good innovation management, firms will be able to innovate in a systematic manner and to enjoy the success of innovation—the ability to complete new or improved products or services. Firms employing innovation management will also be able to compete and to sustain their businesses in a more competitive market.

The discussion shows that the three firms are keen to ensure the success of their innovations, which are key components of their biomass-related businesses. The firms, especially firms A and B, handled their innovations from the pre-inception stage to the end, through stakeholder consultations to ensure that innovation meet customer expectations. For Firm C, the pre-inception stage involved ensuring the ability to secure the electricity supply contract and raw material.

Adoption of biomass innovation requires strong support from governments. The firms have faced several challenges beyond their control, including acute competition for the feedstock, especially PKS, due to the high price of the material elsewhere even in raw form; difficulty in obtaining the right type and amount of financing; non-tariff measures for exports of the products produced by firms A and B; and sustainability of the business in the face of the fuel price volatility. It is recommended that:

1. All businesses should adopt innovation management in their business operations. Research should examine how innovation management is being practiced in innovative renewable energy firms at the regional level, to ensure their agility and survival due to competition from more established fossil fuel-based competitors.
2. Governments should introduce more innovative financing schemes where financial institutions may invest in, rather than solely provide loans to, the businesses. Investment could come in the form of venture capital, owned and managed by experts in the field, with capital injection from the government. The venture capital must provide an adequate amount of funding for this type of firm. Most innovative firms face financial issues as they progress in research and development and commercialisation of their products and services.
3. Governments should find ways to impose quotas for exports of unprocessed raw materials such as PKS. This procedure will ensure adequate access of raw material for domestic biomass-related firms. To ensure easier access to the raw material, governments may also set up biomass exchange as a B2B platform.
4. Governments should provide direct incentives, such as tax breaks and subsidies, to the producers and users of biomass energy. Many countries are providing some form of support for use of fossil fuels, and the same could apply to biomass energy. This approach may level the playing field between biomass energy producers and competitors using fossil fuel.

Acknowledgements Authors would like to thank the Economic Research Institute for ASEAN and East Asia (ERIA) for providing funding for the research paper.

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Chapter 11
Harnessing Wind Energy Potential in ASEAN: Principles, Perspectives and Policy Implications

Youngho Chang and Han Phoumin

Abstract This study examines whether and how harnessing more wind energy can decrease the cost of meeting the demand for electricity and amount of carbon emissions in the Association for Southeast Asian Nations (ASEAN) region, using the ASEAN integrated electricity trade model. Three scenarios are considered: a counterfactual business-as-usual (BAU) scenario, which assumes no wind energy is used; an actual BAU scenario that uses the wind-generation capacity in 2018; and a REmap scenario, which employs the wind-generation capacity from the *Renewable Energy Outlook for ASEAN*. Simulation results suggest that dispatching more wind energy decreases the cost of meeting the demand for electricity and amount of carbon emissions. However, these emissions increase during the late years of the study period, as the no- or low-emitting energy-generation technologies are crowded out.

Keywords Wind energy · Power trade · Counterfactual scenario · ASEAN

JEL Classifications Q41 · Q42

11.1 Introduction

Wind energy can be considered the most promising renewable source for generating electricity. Currently, about 5.3% of the world's electricity is generated by wind power; 1429.6 terawatt-hours (TWh), of the 27,004.7 TWh of electricity generated in 2019, came from wind energy (BP 2020).

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H. Phoumin et al. (eds.), *Energy Sustainability and Climate Change in ASEAN*,
Economics, Law, and Institutions in Asia Pacific,
https://doi.org/10.1007/978-981-16-2000-3_11

Table 11.1 shows the amount of the electricity generated in 2019. Coal has the largest share, followed by natural gas and hydroelectric power.

Amongst the electricity generated from renewable energy sources, wind energy has the largest share. Table 11.2 shows the amount of electricity generated by renewable energy in 2019. Wind covered slightly more than 50% of electricity generated by renewable energy.

For electricity generated from renewable sources, hydropower is the mode most utilised in the Association of Southeast Asian Nations (ASEAN) region, followed by geothermal energy and solid biofuels. Wind energy comprised a very small share of the renewable energy in the region (UNESCAP 2019). Similarly, hydropower had most of the installed capacity of renewable energy in the ASEAN region, and the capacity of wind generation was quite low (UNESCAP 2019).

ASEAN member countries have massive wind energy potential, however (UNESCAP 2019). Across the region, there are many suitable sites where the speed of wind is ideal for harnessing electricity. Harnessing energy from wind can help provide clean energy at affordable prices and reduce carbon emissions. Yet utilisation rates are not realising their potential due to the intermittency of electricity generated from wind, a relatively high levelised cost of electricity (LCOE), and high balance-of-system costs. Financing renewable energy projects, including wind farms, is also a key barrier (Blazquez et al. 2020).

Amongst ASEAN countries, Viet Nam has good sources of wind energy. However, its share of wind energy in its power generation mix in 2020 was 1.7%, lower than that of solar energy (12.8%). The potential of offshore wind energy there is 261 gigawatts (GW) (fixed) and 214 GW (floating). Fourteen offshore wind projects have been proposed, which total 28 GW (Ngo 2020). Indeed, Viet Nam aims to

Table 11.1 Electricity generation by fuels for the world (terawatt-hours)

	Oil	Natural gas	Coal	Nuclear	Hydro	Renewables	Others	Total
Electricity	825.3	6297.9	9824.1	2796.0	4222.2	2805.5	233.6	27,004.7
Share (%)	3.06	23.32	36.38	10.35	15.64	10.39	0.86	100.0

Source BP (2020)
Note ‘Others’ comprises sources not specified elsewhere

Table 11.2 Renewable electricity generation in the world (terawatt-hours)

	Wind	Solar	Others	Total
Electricity	1429.6	724.1	651.8	2805.5
Share (%)	50.96	25.81	23.23	100.00

Source BP (2020)
Note Others include geothermal, biomass, and other sources of renewable energy not already itemised

install 12–15 GW of onshore wind energy and 10–12 GW of offshore wind energy by 2030 (Minh et al. 2020).

Some obstacles exist for Viet Nam's wind energy projects, however, especially offshore in terms of environmental, social, and technical constraints. The offshore sites include protected areas or essential habitats that house vulnerable marine species, birds, and bats. In addition, those sites include oil-related activities, energy and communications infrastructure, and aquaculture. They are commercial fishing grounds, comprise tourism spots, and have great historical and cultural significance. To be fully utilised, they also must also clear technical constraints such as marine traffic, air traffic, and military use (Ngo 2020).

Using a cross-border power trade model in ASEAN (Chang and Li 2014), this study aims to demonstrate that renewable energy resources, especially wind energy, can help ensure energy sustainability and climate change adaptation. As a basis of evaluation for how wind energy can contribute to meet the electricity demand in the ASEAN region, it constructs a counterfactual business-as-usual (BAU) scenario in which no wind energy is used. Following this, an actual BAU scenario is used, using 2018 as the starting year. Finally, this study adopts a REmap scenario against which the counterfactual and actual BAU scenarios are evaluated to see how much wind energy can help meet the demand for electricity and reduce carbon emissions. An International Renewable Energy Agency (IRENA) study is also used to show how renewable energy can contribute to the energy landscape in the ASEAN region, using 2025 as a target year (IRENA and ACE 2019).

The second section reviews prospects of harnessing wind energy and factors dragging this objective. The third section presents principles of harnessing wind energy that constitute the basis of the simulation model, and the fourth section discusses the methodology of this study, its key assumptions, and data. The fifth section discusses results of this study, and the sixth section presents policy implications derived from the study.

11.2 Harnessing Potential Wind Energy

11.2.1 Prospects

Huge potential exists for global wind power (Marris 2008). It can create more than 40 times the current worldwide consumption of electricity and more than 5 times the total global use of energy in all forms (Lu et al. 2009). Wind energy can also bring non-energy benefits, as utilisation does not affect global temperature but does reduce carbon emissions and other air pollutants (Keith et al. 2004).

Some new technologies are currently exploring ways of harnessing energy from wind. One system, installed on the island of Ikaria in Greece, combines wind energy and hydropower so that the excess electricity generated from the wind farm is used to pump water from a lower tank to a higher level—a feasible technology for low-cost electricity production (Bakos 2002). In addition, Navarre, a Spanish region, has exhibited how even small towns can become a big player in wind energy (Fairless 2007). Some have also made efforts to harness energy from high-altitude wind, where the speed of wind is faster, rendering higher energy potential (Vance 2009). Moreover, power generated from offshore wind can be delivered via synoptic-scale interconnection, which appears to solve the underutilisation of wind power due to the fluctuation of electricity generated (Kempton et al. 2010).

11.2.2 Drag Factors

Harnessing energy from renewable sources can have some negative environmental consequences. Indeed, the United Kingdom's Sustainable Development Commission was criticised for its failure to minimise the negative environmental consequences of wind energy such as noise, visual intrusion in sensitive landscapes, and bird strikes. For example, it was reported that 40,000 birds in a year ran into wind turbine blades in the United States (Marris and Fairless 2007). The modern wind turbine does have a height of 125 m—almost as high as London Eye. The fair balancing of the advantages and disadvantages of harnessing wind energy in specific situations must therefore be evaluated (Keay 2005).

Wind farms, thus, often suffer from a poor reputation. After 16 years of litigation, relentless opposition from industrialists, and financial and political setbacks, a plan to build a wind farm in Massachusetts failed. The wind farm could have provided clean energy to 200,000 homes on Cape Cod and would have helped develop wind farms in nearby regions (Seelye 2017).

Financial viability also affects the development of wind energy, as, for example, the credit crunch drastically affected wind-energy projects in the United States during the Global Financial Crisis in 2008 (Schiermeier 2008). In addition, the large-scale deployment of wind turbines appears to reduce wind speed and, in turn, lower turbine efficiency. The reduced wind speed eventually leads to set low generation limits (Miller and Kleidon 2016).

Wind energy, especially onshore wind, is a mature technology that has achieved a certain level of reliability. However, the reliability, or load factor, is affected negatively by the age of the wind turbines. In the United Kingdom, the normalised load factor declined from about 24% during peak (i.e., age 1 year) to 15% at age 10 years, and 11% at age 15 years. The normalised load factor for Danish wind farms showed a similar decline—from 22% at age 1 year to 18% at age 15 years. Offshore Danish wind farms exhibited huge declines in their normalised load factors—from 39% at their peak to 15% at age 10 years (Hughes 2012).

11.2.3 Positive Signs of Harnessing Wind Energy

Wind turbines mounted on buildings appear to be feasible for reducing carbon emissions by contributing significantly to energy requirements in buildings. The aggregate electricity generated from these wind turbines range from 1.7 to 5.0 TWh per year and reduce carbon emissions by from 0.75 million to 2.5 million tons per year (Dutton et al. 2005). An energy company, Royal Dutch Shell, and an operator of oil tankers, Maersk, are also attempting to use wind power to cut tankers' fuel bills. Two 'rotor sails' propel a vessel; solar-powered sails and kites are also being used (Clark 2017).

11.3 Principles of Wind Energy

11.3.1 Wind Energy as Kinetic Energy

Wind energy is kinetic energy that is transformed from potential energy. Scottish physicist William Rankine stated in 1881 that 'the object is gaining the potential to move "by the occurrence of such changes, actual energy disappears and is replaced by Potential or Latent Energy"' (Boyle 2014). Taking the definition of 'work' as the force multiplied by the distance moved in the direction of the force, the amount of energy harnessed from wind is determined by the speed of the wind and volume of air moved. When air flow passes a wind turbine at a given speed, a moving turbine constructs a hypothetical cylinder with the swept area as the length of the wind blade and the height as the speed of wind per second. The hypothetical cylinder captures air mass, which is kinetic energy, and is eventually transformed into electricity.

11.3.2 Kinetic Energy in a Wind Turbine: Calculation

Suppose a wind turbine with a diameter of 60 m and a radius of 30 m and the wind speed (v) of 9 m per second.

- Swept area (A) is $\pi \times r^2 = \pi \times 30^2$
- Wind speed (v) is 9 m per second (9 m/s)
- Volume of the cylinder (V) is v x $A = 9 \times \pi \times 30^2 = 25{,}447$ m^3/s
- Density of air (the mass per cubic metre) is 1.29 kg per cubic metre
- Mass of air arriving per second (m) is $1.29 \times 25{,}447 = 32{,}827$ kg/s
- The kinetic energy of a mass m moving with speed v is ½ mv^2 = ½ × 32,827 × 9^2 = 1,329,494 J/s = 1.33 megawatts (MW).

The principles of kinetic energy suggest that the longer the wind blade and the faster the wind speed, the more energy will be transformed from kinetic energy to electric energy (i.e., electricity). The modern type of wind turbine has a capacity of 1.8 MW (Boyle 2012).

11.3.3 Economic Considerations of Wind Energy

There are various factors that affect the cost of wind energy. The most critical is the annual energy production from the turbine installation. Installation brings about various considerations such as the capital cost of installation, annual capital charge rate that is the capital cost plus any interest payable into an equivalent annual cost, length of the contract with the purchaser of electricity, number of years over which the investment in the project is to be recovered, and operation and maintenance costs.

The cost of wind energy can be calculated as follows. This calculation is based on the information given in Boyle (2012):

The cost per unit (g) is expressed in Eq. 11.1:

$$g = \frac{(C \times R)}{E} + M \tag{11.1}$$

where:

- g the cost per unit of electricity generated
- C the capital cost of the wind farm
- R the capital recovery factor or the annual capital charge rate (expressed as a fraction)
- E the wind farm annual energy output
- M the cost of operating and maintaining the wind farm annual output.

The required annual rate of return net of inflation (R) is expressed as:

$$R = \left[\mathrm{x}/(1 - (1 + \mathrm{x}))^{-\mathrm{n}}\right], \tag{11.2}$$

where:

- x the required annual rate of return net of inflation
- n the number of years over which the investment in the wind farm is to be recovered.

The annual energy output of the wind farm (E) is expressed as:

$$E = (hP_r F)T, \tag{11.3}$$

where:

- h the number of hours in a year (8760)
- P_r the rated power of each wind turbine in kilowatts

F the net annual capacity factor of the turbines at the site
T the number of turbines.

The cost of operating and maintaining the wind farm annual output (M) is expressed as:

$$M = KC/E, \tag{11.4}$$

where:

M the operation and maintenance costs
K the factor representing the annual operating costs of a wind farm as a fraction of the total capital cost.

Generally, a wind turbine operates at only around 25% of turbine capacity due to inconsistent, imperfect wind. On better land-based wind sites, a capacity factor of 35–40% or more is achievable (Boyle 2012). A wind turbine is quick to install, so it will be generating power before significant interest on capital. It is competitive with conventional power generation at sufficiently windy sites.

11.3.4 Unit or Levelised Costs of Wind Energy

A typical wind turbine has three parts: fiberglass blades, a standard gearbox, and a generator. Boyle (2012) described the cost of a 600-kilowatt (kW) wind turbine in Denmark. Installation costs are $1800–$2200 per kW, the turbine lasts about 20 years, the load factor is 25%, and the turbine generates 1,314,000 kilowatt-hours (kWh) per year. If a real discount or interest rate is assumed at 10%, the installation cost is $2000 per kW, or about $1,200,000. The unit or LCOE are $0.106 per kWh.

Table 11.3 presents the cost of generating electric power by various sources. The data are taken from generation costs in the United States in 2017.

Wind energy appears to be competitive with gas and coal. Moreover, the cost of electricity generated from wind is even lower than that of geothermal, although hydro is lower than wind. The cost competitiveness of wind in terms of power generation is also confirmed by the latest cost data provided by IRENA (Table 11.4).

The LCOEs of geothermal and hydropower slightly increased in 2019 compared to 2010. The LCOEs of solar photovoltaic and concentrated solar power decreased immensely, while the LCOEs of offshore and onshore wind energy fell a small amount. Amongst various renewable power technologies, however, the LCOE of onshore wind energy is the second-lowest after hydro. The LCOE of fossil fuels ranges from about $0.05 per kWh to about $0.18 per kWh (IRENA 2020). Except for concentrated solar power and offshore wind energy, all other renewable power-generation technologies have become competitive with fossil fuel power-generation technologies. The cost-competitiveness of wind energy is confirmed further if the cost of carbon disposal and the price of carbon are added to the LCOE.

Table 11.3 Cost of generating electric power, 2017

Type	Cost (2010 $ per megawatt-hour)
Gas (all types)[a]	66.1–127.9
Hydro	88.9
Wind	96.0
Coal (all types)[a]	97.7–138.8
Geothermal	98.2
Advanced nuclear	111.4
Biomass	115.4
Solar photovoltaic	152.7
Solar thermal	242.0

Source Dahl (2015)
[a]includes carbon capture and sequestration

Table 11.4 Weighted average LCOE of renewable power generation technologies (kilowatt-hours)

	Biomass	Geothermal	Hydro	Solar photovoltaic	Concentrated solar power	Offshore wind	Onshore wind
2010	0.076	0.049	0.037	0.378	0.346	0.161	0.086
2019	0.066	0.073	0.047	0.068	0.182	0.115	0.053

Source IRENA (2020)
Notes
1. The LCOE is the weighted average LCOE from utility-scale renewable power generation technologies from 2010 to 2019
2. The fossil fuel LCOE range is $0.05–$0.18 per kilowatt-hour
LCOE levelised cost of energy

Boyle (2012: 473–474) presented a comparison of the costs of various sources of electricity generation at a 10% discount rate. The cost included capital payments, operation and maintenance, fuel, carbon disposal, and carbon price. Fifteen power-generation technologies were considered: combined-cycle gas turbine, conventional coal, combined-cycle gas turbine with carbon capture and storage, coal with carbon capture and storage, nuclear-pressurised water reactor, roof-mounted solar photovoltaic thin-film panels, large biomass non-combined heat and power, run of river, reservoir hydro, onshore wind, offshore wind, tidal barrage, tidal stream, floating, and geothermal. The five lowest-cost technologies were run of river, reservoir hydro, combined-cycle gas turbine, onshore wind energy, and a nuclear-pressurised water reactor. The LCOE of onshore wind is still higher than the combined-cycle gas turbine. If a carbon price is added or the costs of carbon disposal for the combined-cycle gas turbine are included, then onshore wind energy is competitive with these technologies.

11.4 Methodology, Assumptions, and Data

This study explores how harnessing wind energy in the ASEAN region can reduce the cost of meeting the electricity demand and estimates the amount of carbon emissions that can be reduced.

11.4.1 Methodology

This study adopts the ASEAN integrated electricity grid model (Chang and Li 2013) and modifies wind energy-related information. The objective of the integrated power trade model is to minimise the cost of meeting demand for electricity in the ASEAN region from 2018 to 2040. Costs has four components: capital cost, operation cost, transmission cost, and carbon cost. As it has an integrated electricity market and grid, power trade (i.e., the import of electricity) is allowed for up to 30% of domestic demand.

11.4.2 Assumptions

To meet domestic demand and trade surplus electricity, this study made some key assumptions. First, the total installed capacity of power generation in the region is greater or equal to the total demand for electricity in the region. Second, the total output of electricity generation in each country is constrained by the load factor of the installed capacity of all types of electricity generation in the county. Third, the electricity supply of all countries in the region to a certain country should be greater than or equal to the demand for electricity in that country. Fourth, the total supply of electricity from one country to all countries (including the country itself) in the region must be smaller or equal to the total available supply capacity of that country at a given time.

11.4.3 Data

This study updates the initial capacity given in Chang and Li (2013) using the data taken from ACE (2020) and IRENA (2019). Figure 11.1 shows the initial installed capacity in ASEAN by plant type in 2018.

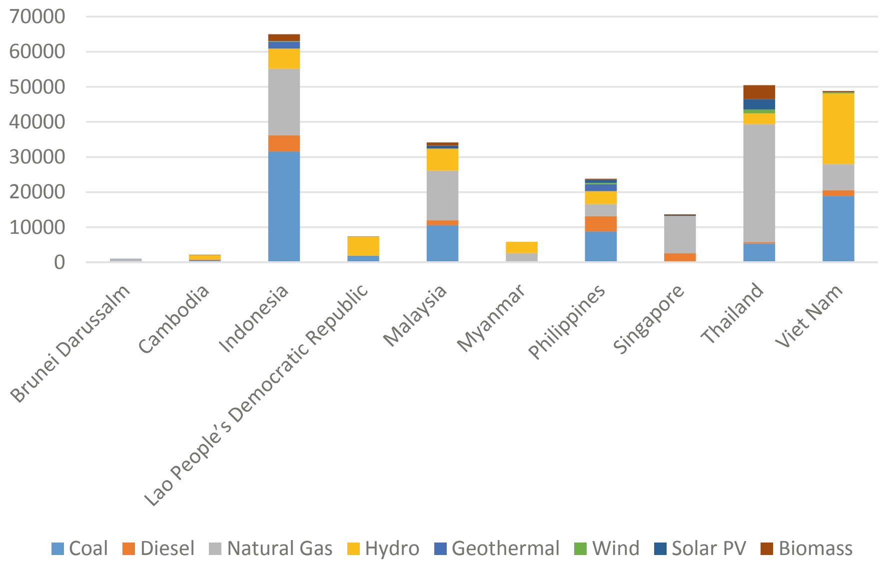

Fig. 11.1 Installed capacity by plant type in ASEAN, 2018 (megawatts). PV = photovoltaic. *Sources* ACE (2020) and IRENA and ACE (2019)

11.4.4 Scenarios

This study establishes three scenarios: a counterfactual BAU scenario, an actual BAU scenario, and a REmap scenario. First, as the objective of this study is to estimate how much wind energy can help reduce the cost of meeting the electricity demand in the ASEAN region, a counterfactual BAU scenario was set as a hypothetical base case. This assumes that no wind energy is used at all. In other words, there is no initial capacity of wind energy, and there is no added capacity of wind energy for the entire study period. This scenario presents the maximum possible contribution of wind energy to the cost of meeting the demand for electricity in the ASEAN region.

Second, an actual BAU scenario is set in 2018 in which the current initial capacity of wind energy is considered.

Third, a REmap scenario adopts the capacity of wind energy assumed in the REmap 2025 case in IRENA and ACE (2019). The REmap approach takes all available energy sources, including renewables, and considers energy supply and demand in power, heating, transport, and cooking. It aims to find a viable way of achieving the gap between the share of renewable energy under the reference case that is 17% and the target share of renewable energy for the region that is 23%. Full utilisation of potential wind energy is to be implemented in 2025 (Table 11.5).

As stated previously, Viet Nam is expected to utilise its huge potential of wind energy and install the largest capacity of wind energy (5700 MW) amongst the 10 ASEAN countries. Indonesia is next at 2900 MW, and Thailand and the Philippines

Table 11.5 Expected wind capacity under REmap scenario

Country	Wind capacity (megawatts)	Remarks
Brunei Darussalam	0	
Cambodia	200	
Indonesia	2900	
Lao People's Democratic Republic	0	
Malaysia	100	
Myanmar	500	
Philippines	1100	
Singapore	270	Offshore wind
Thailand	1800	
Viet Nam	5700	

Source IRENA and ACE (2019)

are in third and fourth with installed wind capacity of 1800 MW and 1100 MW, respectively.

11.5 Results, Discussions, and Policy Implications

11.5.1 No Wind Energy

The counterfactual BAU scenario presents the highest cost of meeting electricity demand in the ASEAN region and has the largest carbon emissions.

11.5.1.1 Cost of Electricity Generation in ASEAN Countries

When all capacities of wind energy are intentionally removed from the available technologies, three distinct trends emerge compared to the actual BAU case (Table 11.6).

Table 11.6 Cost of meeting electricity demand in the ASEAN region ($ billion)

Scenarios	Cost	Difference
Counterfactual BAU	421.05	–
BAU	418.20	0.7%
REmap	409.36	2.8%

Source Authors
BAU business as usual

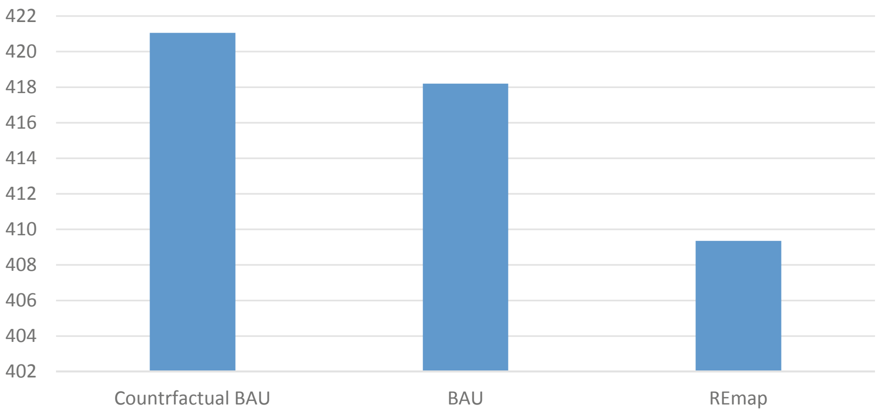

Fig. 11.2 Total cost of meeting the demand for electricity in ASEAN. ($ billion). BAU = business as usual. *Source* Authors

First, more low-cost technologies, such as hydropower, are used across many countries from 2026 to 2040. Second, renewable energy technologies, such as geothermal energy for Indonesia and the Philippines, are dispatched. Along with early utilisation of geothermal energy, more biofuel energy is utilised in Singapore. The Philippines appears to tap into biofuel energy as well. Third, more carbon-intensive and costly carbon-generation technologies, such as coal with carbon capture and storage and gas with carbon capture and storage, appear to be dispatched later in 2036 and 2040.

When ASEAN countries utilise wind energy, however, the cost of meeting electricity demand in the region is lowered by about 0.7%. The share of wind energy, out of the total installed generation capacity in the ASEAN region, is about 0.8%. The cost of wind energy is almost the same as the share of installed generation capacity. Figure 11.2 presents the cost of meeting electricity demand in ASEAN countries.

The total cost of meeting the demand for electricity in the ASEAN region is $421.05 billion if no wind energy is utilised at all, i.e., the counterfactual BAU scenario. Under the BAU scenario in which the current level of wind energy is assumed, the total cost is $418.20 billion, about 0.7% lower than that of the counterfactual BAU scenario. The total cost of the counterfactual BAU scenario is $421.05 billion, while that of the REmap scenario is $409.36 billion. The difference between the counterfactual scenario and the REmap scenario is 2.8%, which is more than three times the difference between the cost of the counterfactual scenario and the BAU scenario, if the capacity of wind energy assumed under the REmap scenario of IRENA and ACE (2019) is to be fully utilised from 2025.

11.5.1.2 Carbon Emissions

The difference in carbon emissions between the counterfactual scenario and REmap scenario is interesting (Fig. 11.3). The difference in the quantity ranges from 0.62

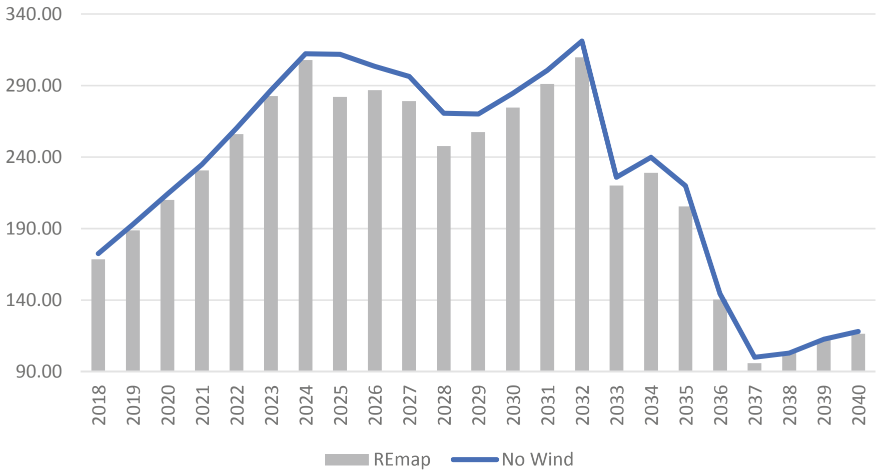

Fig. 11.3 Trajectory of Carbon Emissions under Counterfactual BAU and Remap (million tons). BAU = business as usual. *Source* Authors

million tons in 2039 to 29.71 million tons in 2025, mostly because new capacity of wind energy is assumed to be installed in 2025. Excluding this, the next highest difference is achieved in 2028. The amount of carbon emissions under the counterfactual BAU scenario is slightly higher than the REmap scenario in 2038, probably due to the lower capacity of hydro, which is added in 2038.

Thus, utilising more wind energy could reduce carbon emissions further. The simulation of the REmap scenario shows that a few countries in ASEAN, such as Brunei Darussalam, Malaysia, Singapore, and Thailand, appear to fully utilise their potential for wind energy. If other countries are able to harness their potential for wind energy, then the reduction in carbon emissions could be even larger.

11.5.2 Actual Business-As-Usual Scenario and REmap Scenario

A more realistic evaluation of how wind energy can reduce carbon emissions is shown by comparing the simulation results of the actual BAU scenario with those of the REmap scenario in which the full utilisation of potential for wind energy is expected to start from 2025. Figure 11.4 presents possible amount of carbon emissions reduced in the REmap scenario.

The difference in the quantity of carbon emissions ranges from 1.44 million tons in 2034 to 26.22 million tons in 2025, mostly because new capacity of wind energy is assumed to be installed in 2025. Excluding this, the next highest difference is

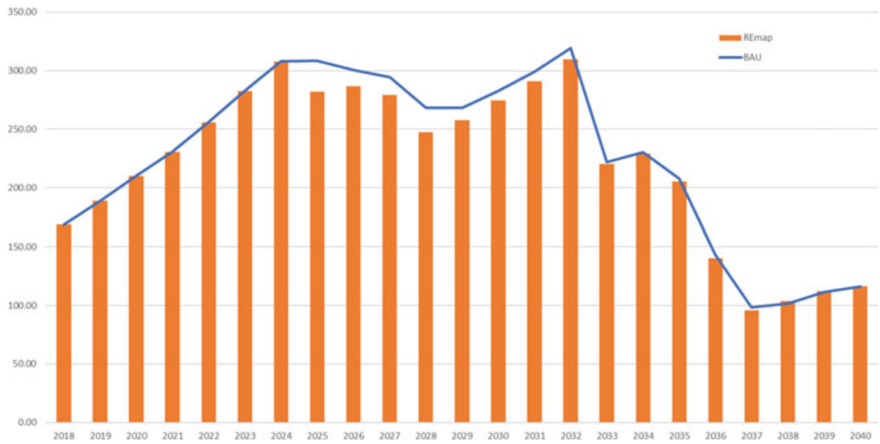

Fig. 11.4 Reductions in carbon emissions under REmap scenario (million tons). BAU = business as usual. *Source* Authors

achieved in 2028. Carbon emissions under the REmap scenario appear to higher than those under the actual BAU scenario during the last 3 years of the study period, caused by less hydro capacity during those years.

11.6 Conclusions and Policy Implications

ASEAN countries have good potential to harness wind energy, especially Viet Nam. Wind energy, however, is not commensurate with the degree of potential capacity. The intermittency of wind and high system costs are the main reasons for low development.

This study found that there would be 0.7% higher costs in meeting the demand for electricity in ASEAN countries if no wind energy was utilised. The costs of meeting the demand for electricity in ASEAN under the REmap scenario appear to be about 2.8% lower than that of the counterfactual scenario. As expected, the amount of carbon emissions from both the actual BAU scenario and the REmap scenario are lower than that of the counterfactual scenario, especially from 2025 when wind energy is extensively harnessed.

The trajectories of carbon emissions exhibit a visible gap between the counterfactual BAU scenario and REmap scenario from 2025 to 2032 and a lesser visible difference toward 2040. All three scenarios show that the level of carbon emissions would peak around the early 2030s when carbon-emitting power-generation technologies are more extensively dispatched to meet the increasing demand for electricity in the ASEAN region.

The REmap scenario shows that both the cost of meeting the demand for electricity and amount of carbon emissions decrease compared to the counterfactual

BAU scenario and actual BAU scenario. However, the amount of carbon emissions appears to increase during later periods, as low- or no-carbon-emitting technology is crowded out. Considering the possible reverse in the trajectories of carbon emissions, whether the added capacity of wind energy will increase the amount of carbon emissions needs to be evaluated. If the reversal in the amount of carbon emissions appears to be the case, then such a case should not proceed.

This study draws a few policy implications from the findings presented above.

First, as shown in the REmap scenario, more wind capacity appears to accelerate the decreasing trend of carbon emissions. Wind energy should thus be promoted in ASEAN countries. As the cost of harnessing wind energy is expected to decrease further, more wind energy will lower the cost of meeting the electricity demand in ASEAN.

Second, the amount of carbon emissions could be larger when more wind capacity is dispatched, although the cost of meeting the demand for electricity will decrease. When a decision to add more wind capacity is made, a rigorous evaluation should proceed to determine whether the wind capacity will crowd out no- or low-carbon-emitting technologies, such as hydro, and eventually increase carbon emissions in the long term.

Third, harnessing more viable renewable energy power-generation technologies in the ASEAN region could decrease the level of carbon emissions. It is uncertain, however, if dispatching more of such technologies would decrease the costs of meeting the demand for electricity. ASEAN countries need to decrease the costs of renewable energy power-generation technologies, therefore, through more research and development.

Harnessing renewable energy power-generation technologies is not immune from damaging the environment and can have negative repercussions on the economy, as identified in Viet Nam's development of offshore wind energy. Thus, ASEAN must evaluate possible negative impacts of harnessing renewable energy on the environment and economy.

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Chapter 12
Sustainability and Life-Cycle Cost Analysis of Solar Photovoltaic-Generation Systems in ASEAN Countries

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Abstract Solar energy is a renewable source that can help the Association of Southeast Asian Nations (ASEAN) region realise its 23% renewable energy target by 2025. However, its development is slow due to a lack of awareness and funds. Many financial institutions are willing to invest in renewable energy projects, but data reliability has been a concern. Approaches that can be used to gather and to analyse data, therefore, should be identified to attract investors towards renewable energy. Quantitative analyses could also help governments more accurately develop reusable energy plans and integrate the procurement of reliable renewable energy systems into them. This study aims to provide a comprehensive assessment of the environmental and economic impacts of various types of solar photovoltaic (PV) systems (e.g., stand-alone, rooftop, and solar farm) by using sustainable quantitative approaches, such as life-cycle analysis and life-cycle cost analysis. Data normalisation was also conducted to compare the performance of each system. It was found that the solar PV rooftop system has the lowest greenhouse gas emissions, life-cycle cost, and levelised cost of energy. This study then offers policy recommendations to attract high, sustainable green investment to the region.

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H. Phoumin et al. (eds.), *Energy Sustainability and Climate Change in ASEAN*, Economics, Law, and Institutions in Asia Pacific,
https://doi.org/10.1007/978-981-16-2000-3_12

Keywords Solar photovoltaic · Greenhouse gas emissions · Energy payback time · Life-cycle cost · Levelised cost of energy

12.1 Introduction

Energy technology is essential to economic development. As energy demand increases proportionally to population numbers, it ensures the continuous growth of a nation through efficient management (Energy Commission 2018). Sustainable energy is also crucial to the Sustainable Development Goals, under which it is to be provided in 'uninterrupted availability at an affordable price' to the population (United Nations 2015). The Association of Southeast Asian Nations (ASEAN) region, with its diversity and dynamic industrial advancement, research progressiveness, structural development, abundant human resources, and financial means, is well-positioned to embark on various climate change mitigation projects (Ferroukhi et al. 2018). Indeed, ASEAN found that regional economy energy intensity has declined to 21.6% compared with its 2005 level—ultimately surpassing the ASEAN Plan of Action for Energy Cooperation target of a 20.0% reduction by 2020 (ASEAN Centre for Energy 2017). In the region's power generation mix, renewable energy-installed capacity is on its way to growing the forecasted amount of 10% by 2025 compared to its 2017 level (Fig. 12.1).

Despite difficulty with resource management, the ASEAN region is working to ensure a secure, affordable, and sustainable pathway for its energy sector, as well as aiming to achieve universal access to electricity by 2030 (ASEAN Centre for Energy 2017). Energy poverty across Asia—that is, people having no access to electricity—can be rectified with access to stand-alone clean energy. Moreover, energy demand is growing rapidly at an average of 6% per year, with the increase in gross domestic

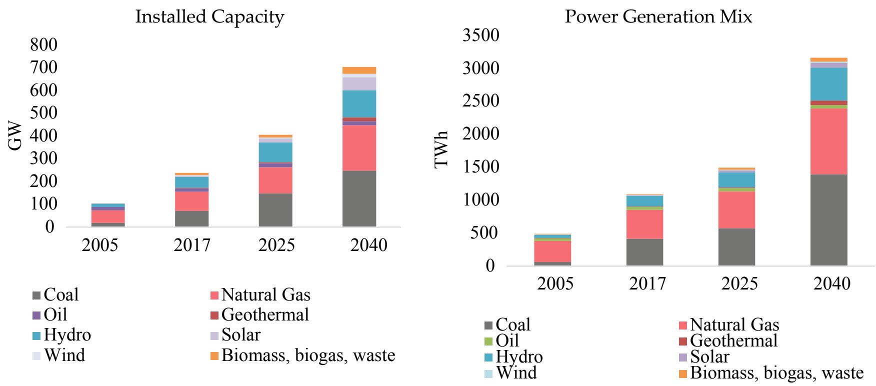

Fig. 12.1 ASEAN baseline energy scenarios, 2005–2040. ASEAN = Association of Southeast Asian nations, GW = gigawatt, TWh = terawatt-hour. *Source* ASEAN Centre for Energy (2017)

product (GDP) projected to be almost 0.03% in the Asia–Pacific region by 2030 (Ferroukhi et al. 2018).

The ASEAN region has rich natural energy resources, including sunlight that ranges from 1.5 to 2.0 megawatts per square metre (MWh/m^2) annually. However, some countries in the region still perform poorly in terms of energy resources (Junxia 2019). Cambodia, the Philippines, Singapore, and Thailand even import energy (ExxonMobil 2017). Renewable energy currently meets only about 15% of the region's energy demand—slow growth compared with the drop in its cost. The insignificant share of green energy is only 1329.9 million tons of oil equivalent, about 10% of all energy used (Erdiwansyah et al. 2019). Solar photovoltaic (PV) and wind contributions remain small (IEA-PVPs 2015). Mitigating pollution has been the strategy adopted worldwide to encourage sustainable energy, yet sustainable energy should also be examined in terms of financial value. Implementing renewable energy power generation plants could also offer many other benefits, including job opportunities. Moreover, achieving sustainability is an innovative way to bypass geographic, climate, and resource constraints, as well as the varying technological availability in the region, as through agriculture-based PV (agro-PV) hybrid systems with monthly harvesting income and energy generation.

Solar is the most viable source that can help the ASEAN region achieve its renewable energy targets. Understanding the principles of various solar PV systems—such as solar farm (land- or water-mounted, best known as floating solar); solar rooftop, known as building-applied PV (BAPV); building-integrated PV (BIPV); and agro-PV—is thus essential. Grid-connected or stand-alone, these systems' current environmental and economic impacts are concentrated on the single or hybrid system.

Historically, it has been difficult to compare the various systems in use in the region due the varied geographical areas and energy mix of subregions (Copper et al. 2017). Typically, the systems have few operational phases, various types of PV technology, different sources of energy, diverse discounted rates, and various financial arrangements in their life cycles. The lack of understanding of their impacts not only occurs amongst policymakers but also amongst developers and investors; it is thus crucial that quantitative approaches be explored to determine the benefits of different PV systems to create more sustainable investment in the ASEAN region (ADB 2018). Financing is the most important part of developing renewable energy projects, but many financial institutions are unwilling to invest in renewable energy projects as data reliability is a concern.

Approaches that can be used to gather and to analyse data regarding, for instance, solar PV systems, should thus be identified to attract investors towards renewable energy. This study, therefore, provides a comprehensive environmental and economic assessment for various solar PV systems using life-cycle analysis (LCA), life-cycle cost analysis (LCCA), and normalisation of scenario data to compare impacts for each system. Towards this goal, various case studies have been selected from Indonesia, Malaysia, and Thailand based on type of solar PV system.

12.2 Sustainable Approach of Solar PV Systems

12.2.1 Life-Cycle Analysis

LCA is a scientific approach behind the decision and policy support for a product, resources, or system. It is based on and conforms to ISO 14040 and 14044 Standards 2006, Transparency and Modern Relevance; thus, it is a comprehensive and internationally standardised method (Energy Commission 2018) (Fig. 12.2). It quantifies and qualifies all relevant emissions and resources consumed, including related environmental and health impacts and resource depletion issues. LCA also considers a full life cycle of a product or system from the extraction of resources from production, operation, and end-of-life management to the disposal of remaining waste. A partial LCA can also be conducted within a defined system boundary.

LCA studies are often implemented to resolve technical issues and questions regarding burden shifting in environmental impact problems. Therefore, LCA helps avoid issues that arise from waste management to emissions, and prove the quantitative values of efficient consumption and production of energy systems (United Nations 2015).

In this study on solar PV systems, the subtext of usability was under some key parameters, including.

- **the module conversion efficiency**, or the percentage of solar energy converted to direct current by the module;
- **performance ratio**, that is, the ratio of AC produced by the PV system minus system losses based on a DC-rated system of module efficiency and irradiance;
- **irradiance**, the average energy flux from the sun in kilowatts per m^2 per year; and
- **system lifetime**, or the years that a PV system operates with routine maintenance and repair (Ferroukhi et al. 2018).

Within the defined scope for this study, a PV system was evaluated through available inventory data information, which was based on identification and assessment in the field in accordance with an environmental assessment method (Rincón et al.

Fig. 12.2 Life-cycle analysis framework. *Source*: European Union (2010)

2013). Inventory data were primarily reflected on all materials and energy flows between life-cycle phases based on the designed framework (Verones et al. 2017). Primary and secondary data were utilised to complete the inventory using the ecoinvent database on SimaPro software. Data collection and calculation were associated with the functional system (Su et al. 2017), carbon dioxide (CO_2) equivalent emissions per m^2, CO_2 equivalent emissions per power generation, and capital cost per power generation in US dollars per kilowatt-hour (kWh).

Life-cycle impact analysis, which involves the intepretation of the life-cycle inventory to forecast the midpoint or endpoint of the study to determine the environmental impact of the whole process, has four steps:

- **classification**, which entails assigning environmental impacts to each component in the inventory according to the goal and scope of a specific study;
- **characterisation**, involving equivalency factors to convert inventory results suitable for comparable impact indicators, thereby allowing many different elements to be compared under a similar basis;
- **normalisation**, or normalising scalable data to determine a reference factor for clarifying relative impacts; and
- **weighting**, to prioritise the importance of a certain element depending on its impact, remaining constant within its own LCA and categories, to assess the impact of products.

The modernity consideration was based on module efficiency, manufacturer, production scale, and module design. According to up-to-date research on PV technology, thin-film solar cells are the most advanced. However, this technology is slow, as is large-scale application, due to reliability and shortages. Modernity was thus reflected by the advancement and trust of people in silicon-based PV that has matured through time (Junxia 2019). PV technologies, in the LCA framework, included risk manifestation, toxic emissions, primary energy, energy payback time (EPBT), land use, and water use. These factors affect PV development as a whole to deliver the best technology. The LCA considered minimal changes in real time to manifest the technology.

12.2.2 Environmental Indicators for the PV System Life Cycle

A complete LCA should include actual environmental impact data that cover the whole product process flow. Environmental footprint impact categories refer to specific categories of environmental impacts considered in an environmental footprint study. These are generally associated with the resources used for process inputs or outputs, such as emissions of greenhouse gases (GHGs) or toxic chemicals. Impact assessment methods for quantifying are grounded by established models; thus, a correlation exists between the inputs and outputs of each unit's process with organisational activities. Each impact category should use an associated, stand-alone environmental footprint impact assessment method (Jungbluth 2020).

The purpose of an environmental footprint impact assessment is to group and to aggregate the collected inventory data according to the respective contributions to each impact category. The selection of categories depends on the issue related to the activities. In this study, the largest impact contribution was the global-warming potential, which inflicts the highest score of environmental impact. However, the Bern model of over a 100-year time zone is far-fetched with the dynamic changes in sustainability actions.

12.2.2.1 Greenhouse Gas Emissions

According to recent studies, a PV system is assumed to have low emissions throughout its life cycle. Emissions are suspected to comprise GHGs, sulphur dioxide, and nitrogen oxides, together with some heavy metal emissions from the downstream phase. For this study, direct GHG emissions were calculated on the basis of IPCC (2015). The GHG emissions projection for each sector also used the linear regression method.

The basic equation used to calculate GHG emissions was

$$\text{GHG Emissions } (\text{CO}_2 \text{ eq/kWh}) = \textit{Activity data} \times \textit{Emissions factor} \tag{12.1}$$

The GHG emissions key parameter comprises conversion efficiency, performance ratio, irradiance and lifetime, and the source information feeds from the manufacturer and data collector were relevant to the age of data.

12.2.2.2 Cumulative Energy Demand

Cumulative energy demand (CED) is the total energy required to manufacture a product. This is also known as the primary energy supplied for the manufacturing and construction of the whole system. It includes direct and indirect energy consumption to utilise material and consumables during acquisition. CED highly depends on the electrical grid supplied by regional mix in total.

The CED of a system was calculated by:

$$\text{CED} = \text{E}_\text{M} + \text{E}_\text{T} + \text{E}_\text{I} + \text{E}_\text{O} + \text{E}_\text{D} \tag{12.2}$$

where:

E_{Mn} manufacturing primary energy demand
E_T transport primary energy demand
E_I installation primary energy demand
E_O operation and maintenance primary energy demand

E_D decommissioning and disposal primary energy demand.

12.2.2.3 Energy Payback Time

Life-cycle energy stresses on EPBT ensure that all energy consumed or invested by a PV system has a short-term energy payback for it to be considered viable. The significance of EPBT is to determine whether the energy invested in manufacturing a PV system is worth its clean-energy production over its lifetime. PV system life-cycle energy includes all five phases mentioned in the scope of the study (i.e., manufacturing, transport, construction, operational, and disposal). The EPBT was calculated by:

$$\mathrm{CED(MJ)/[LEP(MJ)}-\mathrm{E_{OMR}(MJ)]} \tag{12.3}$$

where:

CED CED of the PV system
LEP cumulative energy production by the PV system over 25 years
E_{OMR} operation and maintenance energy demand over 25 years.

12.3 Economic and Sustainable Performance of PV Systems

12.3.1 Life-Cycle Cost Analysis

An LCCA is an economic assessment method that includes all related costs of investing in a project, from its preliminary stage, initialisation, construction, operation, to the disposal of the whole product or system. The tool is compatible with the scope and boundary of LCA; thus, pairing it can yield great results. An LCCA is a comprehensive tool to analyse economic variables in terms of interest rate, time-value of money, and cash flow (Fuller and Petersen 1995). An LCCA can determine whether a project is economically viable and cost-effective. For this study, the LCCAs were calculated as follows (Reddy et al. 2015):

$$LCC = C_I + C_{rep} + C_O - C_{res} \tag{12.4}$$

where:

C_I investment cost
C_{OMR} operation, maintenance, and repair costs
C_{rep} replacement cost
C_O other costs
C_{res} residual value.

Investment cost refers to the initial investment, such as land, PV modules, system design, and installation costs. Operation, maintenance, and repair costs refer to operator pay, inspection, insurance, property taxes, and repair costs. The replacement cost is the total cost for the replacement of equipment required during the life of the system. Other costs include energy, water, and other associated costs during the life of the system. Residual value refers to the resale value, which is the net value of the system in the last year of the life-cycle period.

12.3.2 Discounted Payback and Internal Rate of Return

Economic analysis also includes levelised cost of energy (LCOE), net savings, savings–investment ratio, net present value, internal rate of return (IRR), and payback. Payback is essentially the number of years required to recover the initial investment or early outflow; a simple payback is coveted because capital gains are available early and can reduce the risk of investment. Discounted payback is the time taken for the discounted value of expected cash flows to cover the initial cost when the cumulative net present value is equal to the investment cost. The discount rate does not give simple payback the difference, because cash flows are not discounted to the current value. However, the discount rate affects discounted payback, as cash flows are discounted to the present value.

The equation below was used to obtain a refund period (Universiti Teknologi MARA 2014):

$$PB = (n - 1) + \left[\frac{(C_1 - \mathit{Cumulative\ cash\ flow\ before\ n})}{\mathit{Current\ cash\ flow\ n}} \right] \tag{12.5}$$

where n is the recovery year in which cash flow exceeds the initial investment.

Two types of payback were considered in this study: simple payback and discounted payback. Simple payback does not consider the time-value of money, while discounted payback does.

The IRR is the discount rate where the present value of future cash flows is the same as the initial investment of the project. The larger the IRR, the more likely the project will be for investment. The IRR was calculated as follows (Universiti Teknologi MARA 2014):

$$C_I = \overline{CF}\left(PVIFA_{IRR,n}\right) \tag{12.6}$$

where:

$\overline{CF}$ average cash flow of the project

$PVIFA_{IRR,n}$ the present value of the interest factor with an annuity at the interest rate or discount rate, which is considered equal to the IRR for period n.

12.3.3 Levelised Cost of Energy

LCOE is the most commonly used tool for comparing alternative technologies with different scales of investment, operating time, or economic conditions (ASEAN Centre for Energy 2016). LCOE only considers the cost of a life cycle and amount of energy generated during the period; it can thus eliminate favouritism or bias between technologies. A low LCOE is better because it shows that less money is needed to produce one unit of energy.

To calculate the LCOE, data from the LCCA calculation (Eq. 12.4) were used as follows:

$$LCOE = \frac{LCC}{LEP} \tag{12.7}$$

where *LEP* is the localised energy produced, or the amount of energy generated during the life of the power plant.

12.4 Case Studies

12.4.1 Background

The case studies examined were all within the ASEAN region. Criteria included a matured PV system with more than 2 years of operation, and a polycrystalline or monocrystalline PV module system with an estimated lifetime of 25 years. It had to be within the equatorial climate country of a similar solar irradiance period. The three types of systems included a stand-alone solar, roof-mounted system of 3–50 kilowatts (kW); a solar roof-mounted grid-connected system of 3–100 kW; and a solar farm (i.e., a land-mounted system) of more than 100 kW.

Six case studies were evaluated from Malaysia and from other countries of similar climate that were proposed by experts, Indonesia and Thailand (Table 12.1). The policy measures taken by other countries were also reviewed to widen the proposed policy interventions for PV systems in this region. The capacity factor for usual solar PV sites was only 16–17% from the whole expected system outcome. The result of these case studies were then compared to a previous report for agro-PV and a floating PV system (Agostini et al. 2021).

12.4.1.1 Stand-Alone PV Systems

Stand-alone solar PV systems generate and supply electricity for a single household, especially in rural areas, without being connected to a grid. The system works similarly to that of BIPV, but it does not generate any profit. It only allows users to save a

Table 12.1 List of case studies

Case study	Case and location	Annual average irradiance ($kWh/m^2/year$)	Type of PV system and panel	Panel effective area (m^2)	Power capacity	Service year
	**Case 1** Malaysia	1,571.00	Poly-crystalline	19.22	3.0 kWp	2015
	**Case 2** Thailand	1,672.00	Poly-crystalline	4,548.98	702 kWp	2011
	**Case 3** Malaysia	1,685.39	Poly-crystalline	2,138.40	200 kWp	2016
	**Case 4** Thailand	1,672.00	Amorphous silicon	51.84	2.5 kWp	2011
	**Case 5** Malaysia	1,571.00	Mono-crystalline	47,129.00	8.0 MWp	2014
	**Case 6** Indonesia	1,888.00	Mono-crystalline	13,880.16	2.0 MWp	2014

kWh = kilowatt-hour, kWp = kilowatt peak, m^2 = square metre, MWp = megawatt peak
Source Authors

cumulative amount of cash outflow from buying electricity over time. It can satisfy the demand of electricity in rural homes, such as those on islands, deep forests, and other areas with no source of electricity (Fig. 12.3). If the demand is high, areas can become stand-alone solar farms, with available land space and initial investment. The system size can be tailored to consumers who only desire to power small appliances, such as calculators and wristwatches, to that of a large-scale solar-powered house.

Case 1 is in Malaysia, a stand-alone PV system that was installed on the rooftop of a single-story house in 2015 by the owner to support renewable energy development. It has an annual average irradiance of 1571 kWh/m^2 per year. Twelve units of polycrystalline cover an effective area of 19.22 m^2. The power capacity is 3.0 kilowatt peak (kWp).

Case 2, in Thailand, is a stand-alone solar farm system, which generates electricity for a campus area and does not sell its excess production. The power capacity is 702 kWp, with 2808 units of polycrystalline panel over 4548.98 m^2. The system started operating in 2011, with annual average irradiance of 1672 kWh/m^2 per year.

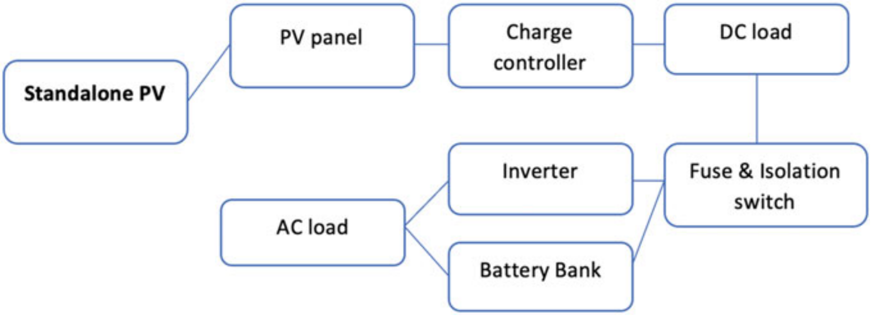

Fig. 12.3 Stand-alone PV system configuration. PV = photovoltaic. *Source* Authors

A stand-alone solar farm is considered a high-risk investment without any generated income, and its payback should only rely on its electrical consumption savings over the years.

12.4.1.2 Solar PV Rooftop Systems

Stand-alone systems usually occupy rooftops as BAPVs (i.e., solar panels). The systems are mounted on existing buildings with empty roof areas and are either flat-mounted or slant-mounted. This system adaptability attracts small investors to begin implementing solar technology, especially for self-consumption. The simple balance-of-system (BOS) installation is compatible to many existing home electrical configurations, easing implementation (Fig. 12.4).

Case 3 is located in Malaysia. The 200-kWp, polycrystalline PV system is mounted on a factory's vast rooftop space. The 2138.4 m^2 flat rooftop was covered with 1320 units in 2016. The annual average irradiance reaches 1685.39 kWh/m^2 per year. Although the system is expected to generate good income with low payback, the factory seems to interfere the effectiveness due to the heavy dust accumulation on top of the panels.

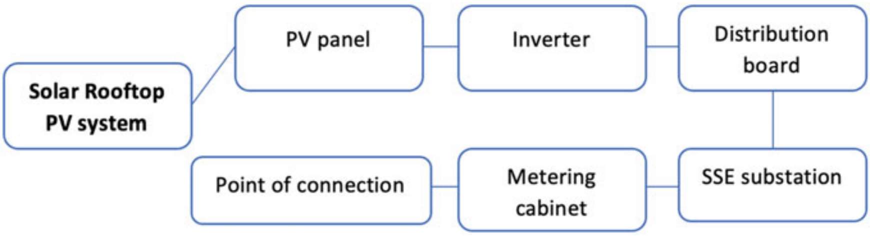

Fig. 12.4 Solar PV rooftop system configuration. PV = photovoltaic, SSE = step-up/step-down equipment. *Source* Authors

Case 4, in Thailand, features a small 2.5-kWp grid-connected system, mounted on the slanted roof of an event hall in 2011. It only has 32 units of amorphous PV panel with an effective area of 51.84 m^2. The annual average irradiance is 1672 kWh/m^2 per year, which is enough to support the small, rarely used event hall. The excess production on a non-eventful day can be sold to the grid for income.

12.4.1.3 Solar Farms

The popularity of solar farms is growing. As they profit from initial investment after a certain period, this promising market has attracted investors to green technology development. Solar farms' large installation accelerates clean energy generation in bulk, often greatly affecting the solar energy market. A typical configuration is displayed in Fig. 12.5.

Solar farm land occupation has become a concern over time, however, as the land could be used for crops instead (Fig. 12.6). Thus, developers often suggest a hybrid

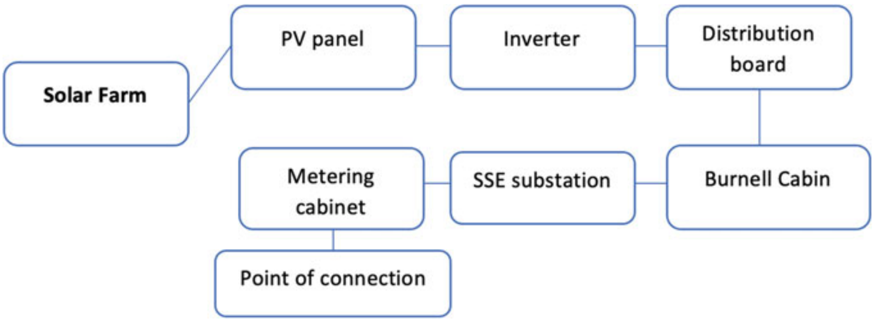

Fig. 12.5 Solar farm system configuration. PV = photovoltaic, SSE = step-up/step-down equipment. *Source* Authors

Fig. 12.6 Solar farm land occupation. *Source* Authors

system, maximising the use of land under the shade of solar panels known as an agro-PV system.

Case 5 is in Malaysia and involves an 8.0-megawatt peak (MWp) solar farm system. The system has 29,092 units of highly efficient monocrystalline PV panel on vacant land. The land totals 47,129 m^2 and is managed by a company, adding to the investment cost. The annual average irradiance is 1571 kWh/m^2 per year and has produced high power generation since 2014. The PV system is maintained regularly to preserve its efficiency.

Case 6, in Indonesia, involves a 2.0-MWp system that started operating in 2014. It has 8568 units of monocrystalline PV panel installed on 13,880.16 m^2 of land. The annual average irradiance is 1888 kWh/m^2 per year and boosts power output by using a transformer to maximise generation. The PV system is owned partially by the government and is regularly maintained.

12.4.2 Life-Cycle Analysis of PV Systems

Many studies on the PV system life cycle have been conducted, especially on their carbon footprints (Table 12.2). However, hidden parameters, which are used to identify the exact differences of each PV system in terms of size and traits, have remained difficult to analyse. For instance, PV system energy consumption is highly dependent on the regional energy mix, which is responsible for panel production. PV panel production not only dominates the energy consumption chart but also is the largest monetary allocation during system installation. PV system performance is based on efficiency, effective area, degradation rate, performance ratio, and irradiance. These variations make its uncertainty value grow by a single assumption.

The normalised value of the GHG emissions of PV systems shows the type of panel installed; system size plays a role in influencing emissions contribution. The majority of the polycrystalline system scores are lower than those of the monocrystalline systems. The latest technologies, such as third-generation PV, score low in terms of energy consumption (Goulouti et al. 2020).

GHG emissions also greatly depend on the PV module installed in the system. Thin-film modules are known to have low GHG emissions. GHG emissions reach 9.4–104 g (g) CO_2 equivalent per kWh for polycrystalline PV systems, 44–280 g CO_2 equivalent per kWh for monocrystalline PV systems, and 15.6–50 g CO_2 equivalent per kWh for amorphous PV systems (Sherwani et al. 2010).

EPBT is influenced by numerous components and activities during the system life cycle, which is about 25 years. Large numbers of EPBT years by ecoinvent include relevant component production, because relying solely on PV production still considers GHG emissions (Althaus 2013).

GHG emissions over the PV system capacity shows that the ratio of GHGs emitted over the PV system capacity normalises the comparison, because the PV systems vary in size and total energy consumption (Fig. 12.7). For typical silicon solar PV technology, the GHG emissions rate is 29–671 g CO_2 equivalent per kWh for m-Si.

Table 12.2 Greenhouse gas emissions of various PV systems

PV system	Size (kW)	Trait	Greenhouse gas emissions (CO_2 equivalent/kWh)	References
Solar farm	>500	Land-mounted polycrystalline	11.40 kg	(Copper et al. 2017; Ludin 2019)
Solar farm	>500	Land-mounted monocrystalline	2.30–2.50 kg	(Kittner et al. 2012)
Agro-PV	>500	Land-mounted roofing plantation	0.07 kg	(Agostini et al. 2021)
Solar rooftop	3–500	Roof-mounted polycrystalline	1.40 kg	(Ludin 2019)
Solar rooftop	3–500	Roof-mounted amorphous	0.80 kg	(Ludin 2019)
Polycrystalline PV system			9.40–104.00 g	(Allouhi et al. 2019)
			12.10–569.00 g	(Copper et al. 2017)
Monocrystalline PV system			44.00–280.00 g	(Kittner et al. 2012)
			29.00–671.00 g	(Chen et al. 2015)
Amorphous PV system			15.60–50.00 g	(Akhter et al. 2020)
Floating PV	>50 kW	Water-buoyant	–	
BIPV	>1 kW	Building integrated	0.70–0.80 g	(Stoichkov et al. 2019; Biyik et al. 2017)

BIPV = building-integrated photovoltaic, g = gram, kW = kilowatt, kWh = kilowatt-hour, PV = photovoltaic

Meanwhile, the p-Si range is approximately 12.1–569.0 g CO_2 equivalent per kWh (Ludin et al. 2018). The ratio for the entire system consistently ranges from 2.8 to 4.2. A high ratio means that a large amount of GHGs is emitted for a certain system capacity.

For Case 2, the ratio is extremely high despite the comparably lower GHG emissions than that of other large-scale solar farms. This result means that the system produces a large amount of GHG emissions over a small-scale system either due to the local PV manufacturing process or the power peak of the PV panel itself.

Normalised CED is energy consumption based on installed system capacity and mix percentage (Fig. 12.8). Country energy mix is affected by energy consumption with respect to fossil fuels. Large-scale, stand-alone solar farms (i.e., Case 2) typically require a massive balance-of-system (BOS), but two systems are not grid-connected, support a certain designated area, and do not sell energy (i.e., Case 1 and Case 2).

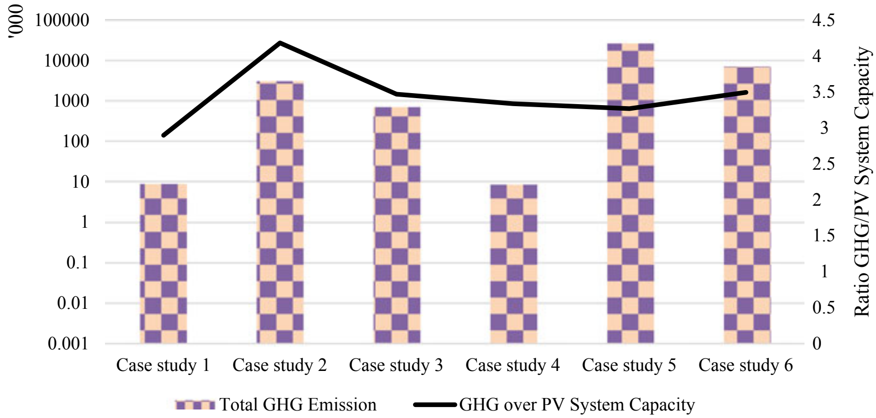

Fig. 12.7 Case studies considering the PV system greenhouse gas emissions over system capacity. GHG = greenhouse gas, PV = photovoltaic. *Source* Authors

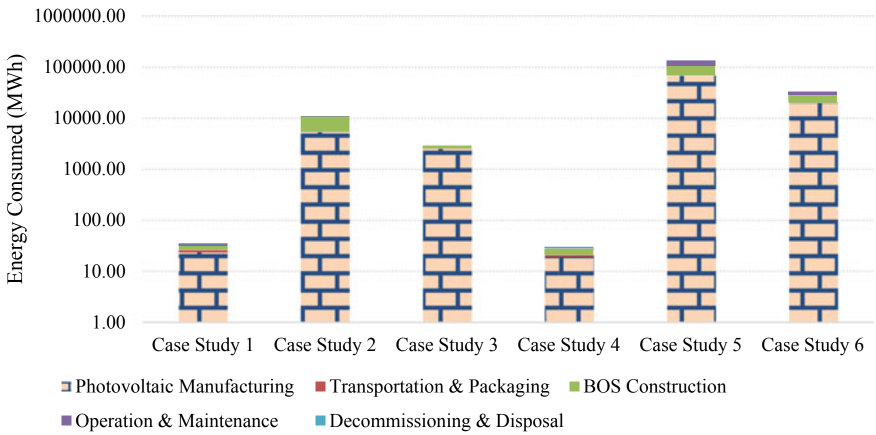

Fig. 12.8 Cumulative energy demand of solar PV systems. BOS = balance-of-system, MWh = megawatt-hour. *Source* Authors

Thus, energy consumption is second to that of PV manufacturing in the solar farm case studies (i.e., Case 5 and Case 6). These cases are different from the small-scale stand-alone system in Case 1, where the decommissioning and disposal phase are greater than the BOS. The difference may be due to the need for disposal management to dominate in small systems.

According to the CED of all case studies, the EPBT shows different patterns (Fig. 12.9). Case 4 has the fastest EPBT of 0.7 year because the system consumed a small amount of energy, particularly in amorphous silicon manufacturing. Indeed, solar PV systems, which use thin-film panels, are preferable because of their low EPBTs.

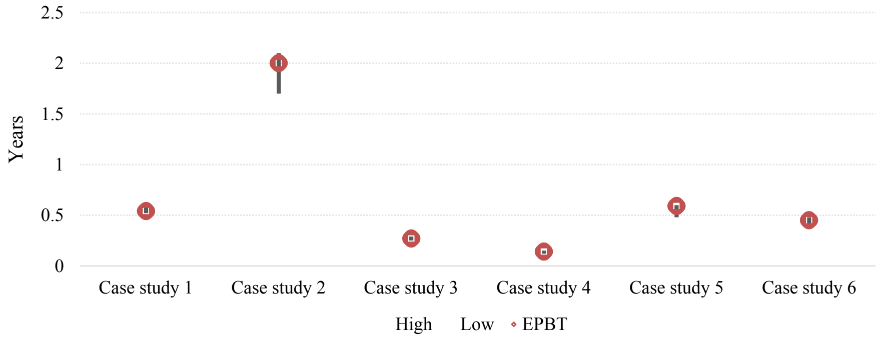

Fig. 12.9 Case studies considering the PV system energy payback time. EPBT = energy payback time, PV = photovoltaic. *Source* Authors

There are many factors affecting the EPBT including PV degradation rate, PV performance ratio, PV conversion efficiency, and maintenance frequency. Figure 12.10 shows the EPBT sensitivity analysis over the PV degradation rate.

The PV system EPBT is directly proportional to the increment of the PV degradation rate (Fig. 12.10). However, the difference is small and still within similar periods of payback time, which support the effectiveness of PV system implementation. Case 2 shows a distinctive difference in EPBT, an average of 2 years, due to the Staebler-Wronski Effect, which affected amorphous silicon modules during their early years (Gottschalg et al. 2013).

PV system components, including PV panels, inverters, wiring, and batteries for stand-alone systems, need maintenance, repair and occasional replacement. This requires energy and energy consumption from the country electricity mix, which were added up to the manufacturing phase before the installation phase. The higher the replacement frequency, the longer it takes for energy payback (Fig. 12.11). However,

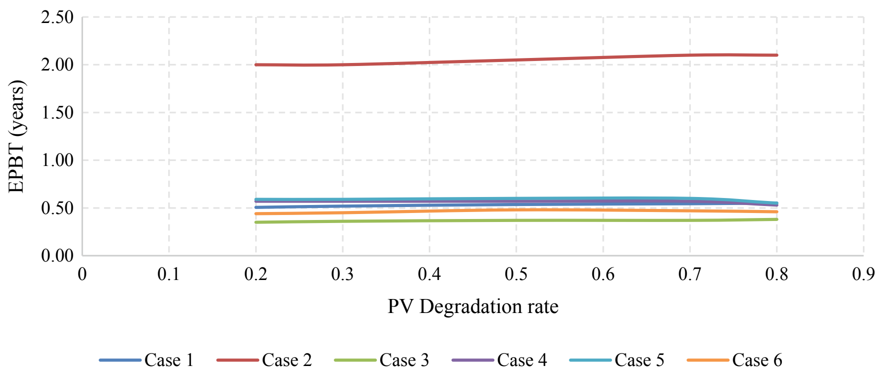

Fig. 12.10 PV degradation rate against energy payback time. EPBT = energy payback time, PV = photovoltaic. *Source* Authors

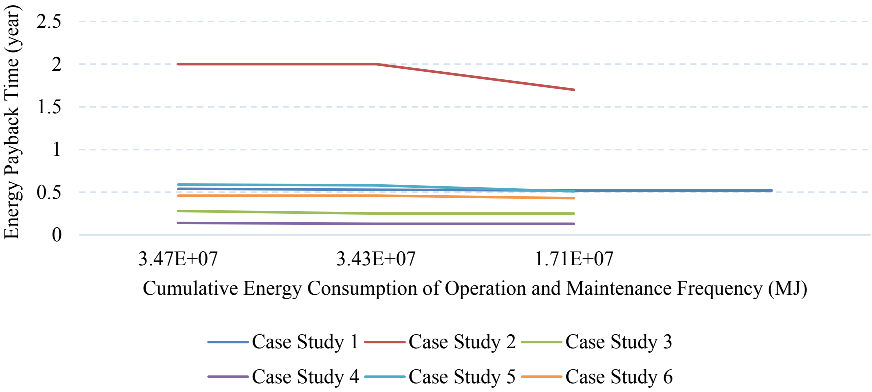

Fig. 12.11 Maintenance and replacement frequency against energy payback time. MJ = megajoule. *Source* Authors

it is expected to remain within 1 to 2 years, unless the system requires complete replacement of all installed panels.

The conversion efficiency percentage against EPBT shows an exponential increment by EPBT years as the PV conversion efficiency decreases (Fig. 12.12). The energy production of the module is sure to have a degradation rate and power loss throughout its lifetime. The type of PV panel ensures efficient energy usage payback. In this study, the lowest EPBT is contributed by Case 6 (i.e., the solar farm).

The environmental impact for all cases is shown in Table 12.3. Case 5 shows the highest CED with 133,419.25 MWh, which is 4 times larger than similar Case 6. Case 5 also emits the highest GHG emissions compared to the other systems, 3.7 times higher. In contrast, in term of EPBT, it shows that Case 5 and Case 6 are similar to Case 1 and Case 4.

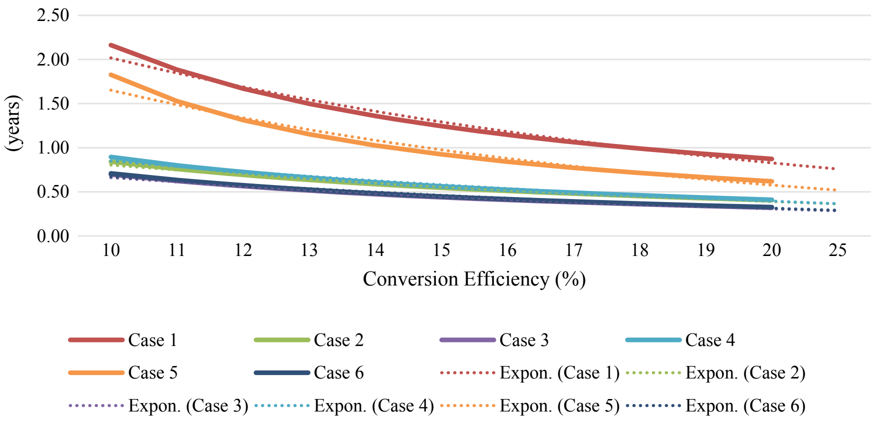

Fig. 12.12 Conversion efficiency percentage against energy payback time. *Source* Authors

Table 12.3 Case studies environmental impact summary

Case study	Cumulative energy demand (MWh)	Greenhouse gas emissions (kilograms per CO_2 equivalent)	Energy payback time (years)
Case 1	35.39	8.69	0.53
Case 2	107.88	3,058.60	2.05
Case 3	2,865.98	693.95	0.37
Case 4	29.97	8.34	0.57
Case 5	133,419.25	26,142.80	0.59
Case 6	32,802.95	6,987.23	0.46

CO_2 = carbon dioxide, MWh = megawatt-hour
Source Ludin et al. (2021)

12.4.3 Life-Cycle Cost Analysis of PV Systems

Economic impact studies have been conducted on various products as platforms for evaluating value-to-money along the entire value chain. LCCA is applied widely in the industry and academia for its comprehensive calculations and outcomes. However, this parameter is not generically standardised, yet it achieves an accurate evaluation and continuous improvement fitting for the economic dimension of this study (PTC 2013).

The cumulative cash flow for relatively small systems, such as Case 1 and Case 2 over 25 years shows a steady increment as the savings accumulated for stand-alone Case 1 (Fig. 12.13). Only after 22 years did both stand-alone systems generate a profit. Stand-alone systems show that value-to-money takes a long time since there is no profit from the energy production except monetary savings.

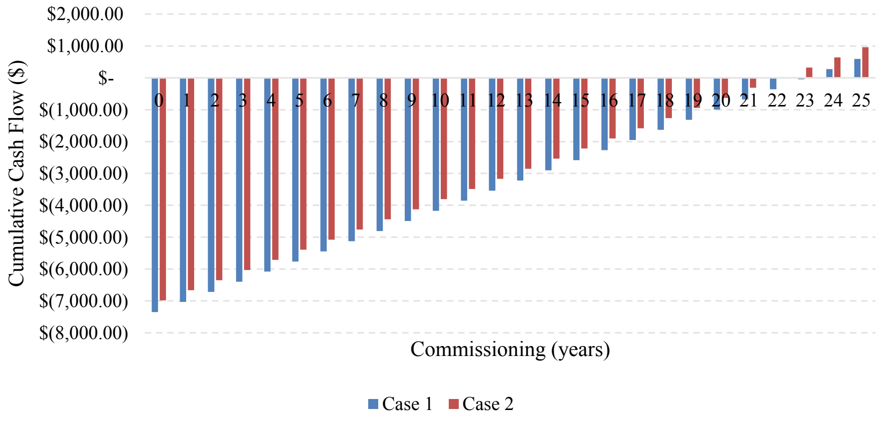

Fig. 12.13 Cumulative cash flow for stand-alone systems (Case 1 and Case 2) over 25 Years. *Source* Authors

Figure 12.14 shows the cumulative cash flow for the larger case study systems (i.e., cases 3, 4, 5, and 6). The relationship shows positive growth, especially profits from solar farms. Case 5 and Case 6 show positive cumulative cash flows after 10 years of operation.

An LCCA for all case studies was calculated on the basis of different discount rates (i.e., 2, 4, and 6%). As illustrated in Fig. 12.15, the LCCA value decreases as the discount rate increases. All case studies follow this trend, except for Case 3 whose LCCA value increases as the discount rate increases. This exemption is due to the total cost of operation, maintenance, and repair costs (C_{OMR}); replacement cost (C_{rep}); and residual value (C_{res}) at 2% (−$22,952.14), which was substantially less than those at 4% and 6%, that is, − $4,437.34 and $4,673.74, respectively. Thus, at

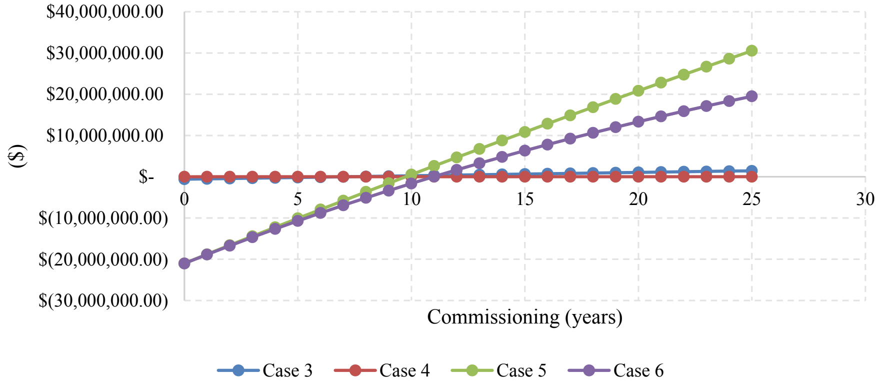

Fig. 12.14 Cumulative cash flow for cases 3, 4, 5, and 6 over 25 years. *Source* Authors

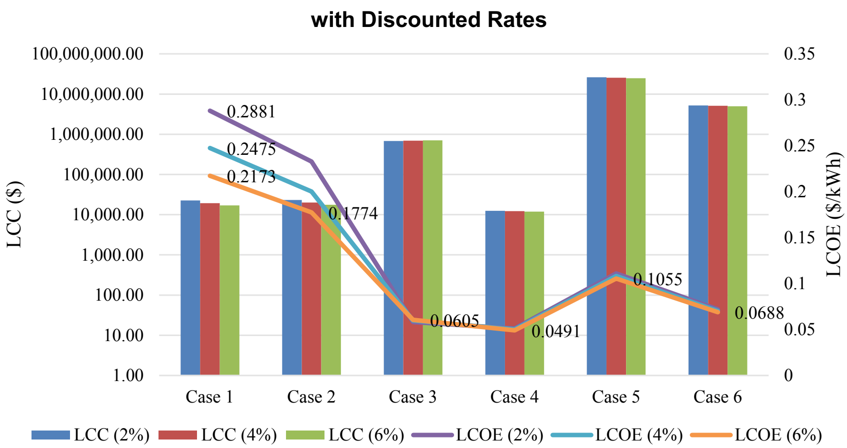

Fig. 12.15 Life-cycle cost analysis and levelised cost of energy of case studies with discounted rates. LCC = life-cycle cost. *Source* Authors

a 2% discount rate, the cash inflow (C_{res} value) was greater than at the 4% and 6% discount rates.

The LCCA and LCOE of all six case studies are shown in Fig. 12.15 under three different discounted rates, 2, 4, and 6%. The bar chart shows a slight decrement from 2 to 6% of the discounted rate for all LCCA values.

The LCOE for Case 1 records values of $0.2881/kWh, $0.2475/kWh, and $0.2173/kWh with discount rates of 2%, 4%, and 6%, respectively. A stand-alone system produces a high LCOE value because the localised energy produced (LEP) is extremely low compared with an LCCA value (Narayan et al. 2019). Case 1 produces 78,033.60 kWh throughout its lifetime, but the LCCA value is extremely high, thus producing a high LCOE value. Case 2 shows a slightly improved LCOE value due to LEP hike simulation. However, the value is still considered high amongst the other PV systems and comparable to the LCOE variety range of $0.06–$0.12 /kWh of a far-fetched PV/T system, as summarised by Gu et al. (2018). The lowest LCOE value is observed in the rooftop PV system (case 4). Both cases showed good performance in LCOE value, especially Case 4.

The rooftop PV system achieves a low LCOE value, because it can produce a large amount of LEP. For example, Case 4 can produce 243,552.50 kWh in its 25 years of operation compared with Case 1 and Case 2, which produce 78,033.60 and 99,569.76 kWh, respectively; these values are notably low for their LCCAs. Meanwhile, Case 3 can produce 11,640,331.37 kWh, similar to a solar farm mounted on the roof of a building. A rooftop system can achieve low LCOE also due to a low LCCA value compared with its LEP value. Rooftops require no land, thus saving considerable amounts in investment. This condition eventually lowers the LCCA value. Unlike solar farms, purchasing land is an extra cost, which contributes to high LCCA values. The findings of LCOE for the solar rooftop systems (Case 3 and Case 4) are in the range value of the other case studies (Table 12.4).

Table 12.5 shows that the fastest simple payback time with all discounted rates is Case 6, which presented 6.26 years of payback, followed by Case 4 with 7.96 years, Case 3 with 8.45 years, Case 5 with 9.75 years, and Case 2 with the slowest. For Case 1, payback was impossible to attain because in the last year of operation, the savings amounted to $1,624.55. An amount of $6,650.00 is needed to attain simple payback.

As for discounted payback, according to Allouhi et al. (2019), the current market conditions in Morocco show that the economic analysis of the monocrystalline-Si/polycrystalline-Si systems are a technology offering the longest discounted payback period with a 20-city average of 28.62 years. In this study, the fastest discounted payback (i.e., 6.76 years) is observed in Case 6 at the 2% discount rate, followed by Case 6 at 4% with a discounted payback of 7.36 years, and Case 6 at 6% with a discounted payback of 8.10 years. These values are comparable to the shortest discounted payback of 17.11 years for p-Si and 21.62 years for m-Si (Allouhi et al. 2019).

The slowest discounted payback is that of Case 2 at 2% at 26.27 years. For others, their discounted payback is in the average range of 8–16 years, except for Case 1 (at 2, 4, and 6%) and Case 2 (at 4 and 6%). For both cases, the payback is impossible

Table 12.4 PV system life-cycle cost analysis range summary

PV system	LCC ($)	LCOE ($/kWh)	DPB (year)	IRR (%)	References
Stand-alone	16,000–23,000	0.17–0.28	20.0 (savings)	–	(Narayan et al. 2019; Ludin et al. 2021)
Solar rooftop (polycrystalline)	670,000–700,000	0.05–0.06	8.0–11.2	8.4–10.8	(Allouhi et al. 2019; Ludin et al.2021)
Solar rooftop (amorphous)	11,000–12,500	0.04–0.05	9.3–12.2	7.9–11.5	(Naves et al. 2018)
BIPV	–	–	3.3–5.4		(Anctil et al. 2020; Calise et al. 2020)
Solar farm	5,000,000–20,000,000	0.06–0.11	6.7–15.3	6.2–15.4	(Naves et al. 2018; Ludin et al.2021)
Agro	–	0.09–0.11	–	12.7–17.4	(Agostini et al. 2021)
Floating	–	0.04–0.07	–	–	(Sahu et al. 2016)

BIPV = building-integrated photovoltaic, IRR = internal rate of return, kWh = kilowatt-hour, LCC = life-cycle cost, LCOE = PV = photovoltaic

Table 12.5 Simple payback and discounted payback times

	Simple payback (year)	Discounted payback (year)			Internal rate of return (%)
Discount rate		2%	4%	6%	
Stand-alone PV					
Case 1	–	–	–	–	–
Case 2	23.14	26.27	–	–	–
Rooftop PV					
Case 3	8.45	9.36	10.55	12.20	10.85
Case 4	7.96	8.77	9.80	11.22	11.59
Solar farm					
Case 5	9.75	10.98	12.69	15.32	8.86
Case 6	6.26	6.76	7.36	8.10	15.44

PV = photovoltaic
Source Authors

to attain because their present value savings are remarkably low. Their savings will reach roughly 24% of their initial investment in the 25th year of their operation. Thus, calculating the discounted payback was impossible. The PV module cost must be lowered by 30% to further signify the competitive LCOE and payback periods to improve the payback of a PV system investment (Alves-Veríssimo et al. 2020).

12.5 Conclusions and Policy Recommendations

In this study, the importance of sustainable approaches—LCAs and LCCAs—was highlighted to determine the impact of a PV system and technology. The application of LCAs and LCCAs can prove the reliability and viability of PV systems under many circumstances according to consumer needs and parameter conditions. These tools can benefit public awareness, and inform policymakers, financial institutions, and renewable energy developers when implementing green technology. Various system choices are crucial for decision making based on lifetime impact and to improve trust for investors. Policymakers can forecast the environmental impact and plan for long-term impact by predicting results for future reference, add-ins, or complements to any additional policies to assist development. Financial institutions can enact sustainable investment as well.

According to the findings of this study, Case 4 had the fastest EPBT of 0.14 year because of its low manufacturing energy consumption of amorphous silicon technology. Moreover, the normalised CEDs for all cases are within the average range of 45–60 megajoules per m^2. The distribution proves that the manufacturing of products eventually dominates the CED of each system and influences the EPBT longevity over time, in addition to those of efficiency and degradation factors on the PV panel itself.

The GHG emissions of a PV system ratio to its total system capacity remains consistent, within 2.8–4.2. The GHG emissions or CO_2 equivalent per 1 kWh of energy produced by a PV system shows whether the system produced enough green energy to cover its non-renewable mix of electricity used to produce the system. Most of the case studies, except Case 5 and Case 6, had more CO_2 than their production. However, whether the PV system requires considerable time to recuperate remains unclear.

Meanwhile, in the LCCA and LCOE analysis, the best system was the rooftop PV system. Both cases of rooftop PV systems recorded the lowest values in the LCCA and LCOE analysis. The LCOE value of Case 4 was the highest with \$0.0491 per kWh, followed by Case 3 with \$0.0582 per kWh. Case 6 (at a 2% discount rate) showed the best performance in supplementary financial measures. Case 6 topped the simple and discounted payback analyses.

A solar farm system is more viable than a rooftop PV system. For the rooftop PV system to be financially viable and to take advantage of its low LCC and LCOE values, it must be operated at a large scale (similar to solar farms) with increased capacity to achieve high energy production. However, the use of PV modules with low degradation rates below 0.2% is highly recommended for solar farms to be more cost-effective and to achieve low LCOE values.

In comparison with the other reports of LCCA, the lowest GHG emissions are in the agro-PV system at 0.07 kg CO_2 equivalent per kWh. The lower GHG emissions are based on the combined power generation and agriculture on a similar land area. However, more theoretical studies and practical exploration of agro-PV must be conducted to optimise the combination of PV power generation and agricultural planting, including new PV materials with higher efficiency and low cost.

Favourable LCOE results include solar PV rooftops with a price of $0.04–$0.05 per kWh. The lower price indicates that the LCC for system installation and maintenance is also small because the cost is most likely focused on the module and mounting parts without land or new area.

National and regional policy interventions play important roles in supporting renewable energy growth and development in their implementation in the ASEAN region. The need to identify priorities, maintain stability, and carve pathways for the renewable energy market is crucial to achieve targets set up by various countries and the region. In general, countries should widen their renewable energy road maps by considering other adaptable policies and measures in their energy portfolios, create attractive programmes and incentives to improve public awareness and to attract investment, and initialise many energy scenarios in a decision-making platform using dynamic data in the sustainable assessment to overcome uncertainty.

The following recommendations are provided on the basis of the findings from the study to realise the 23% renewable energy target in the ASEAN region:

- A sustainable quantitative analysis, such as an LCA and LCCA, should be incorporated when developing a country energy road map. These approaches will assist policymakers in identifying the best renewable sources composition in a targeted energy mix.
- National energy policy should offer a long-term energy mix and allocate a strategic potential renewable energy portion, especially solar PV, based on the advancement of technologies and the area of installation with lower GHG emissions and investment (e.g., BAPV or BIPV systems in urban areas).
- Training and guidelines on sustainable energy approaches and implications to assess the lifetime of project impacts should be developed by policymakers and financial bodies.
- Policymakers should consider affordable clean energy for all levels of society to realise energy transition. Programmes and strategies should be introduced, especially at the household level, to promote and to deploy renewable energy in daily life to expedite the market and cost of solar modules.
- The ASEAN supply chain of renewable energy equipment and services should be strengthened to reduce the cost of solar PV systems and LCOE. Modules and BOS are the major cost of solar PV systems.
- Economic incentives and financial policy instruments, similar to exemptions of value-added tax (VAT), imports, income taxes, export obligations, native taxes,

carbon taxes, and accelerated depreciation, would decrease the upfront cost of solar PV systems.

- Additional incentives should be provided for large-scale solar farms with the integration of modern agriculture. PV technology combined with agriculture not only realises energy savings and environmental protection due to lower GHG emissions but also promotes the transformation of traditional agriculture to modern sustainable practices.

Overall, the ASEAN region holds great promise to scale up renewable energy deployment over the coming decades. Enabling environments, which include comprehensive policy frameworks, fiscal incentives, strong targets, and robust institutions, is necessary to attract private investment and to accelerate the deployment of cost-effective renewable energy solutions across various sectors. To meet regional deployment targets, renewables are needed for on- and off-grid electricity, transport, heating, cooling, and cooking applications. The current patchwork of policies across these diverse markets shows that ASEAN member countries are taking important initial steps, but ample opportunities remain for improving their overall renewable energy policies and regulatory environments.

Acknowledgements The authors would like to acknowledge the publication support and expertise from the Economic Research Institute for ASEAN and East Asia (ERIA).

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Chapter 13
Understanding Quality Energy-Related Infrastructure Development in the Mekong Subregion: Key Drivers and Policy Implications

Han Phoumin, Sopheak Meas, and Hatda Pich An

Abstract Many players have supported infrastructure development in the Mekong Subregion, bridging the missing links in Southeast Asia. While the influx of energy-related infrastructure development investments to the region has improved the livelihoods of millions of people on the one hand, it has brought about a myriad of challenges to the wider region in guiding investments for quality infrastructure and for promoting a low-carbon economy, and energy access and affordability, on the other hand. Besides reviewing key regional initiatives for infrastructure investment and development, this paper examines energy demand and supply, and forecasts energy consumption in the subregion during 2017–2050 using energy modelling scenario analysis. The study found that to satisfy growing energy demand in the subregion, huge power generation infrastructure investment, estimated at around $190 billion–$220 billion, is necessary between 2017 and 2050 and that such an investment will need to be guided by appropriate policy. We argue that without redesigning energy policy towards high-quality energy infrastructure, it is very likely that the increasing use of coal upon which the region greatly depends will lead to the widespread construction of coal-fired power plants, which could result in increased greenhouse gas and carbon dioxide emissions.

Keywords Connectivity · Energy infrastructure · Fossil fuels · Emissions · Mekong subregion

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H. Phoumin et al. (eds.), *Energy Sustainability and Climate Change in ASEAN*, Economics, Law, and Institutions in Asia Pacific,
https://doi.org/10.1007/978-981-16-2000-3_13

13.1 Introduction

The Mekong Subregion is linked by common energy challenges. There are challenges in maintaining economic growth and ensuring energy security, while curbing climate change and reducing air pollution. At the intersection of these challenges is the corresponding need to rapidly develop and deploy energy efficiency, low-emissions coal technology, and double the share of renewables in the energy mix towards more inclusive and sustainable growth, as the region's energy demand is expected to rise significantly over the next 30 years (Han 2020c). Such an increase is bringing both opportunities and challenges, including climate change, which is a result of fossil fuels. Despite significant progress in recent decades in terms of energy poverty alleviation, countries such as Cambodia and Myanmar are still struggling to provide energy access to their rural populations.

The coronavirus disease (COVID-19) pandemic is another major challenge of our time. It has caused a global economic downturn, with economic output set to contract by 2.5% in 2020. This economic impact has also brought about low energy demand in all sectors. As a result, daily global emission levels fell by 17% in the first quarter of 2020 (Han 2020a). However, as governments begin lifting restrictions and business activities resume, so too will the demand for energy. Economic recovery could see levels of carbon dioxide (CO_2) emissions bounce back very quickly. Indeed, global data from late May 2020 show record levels of CO_2 as countries started reopening their economies (2° Institute 2020). The post-COVID-19 economic recovery will drive increased energy demand, which emphasises the need to secure investment to fill infrastructure gaps.

Quality infrastructure, connectivity, and innovation are considered key for the region to ensure prosperity and sustainable development. In fact, fast connectivity—along with high-quality infrastructure and human resources development in the Southeast Asian region—has already resulted in opportunities for growth. These developments have also lifted living standards through income generation and employment opportunities. They have enabled the region to participate in the production network at different degrees and made it ready to benefit from the global value chain in the near future as improved connectivity attracts more investment, cuts logistics costs, and creates synergies and location advantages (Han 2018). The region is arguably fortunate to have different stakeholders supporting infrastructure improvement that has bridged the missing links in Southeast Asia. However, the influx of investment, particularly in energy infrastructure development, has raised questions about both sustainability and quality, as well as the identification of partners the region should prioritise working with to promote long-term development sustainability, quality, and innovation in the Mekong Subregion. This chapter aims to review and analyse major initiatives that drive energy-related infrastructure development in the subregion; conducts energy modelling and estimation for energy demand and supply in the subregion during 2017–2050; and, from there, draws key policy implications that guide high-quality, energy-related infrastructure development.

The chapter comprises seven sections. The second section discusses the study's approaches. The third section reviews regional platforms and initiatives for infrastructure development related to the Mekong Subregion by engaging relevant literature. The fourth section examines economic impacts brought by connectivity. The region's energy landscape, the required investment to meet the rising energy demand in the region for the foreseeable future, and the region's energy transition are discussed in the fifth and sixth sections. The final section concludes with policy implications.

13.2 The Study's Approach

This study employs several approaches to gathering data and information. Data on economic investment, in particular energy for the Mekong Subregion, are available in different forms and for time periods. The study relies on several past studies conducted by the Economic Research Institute for ASEAN and East Asia (ERIA) for the economic impacts brought by infrastructure connectivity in the Mekong Subregion. For project infrastructure investment, the study uses data and information from past projects and studies conducted by the Asian Development Bank (ADB). For the energy data and analysis, we conducted our own energy modelling and estimation for energy demand and supply for the Mekong Subregion. We also reviewed key regional initiatives for infrastructure investment and development platforms, such as quality infrastructure initiated by Japan at the G20 in Osaka; China's Belt and Road Initiative; the United States (US) Blue Dot Network (BDN); the Free and Open Indo-Pacific (FOIP); and other subregional initiatives, such as the Mekong River Commission, Lancang–Mekong Cooperation, and Mekong–Japan Cooperation.

Our analysis of the economic impacts brought by Mekong Subregion connectivity involves the quantitative assessment of existing and proposed infrastructure development up to 2030. The ERIA study on economic impact assessment employed a Geographical Simulation Model (GSM), which was developed to track the progress on quality infrastructure development in the Association of Southeast Asian Nations (ASEAN) and East Asia. Jointly developed by the ERIA and the Institute of Developing Economies in 2007, the model calculates the proposed infrastructure-related projects for connectivity and innovation and includes a sophisticated level of information on infrastructure development status to facilitate any assessment.

For energy demand and supply in the Mekong Subregion, we employ energy modelling using the Long-Range Energy Alternative Planning System (LEAP) software, an accounting system used to develop projections of energy balance tables based on final energy consumption and energy input and output in the transformation sector. Final energy consumption is forecast using energy demand equations by energy and sector and future macroeconomic assumptions. For consistency, the historical energy data in the Mekong Subregion used in this analysis came from the energy balances of the International Energy Agency (IEA) for the Organisation for Economic Co-operation and Development (OECD) and non-OECD countries (IEA

2019). Energy demand and supply has two scenarios: the business-as-usual (BAU) scenario, reflecting each country's current goals, action plans, and policies; and the alternative policy scenario (APS), which includes additional goals, action plans, and policies that countries could achieve with their best efforts given energy policy reforms and technological development. The APS consists of assumptions such as more efficient final energy consumption, more efficient thermal power generation, and higher consumption of new and renewable energy and biofuels.

The study also quantifies the required investment for power generation demand from 2017 to 2050, using the following formula:

$$Investment(i) = GenCapacity(i) \times Unit\,Cost(\$/\mathrm{GW})$$

$$GenCapacity(i) = \frac{GWh(i)}{\left[24\,\mathrm{h} \times 365\,\mathrm{days} \times CapF(i)\right]}$$

where *(i)* is the fuel type, such as coal, gas, hydropower, and renewables; *investment (i)* is the required investment amount of fuel type *(i)*; *GenCapacity (i)* is the generation capacity of fuel type *(i)* in gigawatts; and *CapF(i)* is the capacity factor of fuel type *(i)*.

The study does not consider other required investments in the power grid or connectivity costs. It only estimates the required generation to meet the growing demand from 2017 to 2050.

13.3 Review on Regional Initiatives for Infrastructure Development

13.3.1 Initiatives for Quality Infrastructure

The region is arguably very fortunate to have different stakeholders supporting infrastructure improvement in a manner that bridges the missing links in the wider ASEAN region. But quality is far more critical than quantity if the region is to develop sustainably. The region and particularly ASEAN, therefore, should focus on key development partners that promote long-term development sustainability, especially those that promote quality infrastructure, build responsible human resources, and bring new knowledge and innovation to the region. Some of the key players driving quality infrastructure in Southeast Asia are briefly discussed below.

13.3.1.1 G20 Principles for Quality Infrastructure Investment

Japan has been pioneering and promoting quality infrastructure for many years to empower Asia as a growth centre to drive the global economy. Most importantly, at the G20 in Osaka in June 2019, Japan successfully launched an initiative, known as the G20 Principles for Quality Infrastructure Investment, as a key to promoting investment for sustainable development. According to the Ministry of Finance, Japan (2019), the principles took into account many aspects of sustainability to ensure that quality infrastructure is in harmony with local environments, communities, and people's livelihoods through generating local employment and facilitating technology transfer. So far, Japan has committed $110 billion for quality infrastructure in Asia from 2015 to 2020 (Han 2020b). Such a commitment will accelerate financial resource mobilisation into the region from private companies around the globe. This is in line with Japan's global commitment to promote high-quality infrastructure investment to address sustainable economic growth and reduce poverty and disparity.

Japan's promotion of quality infrastructure in Southeast Asia can be seen in the country's efforts to enhance ASEAN's connectivity through core land and maritime corridors and soft infrastructure development. The land corridors are high-quality hard infrastructure developments. They connect the South China Sea and the Indian Ocean; develop the Southern Economic Corridor that connects Ho Chi Minh City, Phnom Penh, Bangkok, and Dawei; and establish the East–West Economic Corridor (EWEC) that extends from Da Nang to Mawlamyaing in Myanmar as a trading centre and seaport, connecting Southeast Asia to India and beyond. Another hard infrastructure development is the Maritime Economic Corridor, which consolidates connectivity through the development of port and port-associated industries as well as energy and information and communication technology networks, in major cities. This allows the Mekong Subregion to connect to Brunei Darussalam, Indonesia, Malaysia, the Philippines, and Singapore, thus enhancing connectivity across ASEAN.

13.3.1.2 Belt and Road Initiative

In recent years, China has also invested enormously in Asian infrastructure through its Belt and Road Initiative (BRI). The BRI is a major Chinese strategy aiming to push China's economic links to Southeast Asia, South Asia, Central Asia, Pacific Oceania, Africa, and the Baltic region (Central and Eastern Europe) through various infrastructure and development projects (Yu 2017). The BRI has been officially renamed several times since 2013 when Chinese President Xi Jinping announced the policy. It was previously called One Belt, One Road; the Silk Road Economic Belt; and the 21st-Century Maritime Silk Road. The policy was more fully articulated in 2015 as a vision statement, and numerous supporting policy documents have since been produced to support the implementation of the vision statement.

The BRI is expected to involve over $1 trillion in investments, largely in infrastructure development, for ports, roads, railways, and airports, as well as power plants and telecommunications networks (OECD 2018). Financing sources will include those typical of Chinese overseas investments, such as Chinese banks (commercial and policy), bonds, state-owned enterprises, private Chinese equity, private/public partnerships, the Asian Infrastructure Investment Bank, and others. However, it is expected that Chinese banks will continue to be the main source of financing for

Chinese overseas projects, including those along BRI routes. Numerous projects have been proposed or are already in development. According to data from the Ministry of Commerce, China (2016), from January to August 2016, Chinese companies signed almost 4000 project contracts in 61 countries. The value of these projects amounted to close to $70 billion.[1]

There are growing concerns from recent experiences of BRI megaprojects that have come under a host of criticism. There is fear that the BRI could be a *debt trap* due to the high interest rates associated with some of the BRI's projects, as in the notorious case of Sri Lanka's Hambantota Port (Abi-Habib 2018; Geraci 2020; Sultana 2016). There are concerns that projects under the BRI are not transparent and that the BRI itself will be damaging to the environment (Russel and Berger 2019) because it does not offer explicit guidelines on how Chinese investors should regard environmental protection or civil society (Friends of the Earth US 2016). There is also fear that the BRI is modern *Chinese colonialism*, often taking as an example the Chinese presence in Africa, and connecting to the long-standing *yellow peril* phobia (see, for example, Grammaticas (2012) and Wu (2013). There is another fear that, despite its effectiveness in relation to construction speed (Sultana 2016), the projects under the BRI are not sustainable but are the cause of environmental and social issues (OECD 2018). China's official responses have been mostly on the defensive, trying to delink the BRI from geopolitical or hegemonic ambitions, arguing that BRI projects 'benefit the local population' and are opportunities for 'shared development' (see, for example, Cheong (2019)).

The BRI is considered as a second wave of Chinese overseas investment and should be seen as a renewed version of the Chinese policy, also known as China's 'Go Global' strategy (Friends of the Earth US 2016). This policy was the first to call on Chinese enterprises and industries to 'go out' and invest abroad. It is also seen as the key driver to advance China's interests overseas, and demonstrates its growing influence as a rule-shaper in the economic governance of the region and beyond (Yu 2017), something that countries in the Mekong Subregion need to deal with carefully. However, if the BRI is to be successful, the Principles for Quality Infrastructure Investment initiative will need to be considered in all infrastructure investments, and local communities developing BRI projects will have to play an active role. In addition, host-country stakeholders will need to improve the quality of their governance systems.

13.3.1.3 Blue Dot Network

In November 2019, the US, Australia, and Japan came together to establish what is now known as a trilateral BDN to help develop and promote quality infrastructure in

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[1] Data on BRI investments are known to vary, particularly since it is unclear if existing projects are retroactively categorised by the Chinese government as BRI investments. This figure from the Ministry of Commerce is considered official.

the Indo-Pacific region and around the world. Focusing on transparency and sustainability, the BDN aims to set a standard of excellence in infrastructure development. Hansbrough (2020) argued that the BDN is primarily a vision of what global infrastructure should look like. In the eyes of many observers, the BDN is also seen as an alternative to China's BRI, or a counter to the rising debt traps and low-quality infrastructure that boost quantitative and non-transparent aspects of the projects [see, for example, Geraci (2020), Panda (2020), Lyn (2020), McCawley (2019), Heydarian (2020)].

According to the US Department of State (n.d.), the BDN is a multi-stakeholder initiative seeking to bring together governments, the private sector, and civil society to encourage the adoption of trusted standards for quality global infrastructure development in an open and inclusive framework. It also encourages responsible construction and lending practices through international norms. Infrastructure projects have to follow the G20 Principles for Quality Infrastructure Investment, aimed at sustainable lending and borrowing; the G7 Charlevoix Commitment on Innovative Financing for Development; and the Equator Principles, which mandate financial institutions to assess and manage environmental and social risks in a given project. Projects that aim for certification under the BDN will have to give an undertaking that they adhere to these principles. The undertaking will then be scrutinised. Certification by the BDN means that a project is high-quality and has transparent origins, much like an 'organic' label for produce. Likewise, a country that agrees to follow BDN standards signifies that its government values high-quality infrastructure that benefits local communities.

The BDN plans to certify projects around the world (whose investment totals an estimated $94 trillion) that meet high-quality infrastructure standard over the next 2 decades (Kuo 2020). This will meet the projected infrastructure investment need identified by ADB (2017) up to 2040. In Asia alone, the investment will require some $26 trillion from 2016 to 2030, or $1.7 trillion per year, if the region is to maintain its growth momentum, eradicate poverty, and respond to climate change (ADB 2017).

The BDN looks promising for the Mekong Subregion and for the world, as it seeks to build the robust, resilient infrastructure essential to a country's growth and its people's well-being (Basol and Basar 2020). But this remains to be seen. The initiative has not been fully fleshed out and project financing facilities are amongst the many details that have to be clarified (McCawley 2019; Kuo 2020).

13.3.1.4 Free and Open Indo-Pacific

The region has also witnessed another initiative called the FOIP, as a mechanism complementary to other initiatives for infrastructure investment. In Japan, former Prime Minister Shinzo Abe unveiled the FOIP concept in August 2006, just before his first term as Japan's leader, and formally laid it down as a strategy in 2016 (Satake 2019; Szechenyi and Hosoya 2019). In late 2017, the US also launched a new FOIP (Arase 2019), but it was not until 2019 that the concept was actually formalised (US Department of State 2019).

Extending from Japan in the east to India in the west, the FOIP involves middle and major powers such as Japan, the US, Australia, and India; and other regional partners. It seeks to build a vision for Asia established around the concept of a strong coalition of like-minded regional democracies. However, a host of scholars and analysts have viewed the FOIP as a mechanism that provides the region with alternatives to China's BRI (Berkofsky 2018; Brewster 2018; Maslow 2018; Herberg 2020) or for countering China's influence (Berkofsky 2018; Ford 2020; Kawashima 2020; Swaine 2018; Valencia 2018). The Government of Japan, nevertheless, views this differently. The FOIP is an inclusive concept that ultimately aims to incorporate China and other powers in an inclusive political and economic system in the Indo-Pacific (Satake 2019). It is also a comprehensive framework or vision for Japanese regional policies, mostly its economic and development cooperation, such as infrastructure development and support for regional connectivity (Ministry of Foreign Affairs, Japan 2016, 2017; Editorial Desk of the *Gaiko* (*Diplomacy*) 2018).

Despite different views, the Mekong countries welcomed the FOIP. For example, they welcomed Japan's commitment to support their efforts made in line with ASEAN's Outlook on the Indo-Pacific (Ministry of Foreign Affairs, Japan, 2017, 2019). Perhaps they saw this as another option for quality infrastructure projects. As Swaine (2018) argued, infrastructure development initiatives under the FOIP could prove instrumental for both engaging and challenging China by advancing common principles for economic development and enabling developing countries to choose their own economic paths free from coercion. In this respect, the cooperative and competitive elements of the China challenge could merge as the allies pursue dialogue with Beijing on rules and norms while attempting to dilute its influence.

13.3.1.5 The Mekong River Commission

The Mekong River Commission (MRC) is another key driving force behind quality energy infrastructure development in the region. As the only treaty-based river basin organisation in the region, the 25-year-old MRC has put in place two crucial strategies to guide its four member countries—Cambodia, the Lao People's Democratic Republic (Lao PDR), Thailand, and Viet Nam—in assessing and developing hydropower projects in the Lower Mekong Basin (LMB) to optimise transboundary benefits while minimising adverse cross-national impacts.

One of them is the basin-wide Sustainable Hydropower Development Strategy (SHDS) for the LMB adopted in 2001 by the MRC Council of Ministers, the organisation's highest governing body. The SHDS recognises that while each member country has the full responsibility and right to plan and implement hydropower projects nationally, the MRC is tasked with striking a balance between regional and basin needs, and economic development and environmental protection (MRC 2016). The SHDS thus sets out strategic priorities and actions at the basin level to address hydropower opportunities and risks, and strengthens basin-wide cooperation and sustainable development (MRC 2001). It also draws a close linkage between the energy and water sectors because the need for linked planning between the energy and water sectors is now more critical than ever before in the Mekong Region.

The Preliminary Design Guidance for Proposed Mainstream Dams in the LMB is another key strategic guidance resource. Adopted in 2009, it provides performance targets and principles for the design and operation of mainstream dams to help avoid, minimise, and mitigate harmful effects and limit the potential for substantial damage (MRC 2009). It seeks to establish a common design and operational approach, aiming to meet common objectives and mitigate commonly understood risks, and making it possible for developers to plan for and undertake the assessments and designs for mitigation and management measures as early as possible in the project cycle.

However, both documents are ageing and need to be revisited. With rapid development in the basin, especially in the hydropower sector, it is important that the documents are updated, taking into account major changes the basin has faced over the last two decades. Studies by the MRC (MRC 2018, 2019, 2020; MRC/Basist and Williams 2020) and others (Kummu and Varis 2007; Kondolf et al. 2014; Kuenzer et al. 2013) have indicated that hydropower dams constructed on the mainstream in the upper part in China where the river is called the Lancang and on the lower reaches where the river is called the Mekong and on tributaries in the LMB had changed the natural flow regime of the river, yielding both opportunities and risks on hydropower development now and in the future. Gathering the significant economic and greenhouse gas (GHG) reduction benefits offered through hydropower development should not come at the expense of the unique and abundant ecosystem services and biodiversity on which so many communities in the basin depend. Besides, although the MRC has a critical role to play in water diplomacy and energy infrastructure development in the region, this and its wider role have not received sufficient credit (Kittikhoun and Staubli 2018). Thus, the Mekong River Commission (MRC) needs to evolve, and its founding member countries need to empower it further if the Mekong River is to develop sustainably and responsibly (Sok et al. 2019; An et al. 2020).

13.3.1.6 Lancang–Mekong Cooperation

The Lancang–Mekong Cooperation (LMC), despite its relatively young age, is one of the most rapidly progressive and notable platforms in the Mekong Subregion. In 2012, Thailand proposed an initiative for sustainable development of the Mekong Subregion, which received a positive response from China. At the 17th China–ASEAN Summit held in November 2014, Chinese Premier Li Keqiang proposed the establishment of the LMC Framework, which was welcomed by the other five Mekong countries. In March 2016, China and the other five Mekong countries held their first LMC Leaders' Meeting, which released the Sanya Declaration and officially launched the LMC mechanism (LMC 2017).

Although the LMC seeks to promote many aspects of cooperation on security, economic, cultural, agriculture, and poverty reduction issues (LMC 2017; Gong 2020; Zhang and Li 2020), the major driving force is seen through its emphasis on infrastructure development for the region. Some of the major examples are

Myanmar's Kyaukpyu Port and gas pipeline, the Lao PDR and Thailand's high-speed railway projects, Cambodia's irrigation systems and transport infrastructure, and more plans to develop better capacity for navigation along the Mekong River (Busbarat 2018).

As a subregional cooperation mechanism connecting the six countries along the Mekong River, the LMC has seen China emerge as a willing investor and guarantor as part of its wider BRI. While a comprehensive list of LMC projects is not publicly available, the LMC has provided financial support for at least 132 projects in the Mekong Region as of 2018 (The ASEAN Post 2019). During the LMC Ministerial Meeting in 2019, the LMC proposed a further 101 projects, all of which were considered fast-track—to be carried out in 1 year or less—in the six Mekong countries (LMC 2019b) to respond to 'socio-economic demands and water related challenges' (LMC 2019a: 2). The LMC, like the BRI, is often promoted as an effective platform that offers countries in the Mekong Subregion the resources they need for development (see, for example, Liena et al. (2018); Qingrun (2018); Xinhau (2020a; b); Xing (2017)).

Critics, however, have voiced strongly that China is using the LMC to build its regional strategic influence and that the LMC per se does not promote good governance. China's strong interest in driving the development of the LMC stemmed from gaining substantial control over the Mekong Subregion, delimiting the influence of external actors such as the US and Japan, and pushing forward its neighbourhood diplomacy (Biba 2018; Middleton and Allouche 2016). While the LMC can be a building block for stronger regional multilateralism, it can also work against the advancement of broader ASEAN regional cooperation and marginalise other Mekong Subregion bodies (Busbarat 2018). Amongst all the seemingly unchecked development that has flourished as a result of the LMC, perhaps none has had such an impact on local communities and the environment as the dams that have sprouted up across the region, where China has taken the role of developer or funding agency (The ASEAN Post 2019). While Chinese investment in infrastructure development through the LMC is a welcome source of capital for Mekong countries, Southeast Asia should approach it more critically to avoid development that later becomes a debt trap, does not last, and only benefits the few.

13.3.1.7 Mekong–Japan Cooperation

Mekong–Japan connectivity is another important dimension for the Mekong Region. It aims to promote infrastructure development in the region and to enhance institutional connectivity through the improvement of systems, development of Special Economic Zones (SEZs) and other industrial bases, industrial promotion measures, improvement of customs procedures, and people-to-people connectivity to ensure that the whole region benefits from growth (Verbiest 2013). Key pillars of cooperation in the development of infrastructure are to fill the missing links of the East–West and Southern Economic Corridors. Once the links are filled, they will connect the corridors more smoothly through the improvement of systems such as customs procedures; they will also promote land development along the corridors (e.g. the development of industrial parks, industrial promotion measures, and so on) and improve access from neighbouring areas to corridors so that the region can develop as a whole. Finally, they will help to promote the development of industrial human resources that will support growth in the region and strengthen people-to-people networks.

It can be argued that the Mekong Subregion has benefited significantly from the infrastructure improvement brought by official development assistance support from Japan, with high-quality roads, bridges, and other hard and soft infrastructure.

13.4 The Economic Impacts of Connectivity and Infrastructure Investment

13.4.1 The Economic Impacts of Connectivity in the Mekong Subregion

The coordinated development of soft and hard infrastructure is also essential to maintain growth in the region. The new international division of labour calls for a novel approach to infrastructure development, in which the Mekong Subregion is prepared to participate actively in the promotion of economic corridors: the Southern Economic Corridor, the EWEC, and the North–South Economic Corridor. These economic corridors—together with the fast acceleration of domestic infrastructure development including SEZ, urban amenities, and other economic activities—have already promoted regional participation in the production network by reducing the cost of service links that connect remote locations. Mekong Subregion connectivity is just one piece of the puzzle in ASEAN connectivity with the rest of the world. China's BRI is another very large 'connectivity for development' strategy, linking China to Eurasian countries and the rest of Asia.

As the region embarks on rapid infrastructure development, quality infrastructure, connectivity, and innovation are key to ensure prosperity and sustainable development. Infrastructure development and stages of economic development can be explained by the development of recent economic theories: fragmentation theory and new economic geography (ERIA 2015). The theory classifies infrastructure projects into three tiers. Tier 1 includes projects that serve countries/regions that are already in production networks and have started forming industrial agglomerations. Tier 2 consists of projects supporting countries/regions that are about to participate in production networks. Tier 3 is comprised of projects in remote areas where participation in production networks is difficult in the short run, but where better and more reliable connectivity can generate new business models in agriculture, mining, tourism, and other industries. Thus, the ultimate aim of quality infrastructure and services development is in tier 1, in which some ASEAN Member States are experiencing and enjoying quality growth, particularly Singapore and to some extent Brunei

Darussalam. Malaysia and Thailand are also doing well, with the quality of infrastructure in tier 2 possibly moving to tier 1 in the near future. The Mekong Subregion has achieved lower middle-income status, improving infrastructure quality from tier 3 and possibly joining tier 2 in the near future. Indonesia and the Philippines have achieved middle-income status and infrastructure development is in the early stage of tier 2, likely catching Malaysia and Thailand in the near future.

By and large, connectivity and innovation promote agglomeration forces and dispersion forces generated by production–consumption interactions in both internal and external economies in which people and ideas can move easily. Agglomeration forces mean that economic activities and people are attracted to the core, where positive agglomeration effects are found in the form of the ease of finding business partners and proximity to the market, etc. On the other hand, dispersion forces generate movements of economic activities and people from the core to the periphery. One source of dispersion forces is negative agglomeration effects or 'congestion' in the core, which includes wage increases, land price hikes, traffic congestion, and environmental pollution (ERIA 2015).

One practical example of new economic geography creating 'location advantages' through connectivity and innovation is Cambodian labour force migration. Currently, about 1 million (out of a population of 16 million) Cambodians are in Thailand working in unskilled labour-intensive sectors and the informal sector rather than in Phnom Penh. The question is: How can Phnom Penh attract labour from rural areas and, at the same time, attract production blocks from Thailand? If the wage gap between Bangkok and Phnom Penh is too large, people will not move to Phnom Penh; however, at the same time, production blocks may be motivated to move. On the other hand, if the wage gap is too small, production blocks will not move even though people may flow into Phnom Penh. Then, how can Phnom Penh attract both production blocks and people? The answer is the improvement of location advantages and liveability in Phnom Penh.

Another example is the Mekong–India Economic Corridor (MIEC)/EWEC connecting Ho Chi Minh (HCM) City, Phnom Penh, Bangkok Metropolitan Area, and Dawei. This has great potential to become a major manufacturing corridor in the near future. However, the question is how to attract labour and investment to Dawei. In this regard, the MIEC will need to have at least three projects implemented at the same time—industrial estates, highway connection to Thailand, and a deep seaport. According to Han (2018), the road situation between Phnom Penh and HCM City was relatively bad in 1999. Before the road was upgraded, travel time from Phnom Penh to HCM City was about 9–10 h, and cross-border trade at Moc Bai (Viet Nam)–Bavet (Cambodia) was worth about $10 million per year. However, the situation was completely changed in 2014 after both hardware and software infrastructure were implemented between Phnom Penh and HCM City. The travel time was reduced to 5–6 h, and cross-border trade at Moc Bai–Bavet grew to $708 million per year (ERIA 2015). Further, connectivity promoted other economic development corridors, such as investment brought to Trang Bang Industrial Park (in Moc Bai), consisting of 41 projects with $270 million in new investment, creating about 3000 jobs.

The top 10 beneficiaries from the MIEC, based on ERIA (2015), are Dawei, Phnom Penh, Dong Nai, Kawthoung, HCM City, Kandal, Sihanoukville, Banteay Meanchey, Svay Rieng, and Battambang. For Phnom Penh, it was estimated that the connectivity would increase gross domestic product (GDP) by almost 400% as a cumulative impact over 2021–2030. ERIA also estimated the remainder of the economic corridor in the Mekong Subregion, and found significant impacts for all participating countries in the connectivity.

For power connectivity in the Greater Mekong Subregion (GMS), ERIA's study on energy markets in ASEAN and East Asia examined the power trade and development in the subregion for the foreseeable future (Han and Kimura 2014). The study showed that the 2030 Scenario (in which the GMS realises the potential of hydropower) will provide both economic and environmental benefits. The GMS at large will benefit by about \$40 billion and reduce CO_2 emissions by almost 70 million tons per year. For ASEAN power connectivity as a whole, the study estimated that ASEAN would save \$25 billion over 20 years by substituting hydropower for fossil fuels.

13.4.2 Infrastructure Investment Projects in the Mekong Subregion

The GMS regional investment framework, 2014–2022 (RIF 2022) pipeline projects consist of 143 investment projects requiring \$65.7 billion and 84 technical assistance projects requiring \$295 million (GMS Secretariat 2019). Of the total 227 prioritised projects, which require investment of about \$66 billion, there are financing gaps for 121 projects amounting to \$27 billion (about 40% of the total investment). Of the projects currently identified with available financing, 70% have government financing, 18% have ADB financing, 6% have financing through other development partners, and 6% have private sector investment or public–private partnerships.

Regional investment framework 2022 summary by sector

Sector	Number of projects			Cost estimates (\$ million)		
	Investment	TA	Total	Investment	TA	Total
Transport	85	12	97	55,753	10	55,763
Energy	11	8	19	2230	15	2245
Agriculture	9	10	19	1695	96	1791
Environment	3	4	7	560	13	573
Health and other HRD	4	7	11	702	22	724
Urban development	7	6	13	1147	10	1157
Others/BEZ	6	6	12	2085	8	2093
Tourism	12	17	29	1430	83	1513
TTF	3	9	12	91	17	108

(continued)

(continued)

Sector	Number of projects			Cost estimates ($ million)		
	Investment	TA	Total	Investment	TA	Total
ICT	3	5	8	28	22	50
Total	**143**	**84**	**227**	**65,722**	**296**	**66,017**

BEZ = border economic zone, HRD = human resources development, ICT = information and communication technology, TA = technical assistance, TTF = transport and trade facilitation
Source ADB (2019)

The RIF 2022 is heavily skewed towards transportation sector projects, as the table shows. However, inter-sectoral linkages, such as tourism supported through transport networks, are more prominent in the RIF 2022. Furthermore, there is an increase in transportation subsectors, with new projects in ports and waterways, logistics, and border crossing, which were missing or underrepresented in earlier pipelines. Railway infrastructure, because of its greenfield nature and extensive civil works, continues to make up the bulk of the required investment costs in the RIF 2022. Some railway projects have commenced, with domestic budgets and bilateral assistance from China. The GMS Railway Association is assessing which railway lines to prioritise for the subregion and examining alternative modalities to address the vast financing needs for rail infrastructure (GMS Secretariat 2019; ADB 2016). In addition to projects in new transport subsectors in the RIF 2022, projects in border area or border zone development involve multisectoral interventions such as road and/or border infrastructure, trade facilitation, technical and vocational education and training, schools, urban infrastructure, and tourism. The GMS Tourism Infrastructure for Inclusive Growth projects also take this multisectoral approach.

Of the total transport sector investment projects, as shown in the table, railways took 62% of the total (about $35 billion investment in the RIF 2022), followed by roads and bridges at 36% (about $20 billion). If the railway, road, and bridge projects under construction and potential new projects are realised in the near future, the GMS will be a region of connectivity by rail and road, which will play out very well for connectivity to Malaysia and Singapore. Thus, the flows of goods and services could see potential increases in volume, positively affecting economic growth in the region.

13.5 Energy Landscape in the Mekong Subregion

13.5.1 Energy Supply in the Mekong Subregion

The total primary energy supply (TPES) in the Mekong Subregion (Cambodia, the Lao PDR, Myanmar, Thailand, and Viet Nam) is projected to increase by 189% in the BAU scenario, and by 121% in the APS from 2017 to 2050. In actual amounts, it will increase from 234 million tonnes of oil equivalent (Mtoe) in 2017 to 675 Mtoe in the BAU scenario, and to 516 Mtoe in the APS by 2050. It is observed that the

Mekong Subregion is heavily dependent on fossil fuel consumption (oil, coal, and gas). Based on the baseline data in 2017, the fossil fuel share in the energy supply is around 75% of the total in the Mekong Subregion. It is projected that the Mekong Subregion will see growing dependency on fossil fuels in the future. In this regard, the study results showed that by 2050, the share of fossil fuels in the energy supply will be about 88% in the BAU scenario and 81% in the APS. In actual amounts, the combined coal, oil, and gas in the energy supply is expected to increase from 175 Mtoe in 2017 to 595 Mtoe in the BAU scenario and to 420 Mtoe in the APS in 2050. Oil is the dominant energy source in the energy supply, followed by natural gas and coal (Fig. 13.1). Oil is expected to increase from 74 Mtoe in 2017 to 255 Mtoe for the BAU scenario and to 197 Mtoe for the APS in 2050. Natural gas is expected to increase from 49.3 Mtoe in 2017 to 184.3 Mtoe for the BAU scenario and to 133.6 Mtoe for the APS in 2050. Coal will increase from 51.6 Mtoe to 155.8 Mtoe for the BAU scenario and to 89.3 Mtoe for the APS in 2050. Other sectors, including biomass, wind, solar, and electricity, will see increases from 58.8 Mtoe in 2017 to 80.0 Mtoe for the BAU scenario and to 96.5 Mtoe for the APS in 2050.

The difference between the BAU scenario and the APS is the energy saving potential in the TPES. Coal will see the largest energy saving, with potential of 42.7%, followed by 27.5% for natural gas and 22.7% for oil. These large energy savings are expected from the implementation of energy efficiencies, with improved efficiency in thermal power plants and energy efficiency in end-use sectors such as

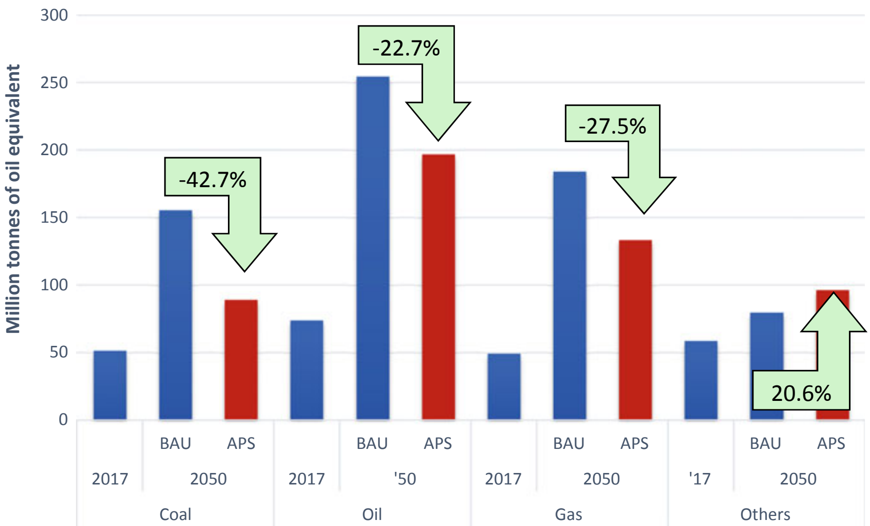

Fig. 13.1 TPES by energy source, BAU versus APS. APS = alternative policy scenario, BAU = business as usual, TPES = total primary energy supply. *Source*: Authors' calculations

transportation, industry, commercial, and residential sectors. The Mekong Subregion is expected to see an increase in renewables of about 20.6% in the energy supply mix by 2050 (Fig. 13.1).

13.5.2 Final Energy Consumption in the Mekong Subregion

In the total final energy consumption (TFEC), industry accounts for the largest share, followed by transportation, and other commercial and residential sectors, as Fig. 13.2 shows. Energy consumption in the industrial sector is expected to increase from 68 Mtoe in 2017 to 217 Mtoe for the BAU scenario and to 184 Mtoe for the APS by 2050. Energy consumption in the transport sector is predicted to increase from 48 Mtoe in 2017 to 160 Mtoe for the BAU scenario and to 104 Mtoe for the APS by 2050. For other sectors, including the commercial and residential sectors, energy consumption is expected to increase from 46 Mtoe in 2017 to 105 Mtoe for the BAU scenario and to 89 Mtoe for the APS by 2050. The non-energy sector (naphtha) is also used in the TFEC, especially for the refinery and petrochemical industries, with its use remaining the same for the BAU scenario and the APS in 2050.

Energy saving is expected to be highest for the transportation sector at 35.2%, 15.2% for the industrial sector, and 15.0% for the commercial and residential sectors, as indicated in Fig. 13.2. The reduction in energy consumption in the final energy sector will derive from fuel efficiencies in the transportation, industry, commercial, and residential sectors (e.g. the introduction of more efficient heat and power, a shift

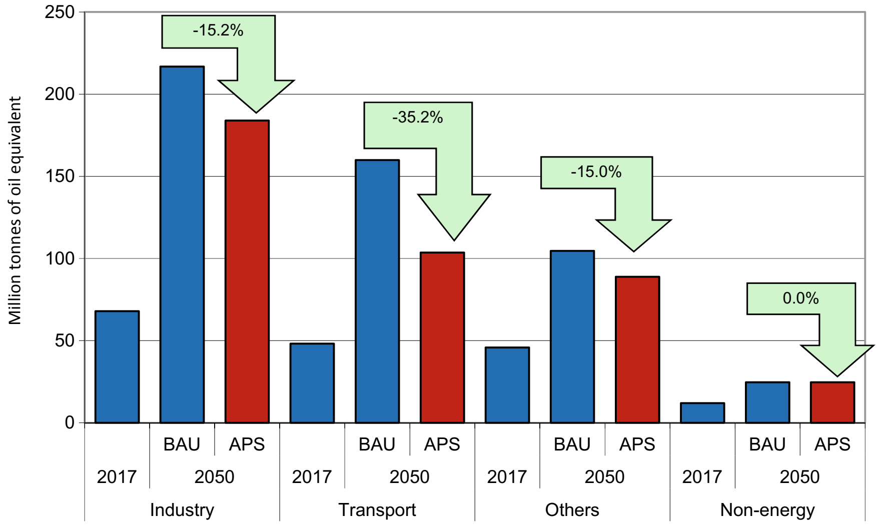

Fig. 13.2 TFEC by sector, BAU versus APS. APS = alternative policy scenario, BAU = business as usual, TFEC = total final energy consumption. *Source* Authors' calculations

to electric vehicles, hybrid and fuel cell vehicles, more efficient electric appliances, and energy-saving buildings).

13.5.3 Power Generation Mix in the Mekong Subregion

In the power sector, remarkable progress has been made in the subregion over the past 2 decades. This includes rural electrification access, rapid provision of large-scale and high-volume national grid systems, successful mobilisation of indigenous resources, the adoption of new technologies, the gradual share of renewables into energy mix, and the beginnings of cross-country trade. However, the future energy landscape in the Mekong Subregion will rely on today's actions/policies and investment to change course towards a cleaner energy system.

Natural gas is the dominant fuel source in power generation, followed by coal and hydropower, as Fig. 13.3 shows. Natural gas is expected to increase from 170.4 megawatt-hours (MWh) in 2017 to 798.7 MWh in 2050 in the BAU scenario and to 690.3 MWh in the APS by 2050. Electricity from coal-fired power generation will increase from 116 MWh in 2017 to 374 MWh in the BAU scenario and 150 MWh in the APS by 2050. Electricity from hydropower is expected to increase from 133 MWh in 2017 to 252 MWh in the BAU scenario and to 245 MWh in the APS by 2050.

Electricity from 'others' (including biomass, wind, and solar) will see a large increase from 6.2 MWh in 2017 to 87.2 MWh in the BAU scenario and to 172.4

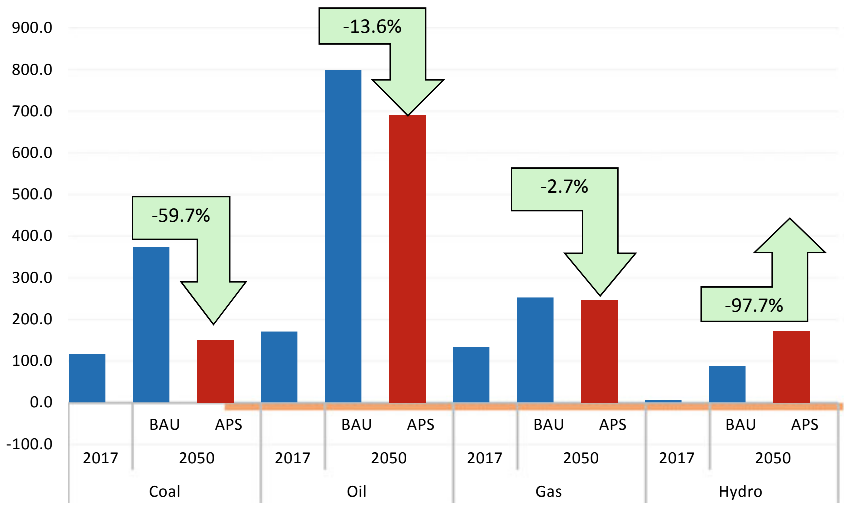

Fig. 13.3 Total power generation (TFEC) by energy source, BAU versus APS. APS = alternative policy scenario, BAU = business as usual, TFEC = total final energy consumption. *Source* Authors' calculations

MWh in the APS by 2050. Significant energy saving is expected in coal-fired power generation (59.7% saving, a reduction from BAU to the APS) followed by the gas combined cycle (13.6%). Energy saving in power generation is expected due to the introduction of high thermal efficiency. Electricity from renewables such as biomass, wind, and solar is expected to increase sharply by 97.7% due to upscaling renewables in the power mix in the APS scenario compared with the BAU scenario.

13.5.4 Required Power Generation Investment to Meet Rising Demand in the Mekong Subregion

To satisfy growing energy demand in the Mekong Subregion, huge power generation infrastructure investment is necessary from 2017 to 2050, as indicated in Fig. 13.4. This study estimates that $191–$217 billion will be needed for cumulative investment in power generation in coal, gas, and hydropower. The investment in natural gas combined cycle power generation will require $55–$67 billion for the BAU scenario and APS from 2017 to 2050. Coal-fired power generation will require around $59 billion in the BAU scenario. However, coal-fired power plant (CPP) capacity may be reduced in the APS, depending on the Mekong Subregion's energy policy. In this case, the estimate for coal-fired power investment could drop to about $8 billion from 2017 to 2050. For renewables such as solar photovoltaic (PV), wind, and biomass, the required investment is expected to increase from $37 billion in the BAU scenario to $76 billion in the APS. More broadly, at the ASEAN level, the *Energy Outlook* projects that $2.1 trillion will be required for oil, gas, coal, and power supply (IEA

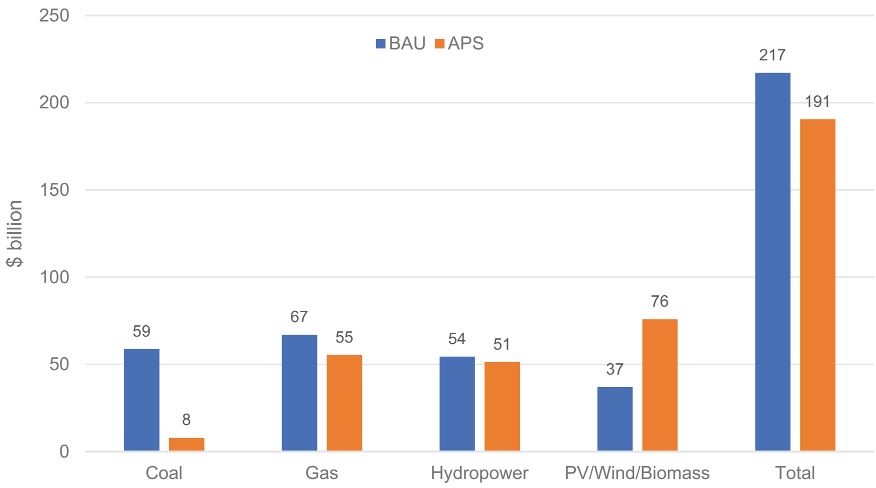

Fig. 13.4 Investment in power generation by energy source, BAU versus APS. APS = alternative policy scenario, BAU = business as usual, PV = photovoltaic. *Source* Authors' calculations

2017). More than 60% of investment goes to the power sector, with transmission and distribution accounting for more than half.

Thus, the huge potential for energy infrastructure related investment will need to be guided by the appropriate policy to promote quality infrastructure and resilience in the Mekong Subregion for growth and sustainability.

13.5.5 Carbon Dioxide Emissions in the Mekong Subregion

The region will continue to rely on fossil fuel consumption in the foreseeable future (Fig. 13.5). This is mainly because of the presence of the high combined share of fossil fuels in the power generation mix of the Mekong Subregion, at 67% in 2017 and 78% in the BAU scenario by 2050, as well as the high share of fossil fuel use in the TFEC. CO_2 emissions rose from 42 million tonnes of carbon equivalent (Mt-C) in 1990 to 127 Mt-C in 2017. CO_2 emissions are expected to rise to 457 Mt-C in the BAU scenario and to 318 Mt-C in the APS by 2050.

Thus, the clean use of fossil fuels through clean technology deployment is indispensable in decarbonising the Mekong Subregion's emissions, as also recently shown in a study by Han et al. (2020). Further, natural gas should be promoted as a transitional fuel to bridge towards more renewable energy in the future.

13.6 Energy Transition in the Mekong Subregion

The Mekong Subregion faces mounting challenges in matching its energy demand with sustainable energy supply. This is because the regional reliance on fossil fuel consumption is projected to last until 2050. The transition to a lower-carbon economy will require the region to develop and deploy greener energy sources and clean use of fossil fuels through innovative technology such as high-efficiency, low emissions (HELE) technologies. Coal-use patterns in the region reflect the rising demand for electricity to power and steer economic growth. Hence, building low-efficiency CPPs is an obvious choice for power-hungry emerging Southeast Asia due to lower capital costs. However, such plants cause more environmental harm and health issues due to air pollution, CO_2, and other GHG emissions. Widespread coal power plant construction could also point to the low environmental standards for coal-fired power generation in the Mekong Subregion (Mitsuru et al. 2017). The Mekong Subregion countries have relatively high allowable emissions in terms of sulphur oxides (SOx), nitrogen oxides (NOx), and particulate matter (PM) (Fig. 13.6). This means that countries in the subregion have lower emissions standards than advanced countries such as Germany, the Republic of Korea, and Japan, where clean coal technology (CCT) is mandatory.

Major harmful air pollutants, such as SOx, NOx, and PM, come from fossil fuel and biomass power plants, which therefore need to be carefully regulated. It is known

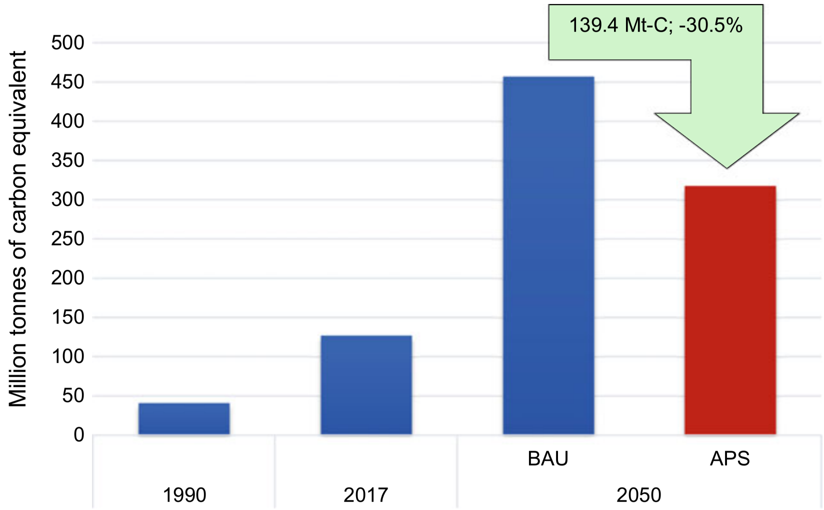

Fig. 13.5 CO_2 emissions in the Mekong subregion, BAU versus APS. APS = alternative policy scenario, BAU = business as usual, CO_2 = carbon dioxide, Mt-C = million tonnes of carbon equivalent. *Source* Authors' calculations

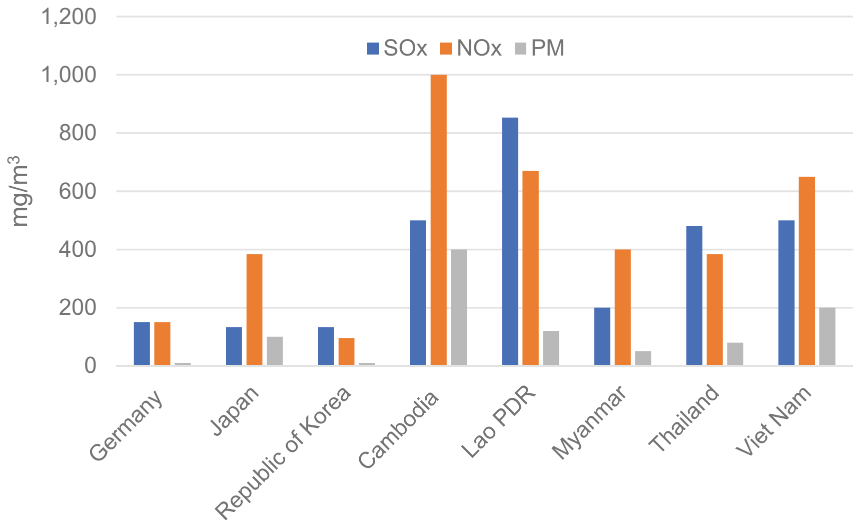

Fig. 13.6 Emissions standards for newly constructed CPPs in selected countries (SOx, NOx, and PM). CPP = coal-fired power plant, Lao PDR = Lao People's Democratic Republic, mg/m^3 = milligram per cubic metre, SOx = sulphur oxides, NOx = nitrogen oxides, PM = particulate matter. *Source* Mitsuru et al. (2017)

that short-term exposure to sulphur dioxide (SO_2) can harm the human respiratory system and make breathing difficult.

Thus, the Mekong Subregion's leaders may need to consider more strongly the promotion of CCT, higher standards or stringent environmental regulation for CPPs, and effective enforcement. This may push investors to select more advanced technologies, especially ultra-supercritical technology, for CPPs. Such plants are considered clean power because they use coal more efficiently and cleanly than traditional subcritical CPPs. Furthermore, supporting frameworks to ensure that developing countries can afford CCT are urgent because the up-front investment costs of CCTs are much higher than those of traditional CPP technologies.

The role of natural gas in the energy transition cannot be overlooked. This is because it can be used as a bridging fuel between high emissions fuels, such as coal and oil, to cleaner energy systems in which renewables and clean fuels take the major share in the energy supply mix. The prospects for using natural gas in the Mekong Subregion are good, with demand likely to quadruple depending on the future stability of gas and liquefied natural gas (LNG) prices in the market; whether a competitive gas/LNG market can be created in Southeast Asia; and the role of gas/LNG from Australia, the US, and other sources. The region is expected to be a key market for future gas demand, thus gas infrastructure investment, such as gas pipelines and LNG terminals, will be crucial in supporting the demand for gas in the region (Kobayashi and Han 2018).

In the current situation, hydropower accounts for quite a large share of the energy mix in the Mekong Subregion. However, as energy demand is expected to increase further, hydropower sources will be fully utilised. Thus, the share of renewables, such as wind, solar, and biomass, will play a critical role in the future clean energy system in the Mekong Subregion. The lower cost of these renewables will make it possible for a higher share of wind and solar in the energy mix (Denholm and Cochran 2015). Since electricity from wind and solar sources is variable and intermittent, there is a need to invest in grid infrastructure with smart grids, using the internet of things (IoT) and other technology to predict electricity production.

The Mekong Subregion may benefit greatly from the development of renewable hydrogen, as the region has large hydropower potential and the possibility of a higher share of solar and wind power (see Han et al. (2020)). Thus, electricity from wind and solar plus other unused electricity during low-demand hours should be converted to hydrogen as stored energy. Fast-moving technological development will drive down the cost of hydrogen production in the future and give hydrogen a bigger role in the clean energy future (IRENA 2019). Thus, the Mekong Subregion may need to prepare a roadmap for rolling out a hydrogen plan in the future.

13.7 Conclusions and Policy Implications

The Mekong Subregion's fast connectivity—including rail, road, port, aviation, and energy infrastructure—has integrated the region further in terms of compressing time and space for the movement of goods and services. However, the wider ASEAN region faces challenges in guiding investments for long-term sustainability, especially on quality infrastructure. In the region, key players channel their investments through regional and subregional initiatives and platforms such as China's BRI and LMC, the US BDN, the FOIP, the MRC, and Mekong–Japan Cooperation. Although there is a clear need for resilience and quality infrastructure in the Mekong Subregion, policy measures and actions undertaken in each country towards high-quality infrastructure vary, reflecting the differences in socio-economic, political, and geographical contexts. Thus, this makes it difficult for the region to promote sustainable growth and a low-carbon economy, energy access and affordability, and resilient and sustainable quality infrastructure.

As the Mekong Subregion continues to rely on fossil fuels, its energy transition will need to consider cleaner use through clean technology investment such as CCT and other high-quality energy infrastructure. Currently, investment in renewable energy and clean technologies is unstable and high in cost. These challenges need to be addressed through political commitment to ensure that an energy technology development and deployment support framework can scale up the share of renewables and clean fuels. Without redesigning energy policy towards high-quality energy infrastructure, it is very likely that the increasing use of coal will lead to the widespread construction of CPPs, which, without the employment of the best available CCT, will result in increased GHG and CO_2 emissions (Han 2020c; Han et al. 2020).

The investment opportunities for energy-related infrastructure are huge. This study estimates that around $190–$220 billion will be required from 2017 to 2050 for power generation alone. However, this estimate does not include the transmission and distribution network, LNG terminals, and refineries. The challenge will be to ensure quality infrastructure to promote sustainability in the region. Energy sustainability in the Mekong Subregion requires an increase in the share of renewables in the energy mix. Currently, it is dominated by coal, gas, and hydropower. Although intermittent renewables (solar and wind) comprise the most abundant energy resources in the region, they have so far taken a minimal share of the power mix.

Key Policy Implications

As this study has shown, what countries in the Mekong Subregion will need, as development accelerates and climate change intensifies, is an environmentally friendly, logistically feasible, and economically responsible alternative energy source and infrastructure. Derived from this study, the following key policy implications are provided with this consideration in mind.

First, the region will need to promote quality infrastructure investment. Given the region's vulnerability to climate change, resilient and high-quality infrastructure will play a key role in the region's long-term sustainability. Thus, regional and subregional platforms and initiatives such as the BRI, quality infrastructure by Japan, the BDN, and other subregional initiatives will need to promote high-quality infrastructure investment. For instance, the region should and will need to discuss the quality and standards that can guide investment to meet the need for high-quality infrastructure. Willingness to pay could be a barrier because of the high cost of quality infrastructure. Thus, a mechanism to reduce costs through innovative financing will be key for the successful deployment of high standards in the region.

Second, the current climate narrative and policy approach of banning coal use will need to be reviewed to assist emerging Asia to afford CCT. This is primarily because there are less available alternative energy options in the medium term to meet energy demand. Treating CCT as a technological solution in the energy transition will be a win–win solution for a climate-friendly world as Asia faces energy accessibility and affordability. Emerging Southeast Asia will rely on whatever CCTs are available in the market at affordable prices. The up-front costs of such ultra-supercritical technology or advanced ultra-supercritical technology are higher than supercritical and subcritical technologies. Thus, it is necessary to lower the up-front costs through policies such as attractive financial/loan schemes or a strong political institution to deliver public financing for CCTs in the region.

Third, there is a need for public consultation on and local participation in the potential impacts of any selected power plant infrastructure and technologies. However, for the Mekong Subregion, the government institutions have not emphasised such local participation strongly enough just yet. Thus, an active organisation or mechanism is needed to disseminate information on the potential harm resulting from less efficient CPPs.

Fourth, the region will see a rise in LNG imports to meet demand. Thus, the region's leaders will need to consider energy policy to increase the use of LNG in the future as a bridging fuel towards a clean energy future. Redesigning policy to promote LNG use will, to some extent, reduce coal use in the power mix. The countries in the Mekong Subregion should investigate the LNG infrastructure gap to develop policy to promote investment. This includes LNG terminals, pipelines, regasification plants, transportation, and storage.

Fifth, the region will need to prepare for a sharp increase in renewable energy from wind, solar, and biomass in the energy supply mix; and at the same time, promote the use of clean fuels and clean technologies. It will also need to look wider in terms of power grid connectivity. In this case, investment in 'hard' quality infrastructure will need to be connected to ASEAN.

Finally, the Mekong Subregion should boldly increase the portion of funding in the economic recovery package on green energy investment, as it will promote jobs, environmental protection, and social benefits for long-term sustainability. Governments and financial institutions may need to promote the financing of green projects through green bonds or other financial instruments. Of course, the region will also need to work on carbon credits in the future, as this will promote renewable and clean technology development.

Author Contributions Conceptualisation, P.H. and S.P.; methodology, P.H.; software, P.H; validation, P.H., S.P. and H.A.; formal analysis, H.P. and S.P.; investigation, H.P.; resources, H.P.; data curation, H.P.; writing—original draft preparation, H.P.; writing—review and editing, S.P., H.A. and H.P.; visualisation, H.P.; supervision, H.P.; project administration, H.P.; funding acquisition, H.P. All authors have read and agreed to the published version of the manuscript.

Funding This research received no external funding.

Conflicts of Interest The authors declare no conflict of interest.

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